Integrated Human Anatomy and Physiology - I

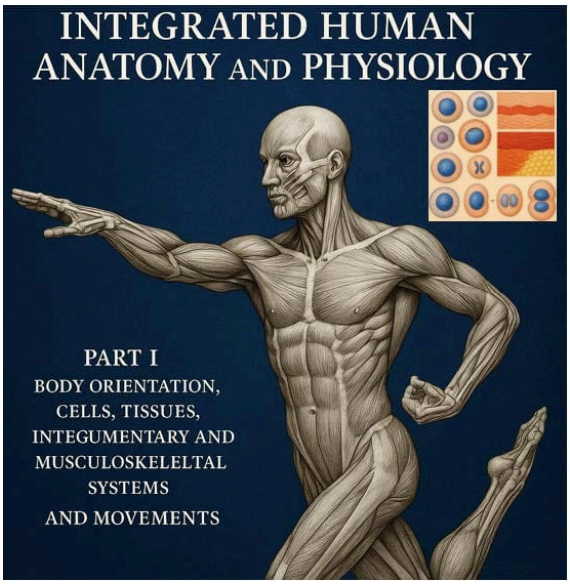
Lakshmikanta Sengupta and Susmita Sengupta

De Anza College

Biology

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Thumbnail: Detailed anatomical human figure with exposed muscles, alongside illustrations of cells and tissues. (AI-generated image created with Nano Banana)

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Detailed Licensing

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Program Page



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De Anza is proud of its diverse student community, and we hold our ZTC materials to the same standard of excellence that defines the college. Faculty across departments write, adapt, and review these resources themselves, keeping them accurate, current, and grounded in the perspectives of the students who use them, with accessibility and inclusive design built in from the start.

This program reflects the time and care our faculty invest in their students. If you have questions, feedback, or come across any issues with a ZTC resource, contact De Anza College's ZTC Grants Coordinator, Shagun Kaur.

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Accessibility Statement

Accessibility

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We selected LibreTexts as our preferred platform because of its commitment to accessibility. In addition to the platform's inherent accessibility, we collaborated with the LibreTexts team to fix any accessibility issues we found.

Our Accessibility Review Process

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1. **Template check.** The project coordinator and instructional designers checked the first chapter for accessibility as a model to ensure later chapters meet accessibility standards.
2. **Progress checks.** The manuscript was checked at approximately 40%, 60%, and 80% completion to catch and correct accessibility issues in production.
3. **Specialist review.** Once the manuscript was complete, an accessibility expert conducted an accessibility check.
4. **Remediation.** The author and the project manager who conducted the earlier progress checks worked together to remediate the issues identified by the accessibility expert.
5. **Final check.** The resource underwent another full check by the accessibility expert before the book was deemed ready for publication.

This process combines ongoing checks during writing with a final specialist review, so issues are caught early and confirmed fixed before publication.

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- The location of the problem (a web address or page/chapter description)
- A description of the problem you encountered
- The device, browser, and any assistive technology you were using (e.g., Windows 11, Google Chrome, JAWS screen reader)

Contact us: De Anza ZTC team

This statement was last updated August 2026

This resource was project-managed by **Shagun Kaur**, overseeing scope, budget, and schedule; stakeholder coordination via monthly meetings; training and platform support (LibreTexts, troubleshooting, technical support); QA/accessibility check scheduling; and licensing and copyright governance.

A Note on Known Limitations

No accessibility check is perfect. We've made a genuine, sustained effort to catch and fix issues throughout the writing and review process described above, but some barriers may remain, especially in complex or interactive content. We'd rather be upfront about that than claim a standard of perfection we can't guarantee.

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About the Book

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About the Authors

Lakshmikanta Sengupta



Figure 1: Portrait of coauthor Lakshmikanta Sengupta.

Lakshmikanta Sengupta, Ph.D., is a biology educator with 40 years of experience teaching and mentoring in postsecondary settings. His teaching areas include genetics, biotechnology, human biology, and human anatomy and physiology.

Over four decades in the classroom, he has developed a strong understanding of how undergraduate students think and learn, the misconceptions they often bring to biology, and the explanations and learning activities that best support student success. He views educational institutions as vibrant communities where learning, mentorship, and collaboration can flourish.

Expertise in Biology Education

Dr. Sengupta combines deep disciplinary knowledge with strong teaching practice. He is well suited to author an undergraduate biology textbook because he brings both subject expertise and a student-centered approach to instruction.

His qualifications include:

- broad knowledge of the biological sciences
- familiarity with the history of biology, current debates, and emerging trends
- continued engagement with current scholarship to keep content accurate and relevant
- skill in explaining complex biological ideas in clear, accessible language

He uses engaging narratives, real-world examples, case studies, and carefully designed visuals such as diagrams, charts, and infographics to help students understand unfamiliar material.

Teaching and Learning Approach

Dr. Sengupta's teaching is grounded in evidence-based, student-centered methods. He designs learning activities and assessments that help students monitor their understanding and strengthen scientific reasoning.

Examples include:

- discussion questions

- quizzes
- hands-on activities
- application-focused exercises

He also promotes collaboration among educators and students to share effective practices, improve teaching, and increase the quality and inclusivity of educational materials.

Scholarship of Teaching and Learning

Beyond the classroom, Dr. Sengupta has contributed to the scholarship of teaching and learning in biology. He collaborated with the Community College Biology Faculty Enhancement through Scientific Teaching (CCB FEST), a National Science Foundation-funded program.

He has also coauthored research publications in the following venues:

- Proceedings of the National Academy of Sciences
- CBE—Life Sciences Education

This combination of research engagement and classroom experience informs his textbook authorship and helps ensure that the content is both scientifically rigorous and pedagogically effective.

Broader Interests

Dr. Sengupta's broader interests enrich his teaching with relatable and concrete examples. These interests include:

- macro and micro photography, which highlight the details of natural and anatomical structures
- cooking, which connects biology to nutrition and health
- gardening, which reflects a commitment to sustainability and the natural world

Together, his disciplinary depth, teaching expertise, assessment-driven approach, and long experience working with diverse undergraduate populations support his qualifications as a high-quality author of this undergraduate biology textbook.

Susmita Sengupta



Figure 2: Portrait of coauthor Susmita Sengupta.

Susmita Sengupta, Ph.D., is a scientist and educator who has taught at Bay Area community colleges for nearly two decades. She has more than 29 years of teaching experience at both the undergraduate and graduate levels.

She currently teaches Human Anatomy and Physiology and Human Biology. She has also taught:

- Genetics
- General Biology
- Mammalian Cell Culture
- Gene Expression in Cell Culture

Professional Development and Training

Dr. Sengupta has participated in a number of professional development programs that support effective biology instruction. These include:

- Summer Institute of Functional Genomics and Bioinformatics for Community College Faculty, University of California, Davis (2005)
- Instructional Skills Workshop, De Anza College (2018, 2020)
- RSI training (Winter 2025)

From 2010 to 2014, she was an active participant in CCB FEST (Community College Faculty Enhancement through Scientific Teaching), a National Science Foundation-funded project at San Francisco State University.

Leadership and Service

Dr. Sengupta is currently a member of the Academic Advisory Committee for Explorer's Guide to Biology.

She has also served on several college committees, including:

- Curriculum Committee
- Educational Policies Committee
- Evaluation Committee
- Professional Development Committee

Through this work, she has contributed to program development and instructional quality.

Scholarship and Publications

Dr. Sengupta is the author of more than 26 publications in peer-reviewed journals. She has also developed laboratory manuals to support the courses she teaches.

Her experience in both classroom and laboratory instruction, combined with her long-term engagement in evidence-based teaching and curriculum design, gives her a strong understanding of how students learn biology.

This combination of:

- disciplinary expertise
- pedagogical training
- curriculum experience
- practical teaching experience with diverse student populations

makes her especially well qualified to serve as the author of an undergraduate textbook.

Selected Publications

- 2004: Molecular mechanisms, proteinopathies and therapeutic strategies in neurodegenerative disorders. Current Genomics, 5(4), 327-346.
- 2002: Pharmacogenetic applications of the post genomic era. Current Pharmaceutical Biotechnology, 3(2), 141-150.
- 2001: Bioengineered crops: commercial and ethical considerations. Current Genomics, 2(2), 181-197.
- 1998: Calcium-dependent metabolic regulations in prokaryotes indicate conserved nature of calmodulin gene. Indian Journal

of Experimental Biology, 36(2), 136-147.
- 1997: Phytolectins: the natural molecules with immense biotechnological potential. Indian Journal of Experimental Biology, 35, 11-18.
- 1990: Cytogenetic studies in human populations exposed to gas leak in Bhopal, India. Environmental Health Perspectives, 86, 323-326.

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1: NAVIGATING THE HUMAN BODY- ORIENTATION AND HOMEOSTASIS

Chapter Overview

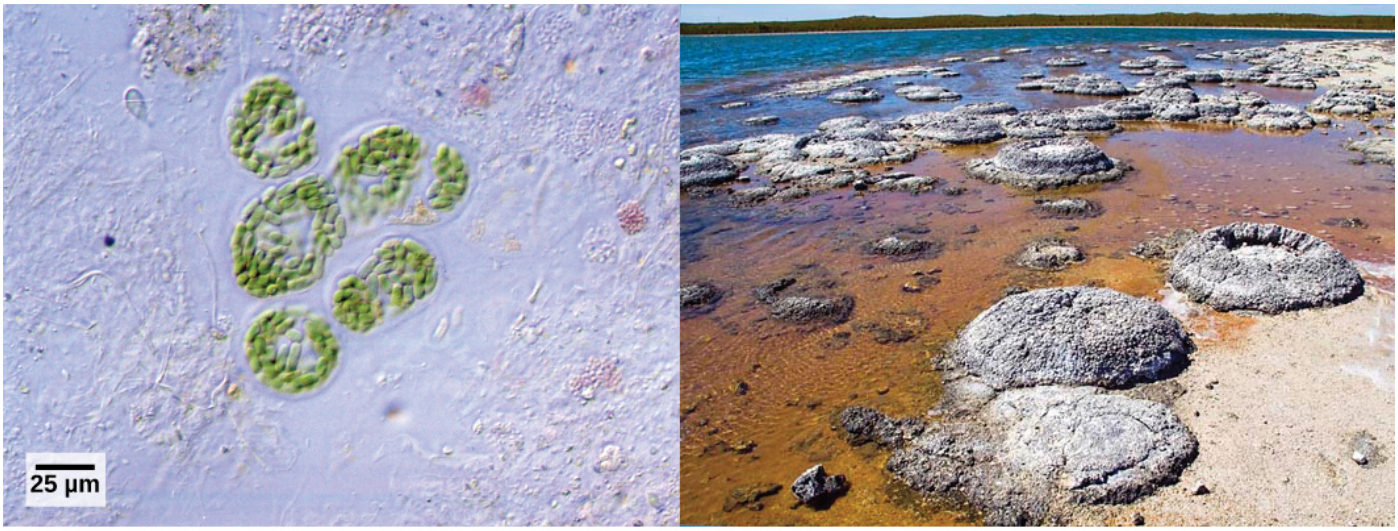


Figure 1.1: (a) Colonial green algae under a microscope and (b) modern stromatolites in a shallow shoreline environment. (CC BY 4.0; via Openstax).

Introduction to Human Anatomy and Physiology

Human anatomy is the scientific study of the body's structures. In the past, anatomy has primarily been studied via observing injuries, and later by the dissection of anatomical structures of cadavers, but in the past century, computer-assisted imaging techniques have allowed clinicians to look inside the living body. Human physiology is the scientific study of the chemistry and physics of the structures of the body. Physiology explains how the structures of the body work together to maintain life. It is difficult to study structure (anatomy) without knowledge of function (physiology). The two disciplines are typically studied together because form and function are closely related in all living things.

Levels of Structural Organization in the Human Body

Life processes of the human body are maintained at several levels of structural organization. These include the chemical, cellular, tissue, organ, organ system, and the organism level. Higher levels of organization are built from lower levels. Therefore, molecules combine to form cells, cells combine to form tissues, tissues combine to form organs, organs combine to form organ systems, and organ systems combine to form organisms.

Essential Life Processes of the Human Body

Most processes that occur in the human body are not consciously controlled. They occur continuously to build, maintain, and sustain life. These processes include: organization, in terms of the maintenance of essential body boundaries; metabolism, including energy transfer via anabolic and catabolic reactions; responsiveness; movement; and growth, differentiation, reproduction, and renewal.

Basic Needs for Human Survival

Humans cannot survive for more than a few minutes without oxygen, for more than several days without water, and for more than

several weeks without carbohydrates, lipids, proteins, vitamins, and minerals. Although the body can respond to high temperatures by sweating and to low temperatures by shivering and increased fuel consumption, long-term exposure to extreme heat and cold is not compatible with survival. The body requires a precise atmospheric pressure to maintain its gases in solution and to facilitate respiration—the intake of oxygen and the release of carbon dioxide. Humans also require blood pressure high enough to ensure that blood reaches all body tissues but low enough to avoid damage to blood vessels.

Homeostasis and Feedback Mechanisms

Homeostasis is the activity of cells throughout the body to maintain the physiological state within a narrow range that is compatible with life. Homeostasis is regulated by negative feedback loops and, much less frequently, by positive feedback loops. Both have the same components of a stimulus, sensor, control center, and effector; however, negative feedback loops work to prevent an excessive response to the stimulus, whereas positive feedback loops intensify the response until an end point is reached.

Anatomical Terminology, Body Planes, and Cavities

Ancient Greek and Latin words are used to build anatomical terms. A standard reference position for mapping the body's structures is the normal anatomical position. Regions of the body are identified using terms such as "occipital" that are more precise than common words and phrases such as "the back of the head." Directional terms such as anterior and posterior are essential for accurately describing the relative locations of body structures. Images of the body's interior commonly align along one of three planes: the sagittal, frontal, or transverse. The body's organs are organized in one of two main cavities—dorsal (also referred to posterior) and ventral (also referred to anterior)—which are further sub-divided according to the structures present in each area. The serous membranes have two layers—parietal and visceral—surrounding a fluid filled space. Serous membranes cover the lungs (pleural serosa), heart (pericardial serosa), and some abdominopelvic organs (peritoneal serosa).

Medical Imaging and the Study of the Living Body

Detailed anatomical drawings of the human body first became available in the fifteenth and sixteenth centuries; however, it was not until the end of the nineteenth century, and the discovery of X-rays, that anatomists and physicians discovered non-surgical methods to look inside a living body. Since then, many other techniques, including CT scans, MRI scans, PET scans, and ultrasonography, have been developed, providing more accurate and detailed views of the form and function of the human body.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own. By the end of this chapter, students should be able to:

- Understand and Apply Scientific Inquiry
  - Learn to formulate questions and hypotheses about the human body using the scientific method.
  - Engage in experiments or thought exercises that demonstrate how scientific inquiry is used to explore and understand physiological processes.
  - Develop critical thinking skills by analyzing data and drawing conclusions about human anatomy and physiology
- Explore Structural and Functional Organization
  - Identify and describe the major levels of structural organization in the human body, from cells to organ systems.
  - Identify and use the standard anatomical position as the reference for all anatomical descriptions; apply common anatomical directional terms (such as superior/inferior, anterior/posterior, medial/lateral, proximal/distal, superficial/deep); major body regions (axial and appendicular) and use regional terms to describe body locations; recognize the major anatomical planes and sections (sagittal, midsagittal, frontal/coronal, transverse/horizontal, oblique); major body cavities and identify key organs within them.
  - Analyze how the organization of body systems supports overall functionality and health.
- Comprehend Homeostasis and its Importance
  - Define homeostasis and explain its role in maintaining stable internal conditions despite external changes.

- Illustrate how feedback mechanisms, such as negative and positive feedback loops, regulate homeostasis in the body.
- Evaluate scenarios where homeostasis is disrupted, discussing the potential effects on health and wellness.

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1.1: The Process of Science

Introduction

Science is a process of learning and acquiring knowledge, and any person that does science is a “scientist.” This means that at any point in time we can all be scientists. The only separation between students learning about human anatomy and physiology, and those in lab coats working to discover the cure for a disease is the approach to understanding a phenomenon. The person performing as a “scientist” will work through a problem in a methodical approach that follows the logical rules of science. The most important part of the rules of science is to not have a prejudiced view of what will happen.

The methods of science include careful observation, record keeping, logical and mathematical reasoning, experimentation, and submitting conclusions to the scrutiny of others. Science also requires considerable imagination and creativity; a well-designed experiment is commonly described as elegant, or beautiful. Like politics, science has considerable practical implications and some science is dedicated to practical applications, such as the prevention of disease (Figure 1.1.1). Other science proceeds largely motivated by curiosity. Whatever its goal, there is no doubt that science, including biology, has transformed human existence and will continue to do so.

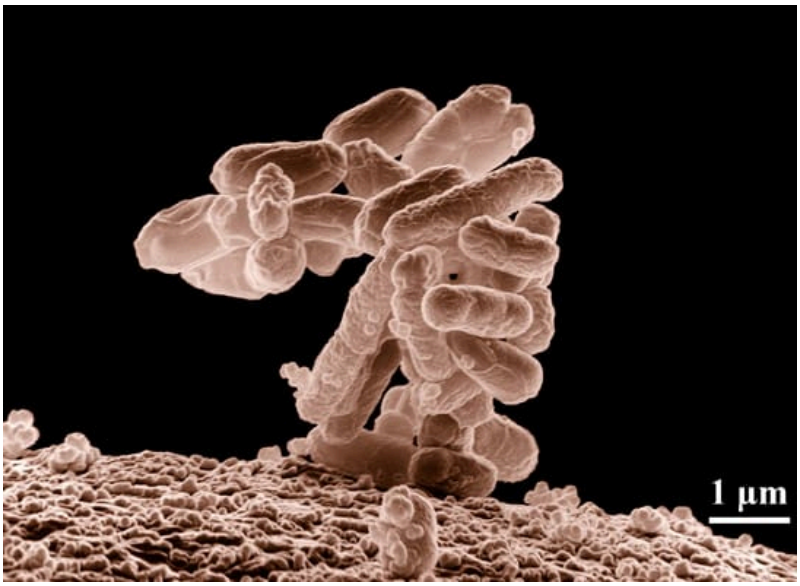


Figure 1.1.1: Biologists may choose to study Escherichia coli (E. coli), a bacterium that is a normal resident of our digestive tracts but which is also sometimes responsible for disease outbreaks. In this micrograph, the bacterium is visualized using a scanning electron microscope and digital colorization. (CC PDM 1.0; Eric Erbe; digital colorization by Christopher Pooley via USDA-ARS). Alternative text description of Figure 1.1.1.

Science as a Way of Knowing

Science is a process of learning and acquiring knowledge, and any person that does science is a “scientist.” This means that at any point in time we can all be scientists. The only separation between students learning about human anatomy and physiology, and those in lab coats working to discover the cure for a disease is the approach to understanding a phenomenon. The person performing as a “scientist” will work through a problem in a methodical approach that follows the logical rules of science. The most important part of the rules of science is to not have a prejudiced view of what will happen. Yes, you will have an idea based on previous experience, but you must approach every problem as a new experience. When you approach each problem that you wish to solve as a new experience then you are beginning to use the scientific approach and thus are using science.

There is no set way on how to do science beyond following the general rules of science. The rules of science, and the scientific method, are intended to make the process as objective as possible, and thereby gain some level of understanding that is as close to a “true reality” as possible. One constant theme is that there is no certainty in science, only levels of probability and possibility for explaining the phenomenon being studied. Because of this, scientific understanding can always be challenged,

or even changed, with new observations, or different interpretations of previous observations. New tools and techniques have resulted in new observations, sometimes forcing revision of what had been taken as fact in the past. With this ever-changing understanding and base of evidence there is only one certainty about science, which is, science does not “prove” it only allows for observations and explanations of those observations based on the assumptions that govern modern science.
Underlying the world of modern science are four major assumptions that must be held as being true for observations to accurate, valid and reliable. First of these assumptions is that the world is real, and that the physical universe exists and is not just our imagination. This is regardless of whether, or not, it is something that can be sensed. Secondly, humans (or animals) can accurately perceive the real world, and that humans can express such understanding. Thirdly, processes that occur in nature can sufficiently explain the existence of the physical universe that we live in. Lastly, that the process being observed operates the same way, everywhere and at all times within the physical universe.
The way that we use these assumptions to study the human body and any other natural phenomenon is through the scientific method. This method of learning follows a set of rules that leads to a process of asking and answering questions to search for cause-and-effect relationships in a phenomenon, or action, that we are examining.

Importance of Scientific Inquiry Process in Healthcare

The scientific inquiry process is crucial in healthcare because it provides a standardized, objective framework for improving patient care through evidence-based medicine, developing new treatments and diagnostic tools, and enhancing disease prevention. By minimizing bias, it ensures that medical decisions and innovations are grounded in reliable data, leading to better patient outcomes and more effective public health strategies.

Scientific Inquiry Process

- Systematically evaluate and apply the best available evidence, combining it with clinical experience and patient values to make the most effective medical decisions.
- Leads to the development of new therapies, diagnostic tools, and interventions, such as advancements in stroke treatment, that directly improve patient outcomes.
- Helps identify risk factors for diseases and is instrumental in developing and implementing prevention strategies, like vaccinations and public health campaigns for lifestyle changes.
- Provides an objective and standardized approach to research, which limits the influence of personal beliefs and preconceived notions, ensuring more reliable results.
- Helps healthcare professionals understand the underlying biological mechanisms of diseases, which is essential for developing effective treatments and management strategies.
- Improves diagnostic accuracy, is vital to reduce errors.
- Can be used to shape health policy and are crucial for both improving clinical practices and addressing public health challenges.

Scientific Investigation: Steps and Principles

It is very important to remember that the use of the scientific method is not developed to “prove” something “true”. Instead, it is intended to test how, what, when, where, and why something occurred. Because of this, we tend to think of the outcome of the use of the scientific method as leading to a contingent base of knowledge, rather than an absolute base of knowledge. That understanding a phenomenon is based on what evidence can support our understanding at any given point in time. This evidence changes over time and therefore our understanding of the phenomenon changes. Two methods of logical thinking are used: inductive reasoning and deductive reasoning.

- Inductive reasoning is a form of logical thinking that uses related observations to arrive at a general conclusion. This type of reasoning is common in descriptive science. A life scientist such as a biologist makes observations and records them. These data can be qualitative (descriptive) or quantitative (consisting of numbers), and the raw data can be supplemented with drawings, pictures, photos, or videos. From many observations, the scientist can infer conclusions (inductions) based on evidence. Inductive reasoning involves formulating generalizations inferred from careful observation and the analysis of a large amount of data. Brain studies often work this way. Many brains are observed while people are doing a task. The part of the brain that lights up, indicating activity, is then demonstrated to be the part controlling the response to that task.
- Deductive reasoning or deduction is the type of logic used in hypothesis-based science. In deductive reasoning, the pattern of thinking moves in the opposite direction as compared to inductive reasoning. Deductive reasoning is a form of logical thinking that uses a general principle or law to forecast specific results. From those general principles, a scientist can extrapolate and predict the specific results that would be valid as long as the general principles are valid. For example, a

prediction would be that if the climate is becoming warmer in a region, the distribution of plants and animals should change. Comparisons have been made between distributions in the past and the present, and the many changes that have been found are consistent with a warming climate. Finding the change in distribution is evidence that the climate change conclusion is a valid one.

Both types of logical thinking are related to the two main pathways of scientific study: descriptive science and hypothesis-based science. Descriptive (or discovery) science aims to observe, explore, and discover, while hypothesis-based science begins with a specific question or problem and a potential answer or solution that can be tested. The boundary between these two forms of study is often blurred, because most scientific endeavors combine both approaches. Observations lead to questions, questions lead to forming a hypothesis as a possible answer to those questions, and then the hypothesis is tested. Thus, descriptive science and hypothesis-based science are in continuous dialogue.

How do we do this investigation? The scientific method is a logical process that can be viewed as a sequential step-wise process that follows these key steps:

1. Observation -The scientific process typically starts with an observation (often a problem to be solved) that leads to a question. Let's think about a simple problem that starts with an observation and apply the scientific method to solve the problem. One Monday morning, a student arrives at class and quickly discovers that the classroom is too warm. That is an observation that also describes a problem: the classroom is too warm.
2. Question about Observation: What? When? Where? Why? How? for the observation. The student then asks a question: "Why is the classroom so warm?"
3. Hypothesis: In order to answer these questions, researchers begin by formulating testable hypotheses. A hypothesis is a tentative statement describing the relationship between the variables in an experiment. Research hypotheses are written as if/then statements that include dependent and independent variables. To solve a problem, several hypotheses may be proposed. For example, one hypothesis might be, "The classroom is warm because no one turned on the air conditioning." But there could be other responses to the question, and therefore other hypotheses may be proposed. A second hypothesis might be, "The classroom is warm because there is a power failure, and so the air conditioning doesn't work." Once a hypothesis has been selected, a prediction may be made. A prediction is similar to a hypothesis but it typically has the format "If . . . then . . . ." For example, the prediction for the first hypothesis might be, "If the student turns on the air conditioning, then the classroom will no longer be too warm."
4. Observation and question
    - Observation: The classroom is uncomfortably warm.
    - Question: "Why is the classroom so warm?"
5. Formulation of hypotheses
    - Hypothesis 1: The classroom is warm because the air conditioning is not turned on. This is a testable and falsifiable statement.
    - Hypothesis 2 (alternative): The classroom is warm because the air conditioning is broken, even if it is turned on. This is a valid hypothesis if the first one is disproven.
6. Make a prediction
    - Predictions often follow an "If... then..." format based on the hypothesis.
    - Prediction for Hypothesis 1: "If I turn on the air conditioning, then the classroom will get cooler."
7. Design and conduct an experiment
    - The experiment is designed to test the prediction. Experiment: Check the thermostat and turn the air conditioning on.
    - Variable: The state of the air conditioning (on or off).
    - Control: The room's initial state (warm) and the experiment without the AC being turned on.
8. Analyze the results and draw a conclusion.
9. If the hypothesis is supported:The air conditioning was off, and turning it on cools the room. The hypothesis is accepted.
10. If the hypothesis is not supported:
    - The air conditioning was already on but not working. The original hypothesis is rejected, and the student would then test an alternative like Hypothesis 2.
    - Imagine that as a student in human anatomy and physiology, you are working on a physiology project involving muscle contraction and temperature. You observe that cold hands do not function as well at performing certain tasks requiring manual dexterity than do warm hands. You decide to test grip strength under different temperature conditions using a handgrip dynamometer, which measures the strength of contraction of hand and forearm muscles.
11. Methods and Data - There are many different methods to study the world, but they can be broken down into two main types – quantitative and qualitative . The data collected can also be broken down into these categories. This may depend on the method used, but it is possible to complete mixed methods research resulting in both types of data.

Table 1.1.1: Comparison of Quantitative and Qualitative Data in Health Research

Category	Quantitative Data	Qualitative Data
Definition	Quantitative data are the result of counting or measuring attributes of a population.	Qualitative data are the result of categorizing or describing attributes of a population.
Data that you will see	Quantitative data are always numbers, determine the what, who, when, and where of health-related events.	Qualitative data include almost any non-numerical data, generally described by words or letters.
Examples	• Demographics: Age, height, weight, and sex • Clinical measurements: Blood pressure, temperature, heart rate, and cholesterol levels • Disease statistics: The number of people with a specific condition (prevalence), the number of new cases (incidence), and mortality rates • Treatment outcomes: The effectiveness of a drug, length of hospital stay, or number of patients achieving a specific health goal	Smoker/Non-smoker Questionnaire response (agree, disagree, neutral) Patient perceptions of quality of care Hair color Blood type Ethnic group

Experimentation and Recording of Results

A reproducible, stepwise sequence of procedures based on the phenomenon under investigation and established scientific principles. The purpose of the experiment is to test the validity of the hypothesis while objectively recording observations and responses.

- Analysis of Results: The logical and statistical evaluation of experimental data used to determine whether the hypothesis is supported or refuted.
- Interpretation and Inference: The process of using inductive reasoning and evidence-based thinking to explain how the results relate to the phenomenon being studied and contribute to scientific understanding.
- Conclusion: A summary of the findings based on the evidence collected. The conclusion indicates whether the hypothesis was supported and may lead to additional questions or new hypotheses for future investigation.

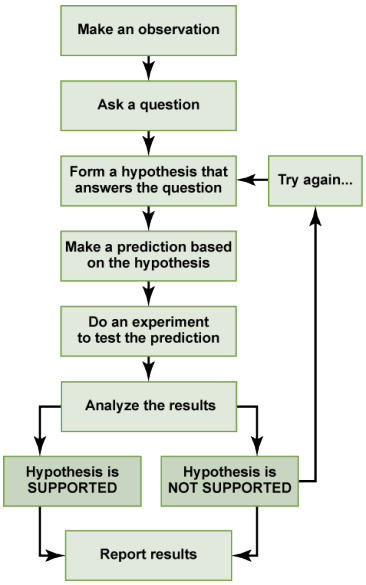


Figure 1.1.2: The scientific method is a series of defined steps that include experiments and careful observation. If a hypothesis is not supported by data, a new hypothesis can be proposed. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 1.1.2.

In practice, the scientific method is not as rigid and structured as it might at first appear. Sometimes an experiment leads to conclusions that favor a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Many times, science does not operate in a linear fashion; instead, scientists continually draw inferences and make generalizations, finding patterns as their research proceeds. Scientific reasoning is more complex than the scientific method alone suggests.

Basic and Applied Science

The scientific community has been debating for the last few decades about the value of different types of science. Is it valuable to pursue science for the sake of simply gaining knowledge, or does scientific knowledge only have worth if we can apply it to solving a specific problem or bettering our lives? This question focuses on the differences between two types of science: basic science and applied science.

Basic science, often referred to as "pure" science, focuses on gaining knowledge and understanding fundamental principles without necessarily aiming for immediate practical applications. It involves the exploration of natural phenomena and underlying mechanisms.

In contrast, applied science uses the principles and findings from basic science to address practical problems and develop new technologies, treatments, or interventions to solve real-world health challenges.

Both are essential; basic science lays the groundwork for applied innovations, while applied science provides feedback and new questions for basic research.

An example of the link between basic and applied research is the Human Genome Project, a study in which each human chromosome was analyzed and mapped to determine the precise sequence of DNA subunits and the exact location of each gene. (The gene is the basic unit of heredity; an individual's complete collection of genes is his or her genome.) Other organisms have also been studied as part of this project to gain a better understanding of human chromosomes. The Human Genome Project (Figure 1.1.3) relied on basic research carried out with non-human organisms and, later, with the human genome. An important end goal eventually became using the data for applied research seeking cures for genetically related diseases.

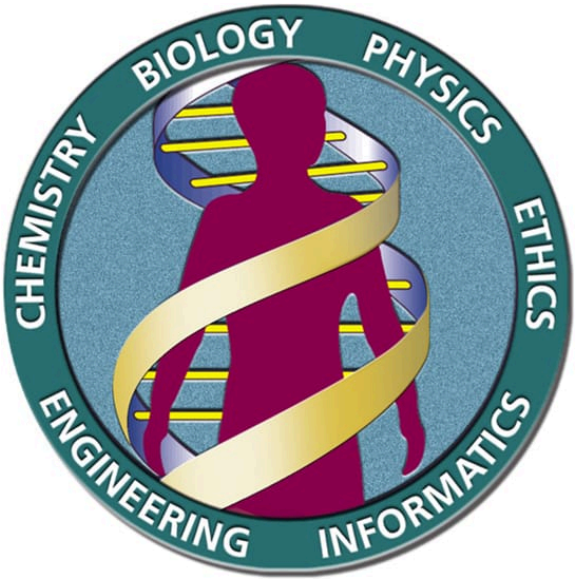


Figure 1.1.3: The Human Genome Project was a 13-year collaborative effort among researchers working in several different fields of science. The project was completed in 2003. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 1.1.3.

While research efforts in both basic science and applied science are usually carefully planned, it is important to note that some discoveries are made by serendipity, that is, by means of a fortunate accident or a lucky surprise. Penicillin was discovered when biologist Alexander Fleming accidentally left a petri dish of Staphylococcus bacteria open. An unwanted mold grew, killing the bacteria. The mold turned out to be Penicillium, and a new antibiotic was discovered. Even in the highly organized world of science, luck—when combined with an observant, curious mind—can lead to unexpected breakthroughs.

Reporting Scientific Work

Whether research is categorized as basic science or applied science, scientists must share their findings so that other researchers can build upon their discoveries. Communication and collaboration within and among scientific disciplines are essential for the advancement of knowledge. For this reason, an important aspect of a scientist's work is disseminating results and communicating with peers. Scientific reporting involves conveying research methods, findings, and conclusions clearly and accurately to both the scientific community and the broader public.

Understanding the "what," "why," "when," "how," and "where" of scientific reporting helps researchers effectively communicate their work and contribute to the advancement of scientific knowledge.

- **Analysis of Results:** The logical and statistical evaluation of experimental data used to determine whether a hypothesis is supported or refuted.
- **Interpretation and Inference:** The process of using inductive reasoning and evidence-based thinking to explain how the results and observations obtained during experimentation contribute to our understanding of a phenomenon and expand scientific knowledge of the principles governing it.
- **Conclusion:** A summary of the findings based on the evidence collected during the investigation. The conclusion indicates whether the hypothesis was supported and may lead to additional questions, revised hypotheses, or further experimentation.

Basic Science

Focus

- Investigating the fundamental organization of cells, tissues, organs, and organ systems.
- Understanding physiological processes such as cellular respiration, neural signaling, and muscle contraction.
- Exploring the molecular and biochemical basis of bodily functions.

Example Topics

- The molecular structure of DNA and its role in genetic inheritance.
- The electrophysiological properties of neurons and how they transmit signals.
- The anatomy and physiology of the cardiovascular system.

Applied Science

Focus

- Developing medical treatments and interventions based on scientific principles.
- Designing diagnostic tools and medical equipment.
- Applying anatomical and physiological knowledge in medicine, rehabilitation, and sports science.

Example Topics

- The design and use of artificial organs and prosthetic devices.
- The development of drugs that target specific physiological pathways.
- Surgical techniques based on detailed anatomical knowledge.
- **What?** Scientific reporting is the structured presentation of research findings, methodologies, and conclusions. It includes papers, articles, reports, and presentations. The goal is to document the research process, communicate findings, and share insights with others.
- **Why?** The primary purpose of scientific reporting is to disseminate knowledge, contribute to the scientific body of knowledge, and allow for peer review and replication. It promotes transparency, facilitates collaboration, and drives innovation by enabling researchers to build on existing work.
- **When?** Scientific findings are reported after data have been collected, analyzed, and interpreted. Research may be communicated in stages, such as preliminary findings presented at conferences, followed by more comprehensive reports published in scholarly journals.
- **How?** Scientific work is typically reported using a structured format that includes sections such as Abstract, Introduction, Methods, Results, Discussion, and Conclusion. Adhering to these conventions enhances clarity, consistency, and reproducibility.
- **Where?** Scientific work is reported through a variety of venues, including academic journals, conferences, symposiums, books, and online repositories. The choice of venue depends on the field of study, the significance of the findings, and the intended audience.

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1.2: Structure and Function Through a Scientific Lens

The Study of Body Structure

Human Anatomy: The Study of Body Structures

Human anatomy is the scientific study of the body's structures. Some of these structures are very small and can only be observed and analyzed with the assistance of a microscope. Other larger structures can readily be seen, manipulated, measured, and weighed. The word "anatomy" comes from a Greek root that means "to cut apart." Human anatomy was first studied by observing the exterior of the body and observing the wounds of soldiers and other injuries. Later, physicians were allowed to dissect bodies of the dead to augment their knowledge. When a body is dissected, its structures are cut apart in order to observe their physical attributes and their relationships to one another. Dissection is still used in medical schools, anatomy courses, and in pathology labs. In order to observe structures in living people, however, a number of imaging techniques have been developed. These techniques allow clinicians to visualize structures inside the living body such as a cancerous tumor or a fractured bone.

Gross and Microscopic Anatomy

Like most scientific disciplines, anatomy has areas of specialization. Gross anatomy is the study of the larger structures of the body, those visible without the aid of magnification (Figure $1.2.1a$). Macro- means "large," thus, gross anatomy is also referred to as macroscopic anatomy. In contrast, micro- means "small," and microscopic anatomy is the study of structures that can be observed only with the use of a microscope or other magnification devices (Figure $1.2.1b$). Microscopic anatomy includes cytology, the study of cells and histology, the study of tissues. As the technology of microscopes has advanced, anatomists have been able to observe smaller and smaller structures of the body, from slices of large structures like the heart, to the three-dimensional structures of large molecules in the body.

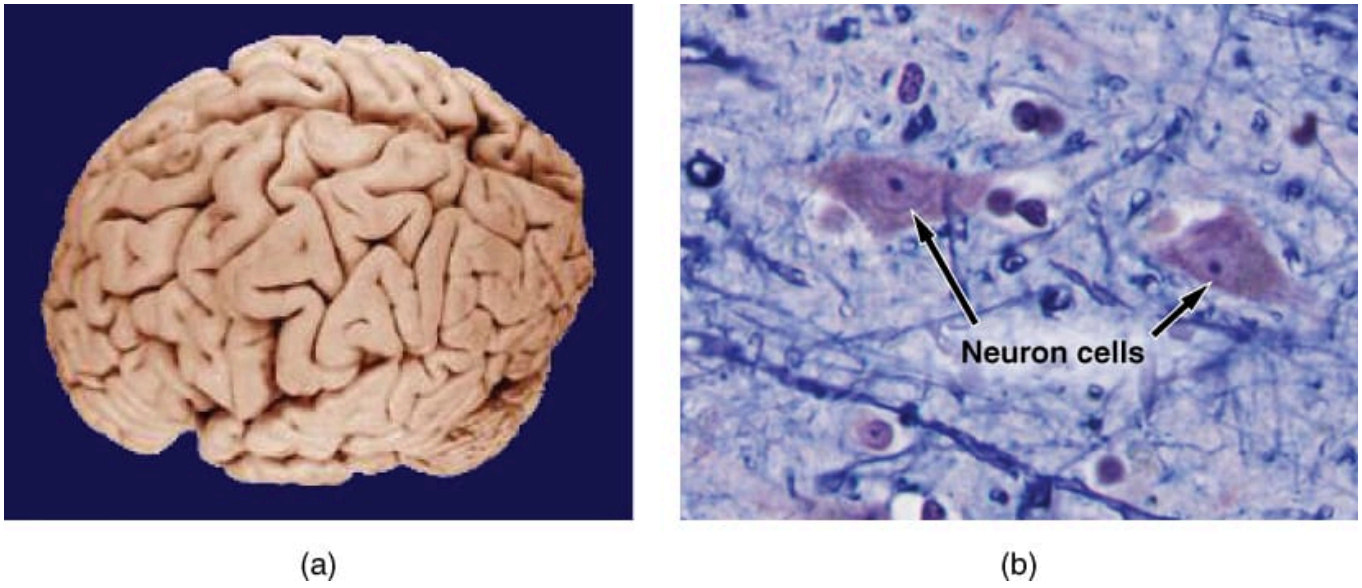


Figure $1.2.1$: Gross and Microscopic Anatomy (a) Gross anatomy considers large structures such as the brain. (b) Microscopic anatomy can deal with the same structures, though at a different scale. This is a micrograph of nerve cells from the brain. LM × 1600. (CC BY 4.0;via Wikimedia Commons). Alternative text description of Figure $1.2.1$.

Anatomists take two general approaches to the study of the body's structures: regional and systemic. Regional anatomy is the study of the interrelationships of all of the structures in a specific body region, such as the abdomen. Studying regional anatomy helps us appreciate the interrelationships of body structures, such as how muscles, nerves, blood vessels, and other structures work together to serve a particular body region. In contrast, systemic anatomy is the study of the structures that make up a discrete body system—that is, a group of structures that work together to perform a unique body function. For example, a systemic

anatomical study of the muscular system would consider all of the skeletal muscles of the body.

Human Physiology: The Study of Body Function

Human physiology is the branch of biological science that investigates the normal functions of the human body, emphasizing the mechanical, physical, and biochemical processes by which cells, tissues, organs, and organ systems operate and interact to maintain homeostasis and support life. Homeostasis is the state of steady internal conditions maintained by living things. The study of physiology certainly includes observation, both with the naked eye and with microscopes, as well as manipulations and measurements. However, current advances in physiology usually depend on carefully designed laboratory experiments that reveal the functions of the many structures and chemical compounds that make up the human body.

Like anatomists, physiologists typically specialize in a particular branch of physiology. For example, neurophysiology is the study of the brain, spinal cord, and nerves and how these work together to perform functions as complex and diverse as vision, movement, and thinking. Physiologists may work from the organ level (exploring, for example, what different parts of the brain do) to the molecular level (such as exploring how an electrochemical signal travels along nerves).

Form is closely related to function in all living things. For example, the thin flap of your eyelid can snap down to clear away dust particles and almost instantaneously slide back up to allow you to see again. At the microscopic level, the arrangement and function of the nerves and muscles that serve the eyelid allow for its quick action and retreat. At a smaller level of analysis, the function of these nerves and muscles likewise relies on the interactions of specific molecules and ions. Even the three-dimensional structure of certain molecules is essential to their function.

Your study of anatomy and physiology will make more sense if you continually relate the form of the structures you are studying to their function. In fact, it can be somewhat frustrating to attempt to study anatomy without an understanding of the physiology that a body structure supports. Imagine, for example, trying to appreciate the unique arrangement of the bones of the human hand if you had no conception of the function of the hand. Fortunately, your understanding of how the human hand manipulates tools—from pens to cell phones—helps you appreciate the unique alignment of the thumb in opposition to the four fingers, making your hand a structure that allows you to pinch and grasp objects and type text messages.

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1.3: Levels of Organization of the Human Body

The Hierarchy of Structural Organization in Human Anatomy

Before you begin to study the different structures and functions of the human body, it is helpful to consider its basic architecture; that is, how its smallest parts are assembled into larger structures. It is convenient to consider the structures of the body in terms of fundamental levels of organization that increase in complexity: subatomic particles, atoms, molecules, organelles, cells, tissues, organs, organ systems, organisms and biosphere Figure 1.3.1.

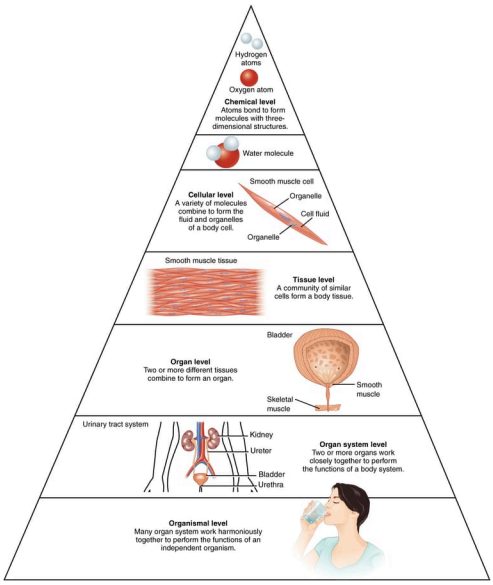


Figure 1.3.1: Levels of Structural Organization of the Human Body. The organization of the body often is discussed in terms of six distinct levels of increasing complexity, from the smallest chemical building blocks to a unique human organism. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 1.3.1.

The Levels of Organization

To study the chemical level of organization, scientists consider the simplest building blocks of matter: subatomic particles, atoms and molecules. All matter in the universe is composed of one or more unique pure substances called elements, familiar examples of which are hydrogen, oxygen, carbon, nitrogen, calcium, and iron. The smallest unit of any of these pure substances (elements) is an atom. Atoms are made up of subatomic particles such as the proton, electron and neutron. Two or more atoms combine to form a molecule, such as the water molecules, proteins, and sugars found in living things. Molecules are the chemical building blocks of all body structures.

A cell is the smallest independently functioning unit of a living organism. Even bacteria, which are extremely small, independently-living organisms, have a cellular structure. Each bacterium is a single cell. All living structures of human anatomy contain cells, and almost all functions of human physiology are performed in cells or are initiated by cells.

A human cell typically consists of flexible membranes that enclose cytoplasm, a water-based cellular fluid together with a variety of tiny functioning units called organelles. In humans, as in all organisms, cells perform all functions of life. A tissue is a group of many similar cells (though sometimes composed of a few related types) that work together to perform a specific function. An organ is an anatomically distinct structure of the body composed of two or more tissue types. Each organ performs one or more specific physiological functions. An organ system is a group of organs that work together to perform major functions or meet physiological needs of the body.

This book covers eleven distinct organ systems in the human body (Figure 1.3.2 and Figure 1.3.3). Assigning organs to organ

systems can be imprecise since organs that “belong” to one system can also have functions integral to another system. In fact, most organs contribute to more than one system.

In this book and throughout your studies of biological sciences, you will often read descriptions related to similarities and differences among biological structures, processes, and health related to a person's biological sex. People often use the words "female" and "male" to describe two different concepts: our sense of gender identity, and our biological sex as determined by our chromosomes, hormones, organs, and other physical characteristics. For some people, gender identity is different from biological sex or their sex assigned at birth. Throughout this book, "female" and "male" refer to sex only, and the typical anatomy and physiology of XX and XY individuals is discussed.

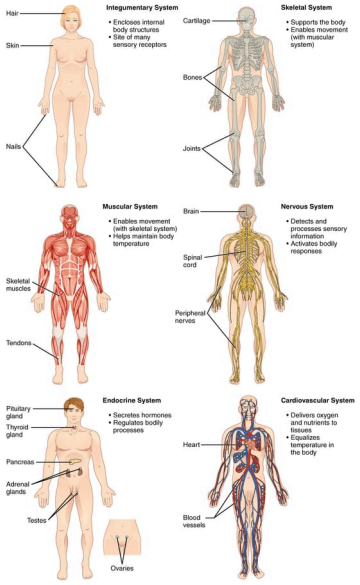


Figure 1.3.2: Organ Systems of the Human Body Organs that work together are grouped into organ systems. (CC BY 4.0; via Anatomy & Physiology). Alternative text description of Figure 1.3.2.

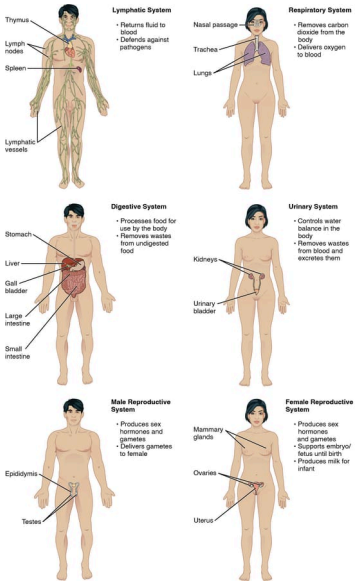


Figure 1.3.3: Organ Systems of the Human Body that work together are grouped into organ systems. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 1.3.3.

The organism level is the highest level of organization. An organism is a living being that has a cellular structure and that can independently perform all physiologic functions necessary for life. In multicellular organisms, including humans, all cells, tissues, organs, and organ systems of the body work together to maintain the life and health of the organism.

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1.4: Essentials of Human Life

Characteristics of Human Life and Physiology

The different organ systems each have different functions and therefore unique roles to perform in physiology. These many functions can be summarized in terms of a few that we might consider definitive of human life: organization, metabolism, responsiveness, movement, development, and reproduction.

Organization

A human body consists of trillions of cells organized in a way that maintains distinct internal compartments. These compartments keep body cells separated from external environmental threats and keep the cells moist and nourished. They also separate internal body fluids from the countless microorganisms that grow on body surfaces, including the lining of certain passageways that connect to the outer surface of the body. The intestinal tract, for example, is home to more bacterial cells than the total of all human cells in the body, yet these bacteria are outside the body and cannot be allowed to circulate freely inside the body.

Cells, for example, have a cell membrane (also referred to as the plasma membrane) that keeps the intracellular environment—the fluids and organelles—separate from the extracellular environment. Blood vessels keep blood inside a closed circulatory system, and nerves and muscles are wrapped in connective tissue sheaths that separate them from surrounding structures. In the chest and abdomen, a variety of internal membranes keep major organs such as the lungs, heart, and kidneys separate from others.

The body's largest organ system is the integumentary system, which includes the skin and its associated structures, such as hair and nails. The surface tissue of skin is a barrier that protects internal structures and fluids from potentially harmful microorganisms and other toxins.

Metabolism

Metabolism is the sum of all chemical reactions in the body that transform energy and matter to sustain life (Figure 1.4.1). In keeping with the first law of thermodynamics, these reactions do not create or destroy energy; they convert it from one form to another so you can fuel movement, maintain vital functions, and build and repair body structures. There are two types of complementary reactions that accomplish this: anabolism and catabolism. These two processes are tightly coupled: energy released by catabolism drives anabolism, maintaining the body's energy balance and homeostasis.

- Anabolism (building) is the process whereby the body uses energy to assemble larger, more complex molecules from smaller, simpler ones. Examples include synthesizing proteins from amino acids, glycogen from glucose. Anabolism supports growth, repair, and storage and is powered mainly by ATP and NADPH.
- In Catabolism (breaking down) the body breaks complex molecules into simpler products, releasing energy that is captured as ATP (and in carriers like NADH/$FADH_2$). Examples include glycolysis, β-oxidation of fatty acids, and the citric acid cycle; end products include CO_2, H_2O, and urea (from nitrogen). Catabolism provides the fuel and building blocks needed for cellular work and for subsequent anabolic processes.

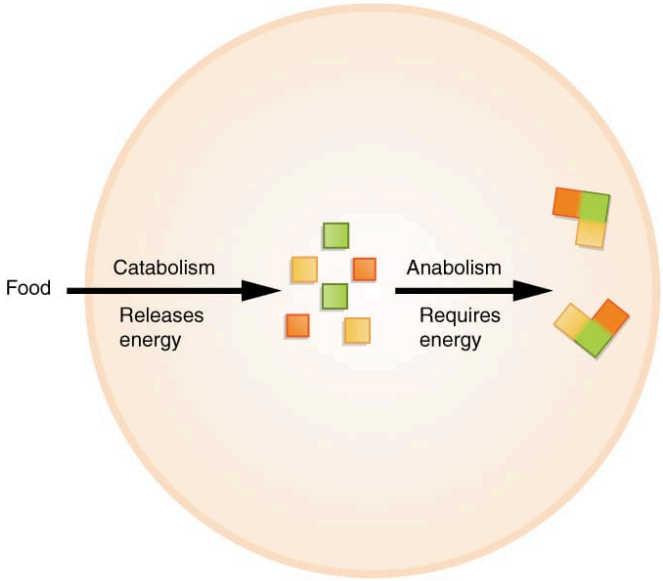


Figure 1.4.1: Anabolic reactions are building reactions, and they consume energy. Catabolic reactions break materials down and release energy. Metabolism includes both anabolic and catabolic reactions. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 1.4.1.

Every cell in your body makes use of a chemical compound, adenosine triphosphate (ATP), to store and release energy. The cell stores energy in the synthesis (anabolism) of ATP, then moves the ATP molecules to the location where energy is needed to fuel cellular activities. Then the ATP is broken down (catabolism) and a controlled amount of energy is released, which is used by the cell to perform a particular job.

Responsiveness

Responsiveness is the ability of an organism to adjust to changes in its internal and external environments. An example of responsiveness to external stimuli could include moving toward sources of food and water and away from perceived dangers. Changes in an organism's internal environment, such as increased body temperature, can cause the responses of sweating and the dilation of blood vessels in the skin in order to decrease body temperature, as shown by the runners in Figure 1.4.2.

Movement

Human movement includes not only actions at the joints of the body, but also the motion of individual organs and even individual cells. As you read these words, red and white blood cells are moving throughout your body, muscle cells are contracting and relaxing to maintain your posture and to focus your vision, and glands are secreting chemicals to regulate body functions. Your body is coordinating the action of entire muscle groups to enable you to move air into and out of your lungs, to push blood throughout your body, and to propel the food you have eaten through your digestive tract. Consciously, of course, you contract your skeletal muscles to move the bones of your skeleton to get from one place to another (as the runners are doing in Figure 1.4.2), and to carry out all of the activities of your daily life.



Figure 1.4.2: Marathon demonstrate two characteristics of living humans—responsiveness and movement. Anatomic structures and physiological processes allow runners to coordinate the action of muscle groups and sweat in response to rising internal body temperature. (CC BY 4.0; via Wikimedia Commons).

Development, Growth and Reproduction

Development is all of the changes the body goes through in life. Development includes the process of differentiation, in which unspecialized cells become specialized in structure and function to perform certain tasks in the body. Development also includes the processes of growth and repair, both of which involve cell differentiation.

Growth is the increase in body size. Humans, like all multicellular organisms, grow by increasing the number of existing cells, increasing the amount of non-cellular material around cells (such as mineral deposits in bone), and, within very narrow limits, increasing the size of existing cells.

Reproduction is the formation of a new organism from parent organisms. In humans, reproduction is carried out by the male and female reproductive systems. Because death will come to all complex organisms, without reproduction, the line of organisms would end.

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1.5: Requirements for Human Life

Survival Needs of the Human Body

Humans have been acclimating to life on Earth for at least the past 200,000 years. Earth and its atmosphere have provided us with air to breathe, water to drink, and food to eat, but these are not the only requirements for survival. Although you may rarely think about it, you also cannot live outside of a certain range of temperature and pressure that the surface of our planet and its atmosphere provides. The next sections explore these four requirements of life.

Oxygen

Atmospheric air is only about 20 percent oxygen, but that oxygen is a key component of the chemical reactions that keep the body alive, including the reactions that produce ATP. Brain cells are especially sensitive to lack of oxygen because of their requirement for a high-and-steady production of ATP. Brain damage is likely within five minutes without oxygen, and death is likely within ten minutes.

Nutrients

A nutrient is a substance in foods and beverages that is essential to human survival. The three basic classes of nutrients are water, the energy-yielding and body-building nutrients, and the micronutrients (vitamins and minerals).

The most critical nutrient is water. Depending on the environmental temperature and our state of health, we may be able to survive for only a few days without water. The body's functional chemicals are dissolved and transported in water, and the chemical reactions of life take place in water. Moreover, water is the largest component of cells, blood, and the fluid between cells, and water makes up about 70 percent of an adult's body mass. Water also helps regulate our internal temperature and cushions, protects, and lubricates joints and many other body structures.

The energy-yielding nutrients are primarily carbohydrates and lipids, while proteins mainly supply the amino acids that are the building blocks of the body itself. You ingest these in plant and animal foods and beverages, and the digestive system breaks them down into molecules small enough to be absorbed. The breakdown products of carbohydrates and lipids can then be used in the metabolic processes that convert them to ATP. Although you might feel as if you are starving after missing a single meal, you can survive without consuming the energy-yielding nutrients for at least several weeks.

Water and the energy-yielding nutrients are also referred to as macronutrients because the body needs them in large amounts. In contrast, micronutrients are vitamins and minerals. These elements and compounds participate in many essential chemical reactions and processes, such as nerve impulses, and some, such as calcium, also contribute to the body's structure. Your body can store some of the micronutrients in its tissues, and draw on those reserves if you fail to consume them in your diet for a few days or weeks. Some others micronutrients, such as vitamin C and most of the B vitamins, are water-soluble and cannot be stored, so you need to consume them every day or two.

Narrow Range of Temperature

You have probably seen news stories about athletes who died of heat stroke, or hikers who died of exposure to cold. Such deaths occur because the chemical reactions upon which the body depends can only take place within a narrow range of body temperature, from just below to just above 37°C (98.6°F). When body temperature rises well above or drops well below normal, certain proteins (enzymes) that facilitate chemical reactions lose their normal structure and their ability to function and the chemical reactions of metabolism cannot proceed.

That said, the body can respond effectively to short-term exposure to heat Figure 1.5.1 or cold. One of the body's responses to heat is, of course, sweating. As sweat evaporates from skin, it removes some thermal energy from the body, cooling it. Adequate water (from the extracellular fluid in the body) is necessary to produce sweat, so adequate fluid intake is essential to balance that loss during the sweat response. Not surprisingly, the sweat response is much less effective in a humid environment because the air is already saturated with water. Thus, the sweat on the skin's surface is not able to evaporate, and internal body temperature

can get dangerously high.



Figure 1.5.1: Humans acclimate to some degree to repeated exposure to high temperatures. (CC BY 2.0; via Wikimedia Commons).

The body can also respond effectively to short-term exposure to cold. One response to cold is shivering, which is random muscle movement that generates heat. Another response is increased breakdown of stored energy to generate heat. When that energy reserve is depleted, however, and the core temperature begins to drop significantly, red blood cells will lose their ability to give up oxygen, denying the brain of this critical component of ATP production. This lack of oxygen can cause confusion, lethargy, and eventually loss of consciousness and death. The body responds to cold by reducing blood circulation to the extremities, the hands and feet, in order to prevent blood from cooling there and so that the body's core can stay warm. Even when core body temperature remains stable, however, tissues exposed to severe cold, especially the fingers and toes, can develop frostbite when blood flow to the extremities has been much reduced. This form of tissue damage can be permanent and lead to gangrene, requiring amputation of the affected region.

Everyday Connection

Controlled Hypothermia

As you have learned, the body continuously engages in coordinated physiological processes to maintain a stable temperature. In some cases, however, overriding this system can be useful, or even life-saving. Hypothermia is the clinical term for an abnormally low body temperature (hypo- = "below" or "under"). Controlled hypothermia is clinically induced hypothermia performed in order to reduce the metabolic rate of an organ or of a person's entire body.

Controlled hypothermia often is used, for example, during open-heart surgery because it decreases the metabolic needs of the brain, heart, and other organs, reducing the risk of damage to them. When controlled hypothermia is used clinically, the patient is given medication to prevent shivering. The body is then cooled to 25–32°C (79–89°F). The heart is stopped and an external heart-lung pump maintains circulation to the patient's body. The heart is cooled further and is maintained at a temperature below 15°C (60°F) for the duration of the surgery. This very cold temperature helps the heart muscle to tolerate its lack of blood supply during the surgery.

Some emergency department physicians use controlled hypothermia to reduce damage to the heart in patients who have suffered a cardiac arrest. In the emergency department, the physician induces coma and lowers the patient's body temperature to approximately 91 degrees. This condition, which is maintained for 24 hours, slows the patient's metabolic rate. Because the patient's organs require less blood to function, the heart's workload is reduced.

Narrow Range of Atmospheric Pressure

Pressure is a force exerted by a substance that is in contact with another substance. Atmospheric pressure is pressure exerted

by the mixture of gases (primarily nitrogen and oxygen) in the Earth's atmosphere. Although you may not perceive it, atmospheric pressure is constantly pressing down on your body. This pressure keeps gases within your body, such as the gaseous nitrogen in body fluids, dissolved. If you were suddenly ejected from a space ship above Earth's atmosphere, you would go from a situation of normal pressure to one of very low pressure. The pressure of the nitrogen gas in your blood would be much higher than the pressure of nitrogen in the space surrounding your body. As a result, the nitrogen gas in your blood would expand, forming bubbles that could block blood vessels and even cause cells to break apart.

Atmospheric pressure does more than just keep blood gases dissolved. Your ability to breathe—that is, to take in oxygen and release carbon dioxide—also depends upon a precise atmospheric pressure. Altitude sickness occurs in part because the atmosphere at high altitudes exerts less pressure, reducing the exchange of these gases, and causing shortness of breath, confusion, headache, lethargy, and nausea. Mountain climbers carry oxygen to reduce the effects of both low oxygen levels and low barometric pressure at higher altitudes Figure 1.5.2.



Figure 1.5.2: Climbers on Mount Everest must accommodate extreme cold, low oxygen levels, and low barometric pressure in an environment hostile to human life. (CC BY 4.0; via Wikimedia Commons).

Homeostatic Imbalances

Decompression Sickness

Decompression sickness (DCS) is a condition caused by a rapid drop in ambient pressure that makes dissolved inert gas (mainly nitrogen) come out of solution and form bubbles in blood and tissues. This condition affects underwater divers who surface from a deep dive too quickly, and it can affect pilots flying at high altitudes in planes with unpressurized cabins. Divers often call this condition "the bends," a reference to joint pain that is a symptom of DCS.

Key concepts for A&P students

- Why pressure matters: It is air pressure that keeps your normal blood gases dissolved in the blood. When pressure is reduced, less gas remains dissolved. You have seen this in effect when you open a carbonated drink. Removing the seal of the bottle reduces the pressure of the gas over the liquid. This in turn causes bubbles as dissolved gases (in this case, carbon dioxide) come out of solution in the liquid.
- At sea level (~1 atm), the body's gases are in equilibrium. Under higher pressure (e.g., diving), more nitrogen dissolves in tissues (Henry's law: gas solubility ↑ with pressure). If pressure falls too quickly during ascent or altitude exposure, tissues become supersaturated and nitrogen forms bubbles. Bubble size also changes with pressure (Boyle's law: volume ↑ as pressure ↓).
- Where it occurs: Scuba diving (breathing compressed gas at depth), high-altitude or unpressurized flight, and spacewalks (very low ambient pressure).
- What bubbles do:

    - Mechanical effects: obstruct microcirculation and joints (“the bends”).
    - Biological effects: injure endothelium, trigger inflammation, activate coagulation and platelets.
    - Organ-specific issues:
        - Musculoskeletal pain (joint/limb pain), skin marbling/itching.
        - Neurologic/spinal symptoms (weakness, numbness, ataxia), inner ear symptoms (vertigo).
        - Pulmonary “chokes” (cough, chest pain, dyspnea).
- Treatment (conceptual): Prompt 100% oxygen to accelerate nitrogen washout and reduce bubble size, supportive care, and recompression therapy in a hyperbaric chamber. Early evaluation is important. Because the hyperbaric chamber introduces oxygen to the body at high pressure, it increases the concentration of oxygen in the blood. This has the effect of replacing some of the nitrogen in the blood with oxygen, which is easier to tolerate out of solution.

The dynamic pressure of body fluids is also important to human survival. For example, blood pressure, which is the pressure exerted by blood as it flows within blood vessels, must be great enough to enable blood to reach all body tissues, and yet low enough to ensure that the delicate blood vessels can withstand the friction and force of the pulsating flow of pressurized blood.

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1.6: Homeostasis

Regulation of the Internal Environment

Homeostasis is the dynamic process of maintaining a stable internal environment within narrow physiological limits despite changes inside or outside the body. It relies mainly on negative feedback loops: sensors (receptors) detect a deviation from a set point, a control center (e.g., brain or endocrine gland) integrates the information, and effectors (muscles, glands) make adjustments to restore balance. Examples include regulation of body temperature, blood glucose, blood pressure, pH, and fluid/osmolarity. Positive feedback exists but is rare and usually short-lived (e.g., blood clotting, childbirth).

Maintaining homeostasis requires that the body continuously monitor its internal conditions. From body temperature to blood pressure to levels of certain nutrients, each physiological condition has a particular set point. A set point is the physiological value around which the normal range fluctuates. A normal range is the restricted set of values that is optimally healthful and stable. For example, the set point for normal human body temperature is approximately 37°C (98.6°F). Physiological parameters, such as body temperature and blood pressure, tend to fluctuate within a normal range a few degrees above and below that point. Control centers in the brain and other parts of the body monitor and react to deviations from homeostasis using negative feedback. Negative feedback is a mechanism that reverses a deviation from the set point. Therefore, negative feedback maintains body parameters within their normal range. The maintenance of homeostasis by negative feedback goes on throughout the body at all times, and an understanding of negative feedback is thus fundamental to an understanding of human physiology.

Negative Feedback

A negative feedback system has three basic components as shown in Figure 1.6.1*a*. A sensor, also referred to a receptor, is a component of a feedback system that monitors a physiological value. This value is reported to the control center. The control center is the component in a feedback system that compares the value to the normal range. If the value deviates too much from the set point, then the control center activates an effector. An effector is the component in a feedback system that causes a change to reverse the situation and return the value to the normal range.

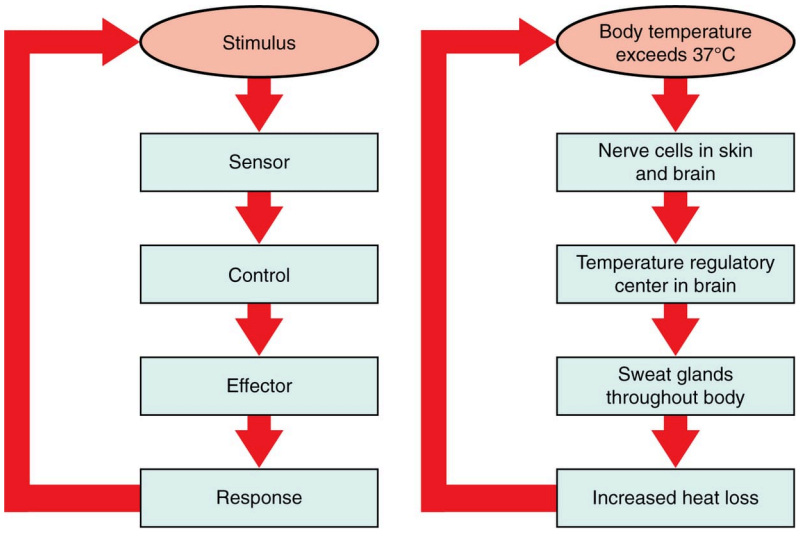


Figure 1.6.1: In a negative feedback system, a stimulus—a deviation from a set point—is resisted through a physiological process that returns the body to homeostasis. (a) A negative feedback system has five basic parts. (b) Body temperature is regulated by negative feedback. (CC BY 4.0 ; via Wikimedia Commons). Alternative text description of Figure 1.6.1.

In order to set the system in motion, a stimulus must drive a physiological parameter beyond its normal range (that is, beyond homeostasis). This stimulus is “heard” by a specific sensor. For example, in the control of blood glucose, specific endocrine cells

in the pancreas detect excess glucose (the stimulus) in the bloodstream. These pancreatic beta cells respond to the increased level of blood glucose by releasing the hormone insulin into the bloodstream. The insulin signals skeletal muscle fibers, fat cells (adipocytes), and liver cells to take up the excess glucose, removing it from the bloodstream. As glucose concentration in the bloodstream drops, the decrease in concentration—the actual negative feedback—is detected by pancreatic alpha cells, and insulin release stops. This prevents blood sugar levels from continuing to drop below the normal range.

Humans have a similar temperature regulation feedback system that works by promoting either heat loss or heat gain as shown in Figure 1.6.1(b). When the brain's temperature regulation center receives data from the sensors indicating that the body's temperature exceeds its normal range, it stimulates a cluster of brain cells referred to as the "heat-loss center." This stimulation has three major effects:

- Blood vessels in the skin begin to dilate allowing more blood from the body core to flow to the surface of the skin allowing the heat to radiate into the environment.
- As blood flow to the skin increases, sweat glands are activated to increase their output. As the sweat evaporates from the skin surface into the surrounding air, it takes heat with it.

In contrast, activation of the brain's heat-gain center by exposure to cold reduces blood flow to the skin, and blood returning from the limbs is diverted into a network of deep veins. This arrangement traps heat closer to the body core and restricts heat loss. If heat loss is severe, the brain triggers an increase in random signals to skeletal muscles, causing them to contract and producing shivering. The muscle contractions of shivering release heat while using up ATP. The brain triggers the thyroid gland in the endocrine system to release thyroid hormone, which increases metabolic activity and heat production in cells throughout the body. The brain also signals the adrenal glands to release epinephrine (adrenaline), a hormone that causes the breakdown of glycogen into glucose, which can be used as an energy source. The breakdown of glycogen into glucose also results in increased metabolism and heat production.

Positive Feedback

Positive feedback intensifies a change in the body's physiological condition rather than reversing it. A deviation from the normal range results in more change, and the system moves farther away from the normal range. Positive feedback in the body is normal only when there is a definite end point. Childbirth and the body's response to blood loss are two examples of positive feedback loops that are normal but are activated only when needed.

Childbirth at full term is an example of a situation in which the maintenance of the existing body state is not desired. Enormous changes in a person's body are required to expel the baby at the end of pregnancy. And the events of childbirth, once begun, must progress rapidly to a conclusion or the life of a person giving birth and the baby are at risk. The extreme muscular work of labor and delivery are the result of a positive feedback system as shown in Figure 1.6.2.

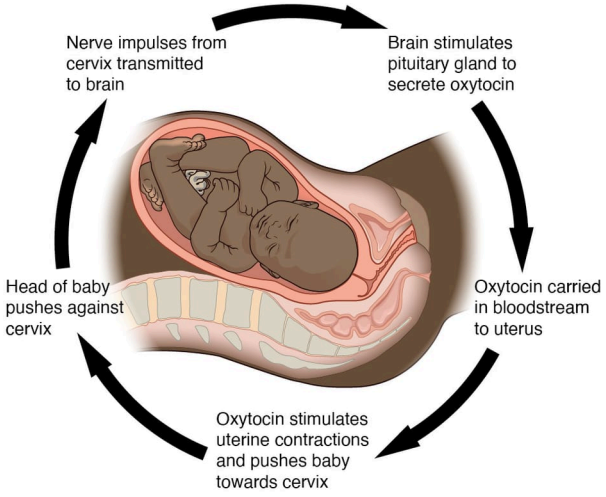


Figure 1.6.2: Normal childbirth is driven by a positive feedback loop. A positive feedback loop results in a change in the body's status, rather than a return to homeostasis. (CC BY 4.0 ; via Wikimedia Commons). Alternative text description of Figure 1.6.2.

The first contractions of labor (the stimulus) push the baby toward the cervix (the lowest part of the uterus). The cervix contains stretch-sensitive nerve cells that monitor the degree of stretching (the sensors). These nerve cells send messages to the brain, which in turn causes the pituitary gland at the base of the brain to release the hormone oxytocin into the bloodstream. Oxytocin causes stronger contractions of the smooth muscles of the uterus (the effectors), pushing the baby further down the birth canal. This causes even greater stretching of the cervix. The cycle of stretching, oxytocin release, and increasingly more forceful contractions stops only when the baby is born. At this point, the stretching of the cervix halts, stopping the release of oxytocin.

A second example of positive feedback centers on reversing extreme damage to the body. Following a penetrating wound, the most immediate threat is excessive blood loss. Less blood circulating means reduced blood pressure and reduced perfusion (penetration of blood) to the brain and other vital organs. If perfusion is severely reduced, vital organs will shut down and the person will die. The body responds to this potential catastrophe by releasing substances in the injured blood vessel wall that begin the process of blood clotting. As each step of clotting occurs, it stimulates the release of more clotting substances. This accelerates the processes of clotting and sealing off the damaged area. Clotting is contained in a local area based on the tightly controlled availability of clotting proteins. This is an adaptive, life-saving cascade of events.

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1.7: Anatomical Terminology

Foundations of Anatomical Description

Anatomists and health care providers use terminology that can be bewildering to the uninitiated. However, the purpose of this language is not to confuse, but rather to increase precision and reduce medical errors. For example, is a scar “above the wrist” located on the forearm two or three inches away from the hand? Or is it at the base of the hand? Is it on the palm-side or back-side? By using precise anatomical terminology, we eliminate ambiguity. Anatomical terms derive from ancient Greek and Latin words. Because these languages are no longer used in everyday conversation, the meaning of their words does not change.

Anatomical terms are made up of roots, prefixes, and suffixes. The root of a term often refers to an organ, tissue, or condition, whereas the prefix or suffix often describes the root. For example, in the disorder hypertension, the prefix “hyper-” means “high” or “over,” and the root word “tension” refers to pressure, so the word “hypertension” refers to abnormally high blood pressure.

Anatomical Position

To further increase precision, anatomists standardize the way in which they view the body. Just as maps are normally oriented with north at the top, the standard body “map,” or anatomical position, is that of the body standing upright, with the feet at shoulder width and parallel, toes forward. The upper limbs are held out to each side, and the palms of the hands face forward as illustrated in Figure 1.7.1. Using this standard position reduces confusion. It does not matter how the body being described is oriented, the terms are used as if it is in anatomical position. For example, a scar in the “anterior (front) carpal (wrist) region” would be present on the palm side of the wrist. The term “anterior” would be used even if the hand were palm down on a table.

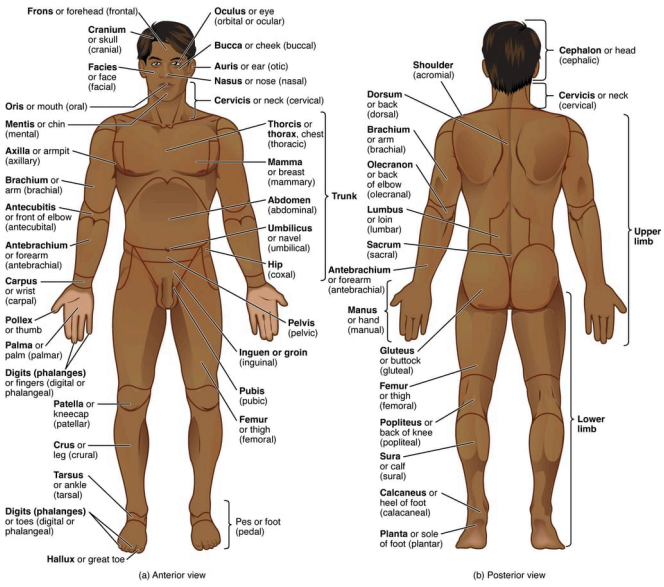


Figure 1.7.1: The human body is shown in anatomical position in an (a) anterior view and a (b) posterior view. The regions of the body are labeled in boldface. (CC BY-NC-ND 4.0; PHED 301 Students via Anatomical Position and Advanced Anatomy 2nd Ed). Alternate text description of Figure 1.7.1.

Regional Terms

The human body’s numerous regions have specific terms to help increase precision as depicted in Figure 1.7.1. Notice that the term “brachium” or “arm” is reserved for the “upper arm” and “antebrachium” or “forearm” is used rather than “lower arm.” Similarly, “femur” or “thigh” is correct, and “leg” or “crus” is reserved for the portion of the lower limb between the knee and the ankle. You will be able to describe the body’s regions using the terms from the figure.

Directional Terms

Certain directional anatomical terms appear throughout this and any other anatomy textbook. These terms are essential for describing the relative locations of different body structures. For instance, an anatomist might describe one band of tissue as “inferior to” another or a physician might describe a tumor as “superficial to” a deeper body structure. Commit these terms to memory to avoid confusion when you are studying or describing the locations of particular body parts.

- Anterior (or ventral) Describes the front or direction toward the front of the body. The toes are anterior to the foot.
- Posterior (or dorsal) Describes the back or direction toward the back of the body. The popliteus is posterior to the patella.
- Superior (or cranial) describes a position above or higher than another part of the body proper. The orbits are superior to the oris.
- Inferior (or caudal) describes a position below or lower than another part of the body proper; near or toward the tail (in humans, the coccyx, or lowest part of the spinal column). The pelvis is inferior to the abdomen.
- Lateral describes the side or direction toward the side of the body. The thumb (pollex) is lateral to the digits.
- Medial describes the middle or direction toward the middle of the body. The hallux is the medial toe.
- Proximal describes a position in a limb that is nearer to the point of attachment or the trunk of the body. The brachium is proximal to the antebrachium.
- Distal describes a position in a limb that is farther from the point of attachment or the trunk of the body. The crus is distal to the femur.
- Superficial describes a position closer to the surface of the body. The skin is superficial to the bones.
- Deep describes a position farther from the surface of the body. The brain is deep to the skull.

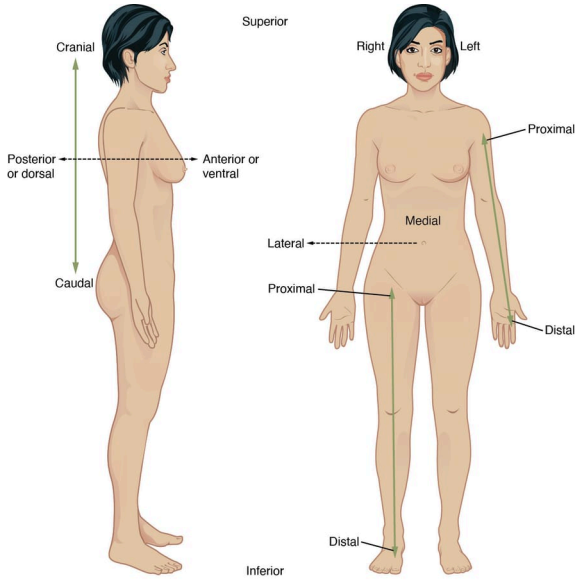


Figure 1.7.2: Paired directional terms are shown as applied to the human body. (CC BY-SA 4.0; Lindsay M. Biga, Staci Bronson, Sierra Dawson, Amy Harwell, Robin Hopkins, Joel Kaufmann, Mike LeMaster, Philip Matern, Katie Morrison-Graham, Kristen Oja, Devon Quick, Jon Runyeon, via OpenStax and Anatomy & Physiology). Alternate text description of Figure 1.7.2.

Body Planes

A section is a two-dimensional surface of a three-dimensional structure that has been cut. Modern medical imaging devices enable clinicians to obtain “virtual sections” of living bodies. We call these scans. Body sections and scans can be correctly interpreted, however, only if the viewer understands the plane along which the section was made. A plane is an imaginary two-dimensional surface that passes through the body. There are three planes commonly referred to in anatomy and medicine, as illustrated in Figure 1.7.3.

- The sagittal plane is the plane that divides the body or an organ vertically into right and left sides. If this vertical plane runs directly down the middle of the body, it is called the midsagittal or median plane. If it divides the body into unequal right and left sides, it is called a parasagittal plane or less commonly a longitudinal section.
- The frontal plane is the plane that divides the body or an organ into an anterior (front) portion and a posterior (rear) portion.

The frontal plane is often referred to as a coronal plane. (“Corona” is Latin for “crown.”)

- The transverse plane is the plane that divides the body or organ horizontally into upper and lower portions. Transverse planes produce images referred to as cross sections.

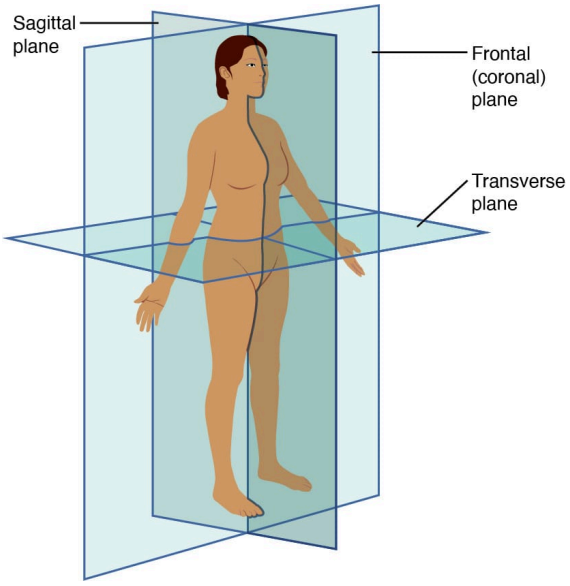


Figure 1.7.3: The three planes most commonly used in anatomical and medical imaging are the sagittal, frontal (or coronal), and transverse plane. (CC BY 3.0; via Wikimedia Commons). Alternate text description of Figure 1.7.3.

Body Cavities and Serous Membranes

The body maintains its internal organization by means of membranes, sheaths, and other structures that separate compartments. The dorsal (posterior) cavity and the ventral (anterior) cavity are the largest body compartments Figure 1.7.4. These cavities contain and protect delicate internal organs, and the ventral cavity allows for significant changes in the size and shape of the organs as they perform their functions. The lungs, heart, stomach, and intestines, for example, can expand and contract without distorting other tissues or disrupting the activity of nearby organs.

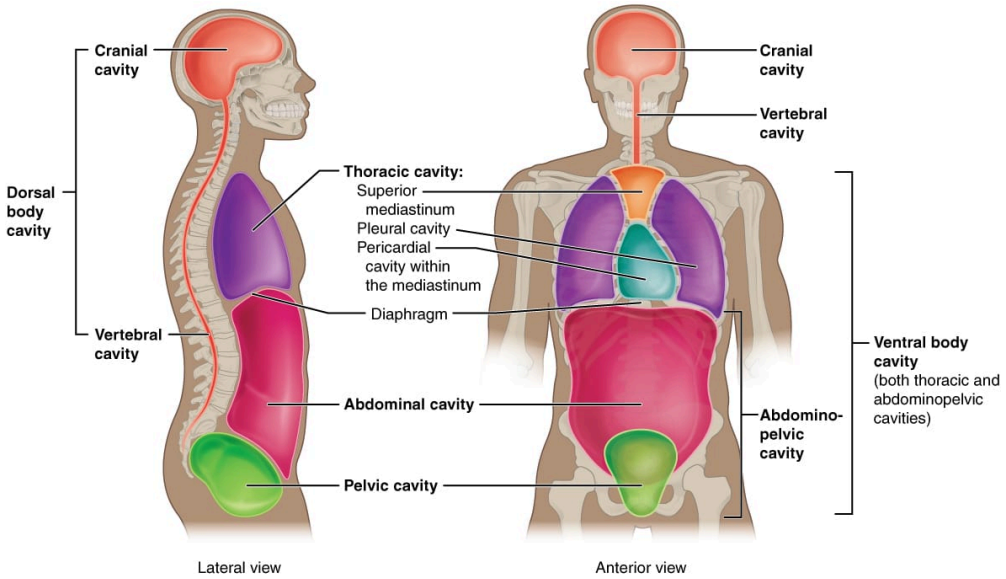


Figure 1.7.4: The ventral cavity includes the thoracic and abdominopelvic cavities and their subdivisions. The dorsal cavity includes the cranial and spinal cavities. (CC BY 4.0; Kimberlee Carter; Marie Rutherford; and Connie Stevens via Building a Medical Terminology Foundation 2e). Alternate text description of Figure 1.7.4.

The cranial cavity is a large, bean-shaped cavity filling most of the upper skull where the brain is located. The vertebral cavity is a very narrow, thread-like cavity running from the cranial cavity down the entire length of the spinal cord. Together the cranial cavity and vertebral cavity can be referred to as the dorsal body cavity. The thoracic cavity consists of three cavities that fill the interior area of the chest. The two pleural cavities are situated on both sides of the body, anterior to the spine and lateral to the breastbone. The superior mediastinum is a wedge-shaped cavity located between the superior regions of the two thoracic cavities. The pericardial cavity within the mediastinum is located at the center of the chest below the superior mediastinum. The pericardial cavity roughly outlines the shape of the heart. The diaphragm divides the thoracic and the abdominal cavities. The abdominal cavity occupies the entire lower half of the trunk, anterior to the spine. Just under the abdominal cavity, anterior to the buttocks, is the pelvic cavity. The pelvic cavity is funnel shaped and is located inferior and anterior to the abdominal cavity. Together the abdominal and pelvic cavity can be referred to as the abdominopelvic cavity while the thoracic, abdominal, and pelvic cavities together can be referred to as the ventral body cavity.

Subdivisions of the Posterior (Dorsal) and Anterior (Ventral) Cavities

The posterior (dorsal) and anterior (ventral) cavities are each subdivided into smaller cavities. In the posterior (dorsal) cavity, the cranial cavity houses the brain, and the spinal cavity (or vertebral cavity) encloses the spinal cord. Just as the brain and spinal cord make up a continuous, uninterrupted structure, the cranial and spinal cavities that house them are also continuous. The brain and spinal cord are protected by the bones of the skull and vertebral column and by cerebrospinal fluid, a colorless fluid produced by the brain, which cushions the brain and spinal cord within the posterior (dorsal) cavity.

The anterior (ventral) cavity has two main subdivisions: the thoracic cavity and the abdominopelvic cavity (see Figure 1.7.4). The thoracic cavity is the more superior subdivision of the anterior cavity, and it is enclosed by the rib cage. The thoracic cavity contains the lungs and the heart, which is located in the mediastinum. The diaphragm forms the floor of the thoracic cavity and separates it from the more inferior abdominopelvic cavity. The abdominopelvic cavity is the largest cavity in the body. Although no membrane physically divides the abdominopelvic cavity, it can be useful to distinguish between the abdominal cavity, the division that houses the digestive organs, and the pelvic cavity, the division that houses the organs of reproduction.

Abdominal Regions and Quadrants

To promote clear communication, for instance about the location of a patient's abdominal pain or a suspicious mass, health care providers typically divide up the cavity into either nine regions or four quadrants.

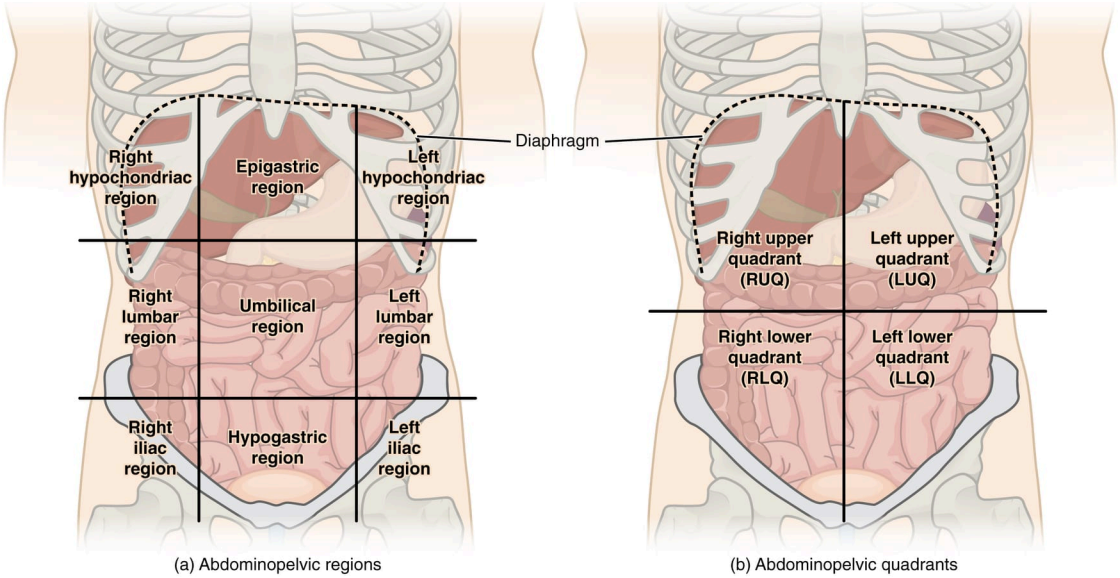


Figure 1.7.5: There are (a) nine abdominal regions and (b) four abdominal quadrants in the peritoneal cavity. (CC BY-SA 4.0; Lindsay M. Biga, Staci Bronson, Sierra Dawson, Amy Harwell, Robin Hopkins, Joel Kaufmann, Mike LeMaster, Philip Matern, Katie Morrison-Graham, Kristen Oja, Devon Quick, Jon Runyeon, via OpenStax and Anatomy & Physiology). Alternate text description of Figure 1.7.5.

The more detailed regional approach subdivides the cavity with one horizontal line immediately inferior to the ribs and one immediately superior to the pelvis, and two vertical lines drawn as if dropped from the midpoint of each clavicle (collarbone).

There are nine resulting regions. The simpler quadrants approach, which is more commonly used in medicine, subdivides the cavity with one horizontal and one vertical line that intersect at the patient's umbilicus (navel).

Membranes of the Anterior (Ventral) Body Cavity

A serous membrane (also referred to a serosa) is one of the thin membranes that cover the walls and organs in the thoracic and abdominopelvic cavities. The parietal layers of the membranes line the walls of the body cavity (pariet- refers to a cavity wall). The visceral layer of the membrane covers the organs (the viscera). Between the parietal and visceral layers is a very thin, fluid-filled serous space, or cavity.

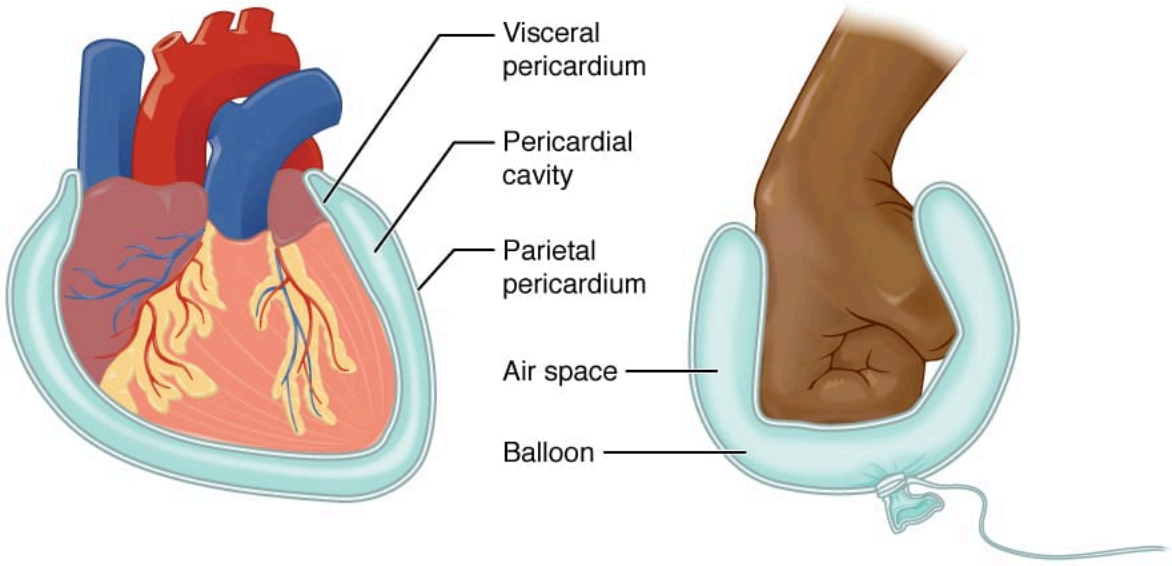


Figure 1.7.6: Serous membrane lines the pericardial cavity and reflects back to cover the heart—much the same way that an under inflated balloon would form two layers surrounding a fist. (CC BY 4.0 via OpenStax). Alternate text description of Figure 1.7.6.

There are three serous cavities and their associated membranes. The pleura is the serous membrane that encloses the pleural cavity; the pleural cavity surrounds the lungs. The pericardium is the serous membrane that encloses the pericardial cavity; the pericardial cavity surrounds the heart. The peritoneum is the serous membrane that encloses the peritoneal cavity; the peritoneal cavity surrounds several organs in the abdominopelvic cavity. The serous membranes form fluid-filled sacs, or cavities, that are meant to cushion and reduce friction on internal organs when they move, such as when the lungs inflate or the heart beats. Both the parietal and visceral serosa secrete the thin, slippery serous fluid located within the serous cavities. The pleural cavity reduces friction between the lungs and the body wall. Likewise, the pericardial cavity reduces friction between the heart and the wall of the pericardium. The peritoneal cavity reduces friction between the abdominal and pelvic organs and the body wall. Therefore, serous membranes provide additional protection to the viscera they enclose by reducing friction that could lead to inflammation of the organs.

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1.8: Visualizing Anatomy - From X-rays to MRI

Medical Imaging

For thousands of years, fear of the dead and legal sanctions limited the ability of anatomists and physicians to study the internal structures of the human body. An inability to control bleeding, infection, and pain made surgeries infrequent, and those that were performed—such as wound suturing, amputations, tooth and tumor removals, skull drilling, and cesarean births—did not greatly advance knowledge about internal anatomy. Theories about the function of the body and about disease were therefore largely based on external observations and imagination. During the fourteenth and fifteenth centuries, however, the detailed anatomical drawings of Italian artist and anatomist Leonardo da Vinci and Flemish anatomist Andreas Vesalius were published, and interest in human anatomy began to increase. Medical schools began to teach anatomy using human dissection; although some resorted to grave robbing to obtain corpses. Laws were eventually passed that enabled students to dissect the corpses of criminals and those who donated their bodies for research. Still, it was not until the late nineteenth century that medical researchers discovered non-surgical methods to look inside the living body.

X-Rays

German physicist Wilhelm Röntgen (1845–1923) was experimenting with electrical current when he discovered that a mysterious and invisible “ray” would pass through his flesh but leave an outline of his bones on a screen coated with a metal compound. In 1895, Röntgen made the first durable record of the internal parts of a living human: an “X-ray” image (as it came to be called) of his wife’s hand. Scientists around the world quickly began their own experiments with X-rays, and by 1900, X-rays were widely used to detect a variety of injuries and diseases. In 1901, Röntgen was awarded the first Nobel Prize for physics for his work in this field.

The X-ray is a form of high energy electromagnetic radiation with a short wavelength capable of penetrating solids and ionizing gases. As they are used in medicine, X-rays are emitted from an X-ray machine and directed toward a specially treated metallic plate placed behind the patient’s body. The beam of radiation results in darkening of the X-ray plate. X-rays are slightly impeded by soft tissues, which show up as gray on the X-ray plate, whereas hard tissues, such as bone, largely block the rays, producing a light-toned “shadow.” Thus, X-rays are best used to visualize hard body structures such as teeth and bones, see Figure 1.8.1. Like many forms of high energy radiation, however, X-rays are capable of damaging cells and initiating changes that can lead to cancer. This danger of excessive exposure to X-rays was not fully appreciated for many years after their widespread use.



Figure 1.8.1: High energy electromagnetic radiation allows the internal structures of the body, such as bones, to be seen in X-rays like these. (CC BY 4.0; via Wikimedia Commons).

Figure 1.8.1 image shows an X ray image of the palmar surface of the left hand. The bones appear bright white against a gray outline of the skin of the hand. The four segments of the finger bones are clearly visible, as well as the collection of round bones that compose the wrist and connect the hand to the two bones of the forearm.

Refinements and enhancements of X-ray techniques have continued throughout the twentieth and twenty-first centuries. Although often supplanted by more sophisticated imaging techniques, the X-ray remains a “workhorse” in medical imaging, especially for viewing fractures and for dentistry. The disadvantage of irradiation to the patient and the operator is now attenuated by proper shielding and by limiting exposure.

Modern Medical Imaging

X-rays can depict a two-dimensional image of a body region, and only from a single angle. In contrast, more recent medical imaging technologies produce data that is integrated and analyzed by computers to produce three-dimensional images or images that reveal aspects of body functioning.

Computed Tomography

Tomography refers to imaging by sections. Computed tomography (CT) is a noninvasive imaging technique that uses computers to analyze several cross-sectional X-rays in order to reveal minute details about structures in the body in Figure 1.8.2(a). The technique was invented in the 1970s and is based on the principle that, as X-rays pass through the body, they are absorbed or reflected at different levels. In the technique, a patient lies on a motorized platform while a computerized axial tomography (CAT) scanner rotates 360 degrees around the patient, taking X-ray images. A computer combines these images into a two-dimensional view of the scanned area, or “slice.”

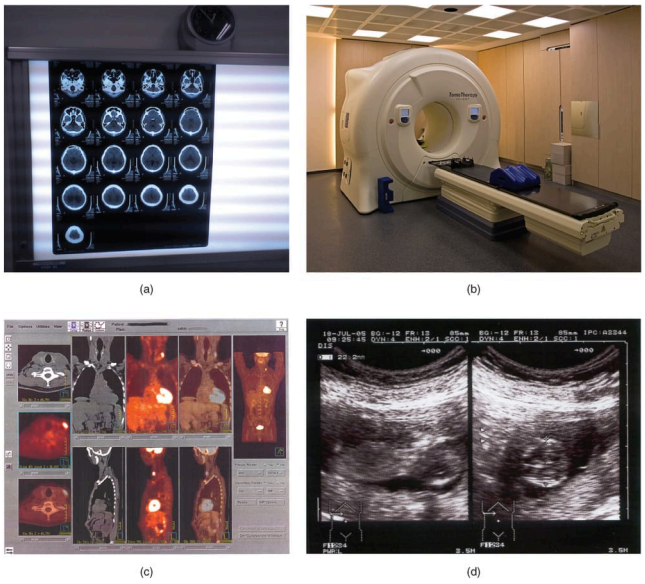


Figure 1.8.2: Medical Imaging Techniques (a) The results of a CT scan of the head are shown as successive transverse sections. (b) An MRI machine generates a magnetic field around a patient. (c) PET scans use radiopharmaceuticals to create images of active blood flow and physiologic activity of the organ or organs being targeted. (d) Ultrasound technology is used to monitor pregnancies because it is the least invasive of imaging techniques and uses no electromagnetic radiation. (CC BY 4.0; via Wikimedia Commons).

Figure 1.8.2 shows four types of imaging equipment. Photo A, the results of a CT scan, shows 17 different transverse views of the skull, each taken at a different depth along the superior-inferior axis. The images are translucent, similar to an X ray, and are viewed on a light board. Photo B shows an MRI machine, which is a large drum into which lying patients enter via a conveyor belt. Photo C shows computer images of the body taken with PET scans. This produces anterior, lateral, posterior, and transverse views of the body that reveal the structure of the internal organs. Photo D shows an ultrasound readout, which is black and white. The image depicts solid tissues as light areas and empty space as dark areas. Some of the features of a young fetus can be seen in the empty space at the center of the image. The space containing the fetus is surrounded by the solid tissue of the uterus.

Since 1970, the development of more powerful computers and more sophisticated software has made CT scanning routine for

many types of diagnostic evaluations. It is especially useful for soft tissue scanning, such as of the brain and the thoracic and abdominal viscera. Its level of detail is so precise that it can allow physicians to measure the size of a mass down to a millimeter. The main disadvantage of CT scanning is that it exposes patients to a dose of radiation many times higher than that of X-rays. In fact, children who undergo CT scans are at increased risk of developing cancer, as are adults who have multiple CT scans.

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is a noninvasive medical imaging technique based on a phenomenon of nuclear physics discovered in the 1930s, in which matter exposed to magnetic fields and radio waves was found to emit radio signals. In 1970, a physician and researcher named Raymond Damadian noticed that malignant (cancerous) tissue gave off different signals than normal body tissue. He applied for a patent for the first MRI scanning device, which was in use clinically by the early 1980s. The early MRI scanners were crude, but advances in digital computing and electronics led to their advancement over any other technique for precise imaging, especially to discover tumors. MRI also has the major advantage of not exposing patients to radiation.

Drawbacks of MRI scans include their much higher cost, and patient discomfort with the procedure. The MRI scanner subjects the patient to such powerful electromagnets that the scan room must be shielded. The patient must be enclosed in a metal tube-like device for the duration of the scan, sometimes as long as thirty minutes, which can be uncomfortable and impractical for ill patients. The device is also so noisy that, even with earplugs, patients can become anxious or even fearful. These problems have been overcome somewhat with the development of “open” MRI scanning, which does not require the patient to be entirely enclosed in the metal tube. Patients with iron-containing metallic implants (internal sutures, some prosthetic devices, and so on) cannot undergo MRI scanning because it can dislodge these implants.

Functional MRIs (fMRIs), which detect the concentration of blood flow in certain parts of the body, are increasingly being used to study the activity in parts of the brain during various body activities. This has helped scientists learn more about the locations of different brain functions and more about brain abnormalities and diseases.

Positron Emission Tomography

Positron emission tomography (PET) is a medical imaging technique involving the use of so-called radiopharmaceuticals, substances that emit radiation that is short-lived and therefore relatively safe to administer to the body. Although the first PET scanner was introduced in 1961, it took 15 more years before radiopharmaceuticals were combined with the technique and revolutionized its potential. The main advantage is that PET (Figure $1.8.2$(c)) can illustrate physiologic activity—including nutrient metabolism and blood flow—of the organ or organs being targeted, whereas CT and MRI scans can only show static images. PET is widely used to diagnose a multitude of conditions, such as heart disease, the spread of cancer, certain forms of infection, brain abnormalities, bone disease, and thyroid disease.

Ultrasonography

Ultrasonography is an imaging technique that uses the transmission of high-frequency sound waves into the body to generate an echo signal that is converted by a computer into a real-time image of anatomy and physiology (Figure $1.8.2$(d)). Ultrasonography is the least invasive of all imaging techniques, and it is therefore used more freely in sensitive situations such as pregnancy. The technology was first developed in the 1940s and 1950s. Ultrasonography is used to study heart function, blood flow in the neck or extremities, certain conditions such as gallbladder disease, and fetal growth and development. The main disadvantages of ultrasonography are that the image quality is heavily operator-dependent and that it is unable to penetrate bone and gas.

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1.9: Terms and Definitions

Key Terms

Select to view definitions

Abdominopelvic cavity
division of the anterior (ventral) cavity that houses the abdominal and pelvic viscera

Anabolism
assembly of more complex molecules from simpler molecules

Anatomical position
standard reference position used for describing locations and directions on the human body

Anterior
describes the front or direction toward the front of the body; also referred to as ventral

Anterior cavity
larger body cavity located anterior to the posterior (dorsal) body cavity; includes the serous membrane-lined pleural cavities for the lungs, pericardial cavity for the heart, and peritoneal cavity for the abdominal and pelvic organs; also referred to as ventral cavity

Applied science
a form of science that solves real-world problems

Basic science
science that seeks to expand knowledge regardless of the short-term application of that knowledge

Catabolism
breaking down of more complex molecules into simpler molecules

Caudal
describes a position below or lower than another part of the body proper; near or toward the tail (in humans, the coccyx, or lowest part of the spinal column); also referred to as inferior

Cell
smallest independently functioning unit of all organisms; in animals, a cell contains cytoplasm, composed of fluid and organelles

Computed tomography (CT)
medical imaging technique in which a computer-enhanced cross-sectional X-ray image is obtained

Control
a part of an experiment that does not change during the experiment

Control center
compares values to their normal range; deviations cause the activation of an effector

Cranial
describes a position above or higher than another part of the body proper; also referred to as superior

Cranial cavity
division of the posterior (dorsal) cavity that houses the brain

Deductive reasoning
a form of logical thinking that uses a general statement to forecast specific results

Descriptive science
a form of science that aims to observe, explore, and find things out

Deep
describes a position farther from the surface of the body

Development
changes an organism goes through during its life

Differentiation
process by which unspecialized cells become specialized in structure and function

Distal
describes a position farther from the point of attachment or the trunk of the body

Dorsal
describes the back or direction toward the back of the body; also referred to as posterior

Dorsal cavity
posterior body cavity that houses the brain and spinal cord; also referred to the posterior body cavity

Effector
organ that can cause a change in a value

Falsifiable
able to be disprove by experimental results

Frontal plane
two-dimensional, vertical plane that divides the body or organ into anterior and posterior portions

Gross anatomy
study of the larger structures of the body, typically with the unaided eye; also referred to macroscopic anatomy

Growth
process of increasing in size

Homeostasis
steady state of body systems that living organisms maintain

Hypothesis
a suggested explanation for an event, which can be tested

Hypothesis-based science
a form of science that begins with a specific explanation that is then tested

Inductive reasoning
a form of logical thinking that uses related observations to arrive at a general conclusion

Inferior
describes a position below or lower than another part of the body proper; near or toward the tail (in humans, the coccyx, or lowest part of the spinal column); also referred to as caudal

Lateral
describes the side or direction toward the side of the body

Life science
a field of science, such as biology, that studies living things

Magnetic resonance imaging (MRI)
medical imaging technique in which a device generates a magnetic field to obtain detailed sectional images of the internal structures of the body

Medial
describes the middle or direction toward the middle of the body

Metabolism
sum of all of the body's chemical reactions

Microscopic anatomy
study of very small structures of the body using magnification

Natural science
a field of science that studies the physical world, its phenomena, and processes

Negative feedback
homeostatic mechanism that tends to stabilize an upset in the body's physiological condition by preventing an excessive response to a stimulus, typically as the stimulus is removed

Normal range
range of values around the set point that do not cause a reaction by the control center

Nutrient
chemical obtained from foods and beverages that is critical to human survival

Organ
functionally distinct structure composed of two or more types of tissues

Organ system
group of organs that work together to carry out a particular function

Organism
living being that has a cellular structure and that can independently perform all physiologic functions necessary for life

Peer-reviewed article
a scientific report that is reviewed by a scientist's colleagues before publication

Pericardium
sac that encloses the heart

Peritoneum
serous membrane that lines the abdominopelvic cavity and covers the organs found there

Physical science
a field of science, such as astronomy, physics, and chemistry, that studies nonliving matter

Physiology
science that studies the chemistry, biochemistry, and physics of the body's functions

Plane
imaginary two-dimensional surface that passes through the body

Pleura
serous membrane that lines the pleural cavity and covers the lungs

Positive feedback
mechanism that intensifies a change in the body's physiological condition in response to a stimulus

Positron emission tomography (PET)
medical imaging technique in which radiopharmaceuticals are traced to reveal metabolic and physiological functions in tissues

Posterior
describes the back or direction toward the back of the body; also referred to as dorsal

Posterior cavity
posterior body cavity that houses the brain and spinal cord; also referred to as dorsal cavity

Pressure
force exerted by a substance in contact with another substance

Prone
face down

Proximal
describes a position nearer to the point of attachment or the trunk of the body

Regional anatomy
study of the structures that contribute to specific body regions

Renewal
process by which worn-out cells are replaced

Reproduction
process by which new organisms are generated

Responsiveness
ability of an organisms or a system to adjust to changes in conditions

Science
knowledge that covers general truths or the operation of general laws, especially when acquired and tested by the scientific method

Scientific law
a description, often in the form of a mathematical formula, for the behavior of some aspect of nature under certain specific conditions

Scientific method
a method of research with defined steps that include experiments and careful observation

Scientific theory
a thoroughly tested and confirmed explanation for observations or phenomena

Thoracic cavity
division of the anterior (ventral) cavity that houses the heart, lungs, esophagus, and trachea

Tissue
group of similar or closely related cells that act together to perform a specific function

Transverse plane
two-dimensional, horizontal plane that divides the body or organ into superior and inferior portions

Ultrasonography
application of ultrasonic waves to visualize subcutaneous body structures such as tendons and organs

Variable
a part of an experiment that can vary or change

Ventral
describes the front or direction toward the front of the body; also referred to as anterior

Ventral cavity
larger body cavity located anterior to the posterior (dorsal) body cavity; includes the serous membrane-lined pleural cavities for the lungs, pericardial cavity for the heart, and peritoneal cavity for the abdominal and pelvic organs; also referred to as anterior body cavity

X-ray

form of high energy electromagnetic radiation with a short wavelength capable of penetrating solids and ionizing gases; used in medicine as a diagnostic aid to visualize body structures such as bones

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1.10: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice

1. During an anatomy lab, students collect data on cadaver hearts: mass of the heart (in grams); presence or absence of visible coronary artery plaques (yes/no); and color description of myocardium: “pale,” “normal,” “dark.” Which combination correctly groups the quantitative variables only?
   A. Heart mass and presence/absence of plaques
   B. Heart mass and color description
   C. Presence/absence of plaques and color description
   D. Heart mass only
2. Students investigate forearm muscle fatigue and record:
   A. Time until fatigue in seconds
   B. Grip strength in kilograms
   C. Participant’s dominant hand (right or left)
   D. Participant’s future study program (e.g., nursing, physiotherapy, medicine)
3. Which variables are qualitative?
   A. Time until fatigue and grip strength
   B. Dominant hand and study program
   C. Time until fatigue, grip strength, and dominant hand
   D. All four variables
4. A clinician asks a patient with chest pain to rate pain on a 0–10 numeric scale and describe the pain as “sharp,” “dull,” or “burning.” Which statement is most accurate?
   A. Both measures are quantitative
   B. Both measures are qualitative
   C. The 0–10 scale is quantitative; the description (“sharp,” etc.) is qualitative
   D. The 0–10 scale is qualitative; the description (“sharp,” etc.) is quantitative
5. Which of the following specialties might focus on studying all of the structures of the ankle and foot?
   A. Microscopic anatomy
   B. Muscle anatomy
   C. Regional anatomy
   D. Systemic anatomy
6. A scientist wants to study how the body uses foods and fluids during a marathon run. This scientist is most likely:
   A. An exercise physiologist
   B. A microscopic anatomist
   C. A regional physiologist
   D. A systemic anatomist
7. A patient is undergoing treatment for a genetic disorder that affects how a specific structure in the body produces proteins. The physician explains that this structure is the smallest independently functioning biological unit of the body and that many of these units group together to form tissues. What is this structure called?
   A. Atom
   B. Molecule
   C. Cell

D. Tissue

8. A patient is diagnosed with a condition in which the structure responsible for pumping blood is damaged. The physician explains that this structure is made up of muscle tissue, nervous tissue, and connective tissue that work together to perform the specific function of circulating blood throughout the body. This structure is an example of:
   A. A cell
   B. A tissue
   C. An organ
   D. An organ system
9. The body system primarily responsible for providing structural support (maintaining body shape, protecting vital organs, and serving as an attachment framework) and enabling movement (through levers for muscles and joint articulation) is the:
   A. Nervous system
   B. Skeletal system
   C. Endocrine system
10. Metabolism can be defined as the:
   A. Adjustment by an organism to external or internal changes.
   B. Process whereby all unspecialized cells become specialized to perform distinct functions.
   C. Process whereby new cells are formed to replace worn-out cells.
   D. Sum of all chemical reactions in an organism.

11. During a long study session, J.M. realizes they have not eaten in several hours but are still able to think clearly, move around, and maintain their posture. Their instructor explains that even between meals, the body's cells rely on adenosine triphosphate (ATP) to temporarily hold energy released from breaking down nutrients and then make that energy available in a controlled way for cell activities such as muscle contraction and nerve signaling. Adenosine triphosphate (ATP) is an important molecule primarily because it:
   A. Is the result of catabolism and immediately releases all energy as heat.
   B. Releases energy in large, uncontrolled bursts that cannot be captured by cells.
   C. Stores energy in a usable form for body cells and releases it in controlled amounts.
   D. Does not participate in energy transfer and only provides structural support to cells.
12. A 55-year-old patient is diagnosed with an aggressive cancer. The oncologist explains that the cancer cells are behaving like "generic" cells: they no longer carry out the specialized functions of the tissue from which they originated and instead are dividing rapidly without contributing to normal body activities. In other words, these cancer cells have lost the ability to develop and maintain specialized structures and roles. The cancer cells therefore lack:
   A. Differentiation
   B. Reproduction
   C. Responsiveness
   D. Both reproduction and responsiveness
13. Which of the following statements about nutrients is accurate?
   A. Carbohydrates, lipids, and proteins are macronutrients because the body needs them in relatively large amounts.
   B. Because the body cannot store any micronutrients, they must all be consumed every day.
   C. Vitamins and minerals are macronutrients because they are needed for energy.
   D. All nutrients are considered micronutrients because they are required only in small amounts.
14. A 20-year-old college student goes for a long run on a hot, humid afternoon. After about 30 minutes, they begin to sweat heavily and notice that their skin feels warm and flushed. Despite the high temperature outside, their internal body temperature remains close to 37°C (98.6°F). Later, when they cool down and rest in the shade, the sweating gradually stops and their skin temperature returns toward normal. This situation is an example of which key physiological process?
   A. Homeostasis, because the body is maintaining a stable internal environment despite external changes.
   B. Metabolism, because the body is converting food directly into sweat.
   C. Differentiation, because cells are becoming more specialized during exercise.
   D. Anabolism, because the body is building new molecules to cool the skin.
15. Chester is stuck in a car during a bitterly cold blizzard for several hours. Chester is shivering and notices that the fingers and toes are becoming very cold and slightly numb. Despite not eating recently, the body is working to maintain a stable internal temperature (around 37°C or 98.6°F) by generating heat from within. Which of the following best describes one way the body responds to the cold in this situation?
   A. Increasing the blood flow to the hands and feet to warm them.
   B. Becoming lethargic to conserve heat, which rapidly lowers core body temperature.
   C. Breaking down stored energy (such as glycogen and fat) to produce heat and maintain body temperature.
   D. Significantly increasing blood oxygen levels to prevent frostbite.
16. After a long morning class, A.L. eats a large lunch. As the food enters the stomach, the stomach wall stretches. Specialized

nerve cells in the stomach wall detect this distension and send signals so that appropriate responses (such as increased stomach muscle contractions and secretion of digestive juices) can occur. In terms of a typical feedback control loop, these nerve cells relay the information about stomach distension to which component?

A. A control center
B. A set point
C. Effectors
D. Sensors

17. On a very hot day, K.R. has been running outdoors for nearly an hour. Their internal body temperature starts to rise slightly above normal. In response, temperature-sensitive nerve cells in the skin and brain send signals to the heat-loss center in the brain. A short time later, K.R. notices that their skin feels flushed and damp, and sweat is forming on their face and arms. Which of the following best describes a response triggered by stimulation of the heat-loss center in this situation?
    A. Blood vessels in the skin constrict to reduce blood flow to the surface.
    B. Breathing becomes slow and shallow to conserve heat.
    C. Sweat glands increase their output to promote evaporative cooling.
    D. All of the above
18. A 19-year-old athlete finishes a hard workout on a hot day. Their body temperature rises slightly above normal, and receptors in the skin and brain detect this change. In response, the brain activates mechanisms that cause the body to cool down (for example, increased sweating and dilation of skin blood vessels). As the body temperature returns toward normal, these cooling responses gradually decrease and eventually stop. This scenario best illustrates which type of homeostatic feedback loop?
    A. Positive feedback loop, because the response amplifies the original change.
    B. Negative feedback loop, because the response reverses the original change.
    C. Positive feedback loop, because the response continues to increase indefinitely.
    D. No feedback loop, because body temperature is not regulated.
19. What is the position of the body when it is in the “normal anatomical position?”
    A. The person is prone with upper limbs, including palms, touching sides and lower limbs touching at sides.
    B. The person is standing facing the observer, with upper limbs extended out at a ninety-degree angle from the torso and lower limbs in a wide stance with feet pointing laterally.
    C. The person is supine with upper limbs, including palms, touching sides and lower limbs touching at sides.
    D. None of the above.
20. To make a banana split, you halve a banana into two long, thin, right and left sides along the:
    A. Coronal plane
    B. Longitudinal plane
    C. Midsagittal plane
    D. Transverse plane
21. A patient is lying on an exam table in the standard anatomical position: standing upright, facing forward, arms at the sides with palms facing forward, and feet slightly apart. The physician wants to describe the location of the elbow relative to the wrist using correct anatomical terminology. Which of the following is the most accurate description?
    A. The elbow is distal to the wrist.
    B. The elbow is proximal to the wrist.
    C. The elbow is inferior to the wrist.
    D. The elbow is superficial to the wrist.
22. A nurse documents pain in the front of a patient’s elbow. Which body region is being described?
    A. Antecubital
    B. Popliteal
    C. Axillary
    D. Inguinal
23. During a CT scan, the body is divided into upper and lower portions. Which anatomical plane is being used?
    A. Sagittal plane
    B. Frontal plane
    C. Transverse plane
    D. Oblique plane
24. In 1901, Wilhelm Röntgen became the first person to receive the Nobel Prize in Physics. For which discovery was he honored?
    A. Nuclear physics
    B. Radiopharmaceuticals
    C. The link between radiation and cancer
    D. X-rays
25. A patient is being evaluated for a rapidly growing tumor. The oncologist wants to see which areas of the body are taking

up the most glucose (a nutrient), so they can identify regions of high metabolic activity typical of rapidly multiplying cancer cells. A small amount of a radioactive glucose-like substance is injected, and a scanner creates images showing where this substance is being used most in the body. Which imaging technique is best suited for this purpose?

A. CT (computed tomography)
B. MRI (magnetic resonance imaging)
C. PET (positron emission tomography)
D. Ultrasonography

26. A pregnant patient needs an imaging study to check on the health and development of the fetus. The healthcare provider chooses a method that uses sound waves instead of ionizing radiation, making it the safest option for both the patient and the fetus. Which imaging study is most appropriate in this situation?

A. CT scan
B. PET scan
C. Ultrasound
D. X-ray

27. A patient is scheduled for a magnetic resonance imaging (MRI) scan to evaluate a possible knee injury. The radiology technician explains that MRI does not use ionizing radiation, but it does have some drawbacks. The machine is very expensive, and the powerful magnetic field requires special shielding and safety precautions in the imaging room. Which of the following best identifies two major disadvantages of MRI scans?

A. Release of radiation and poor quality images.
B. High cost and the need for shielding from the magnetic signals.
C. Can only view metabolically active tissues and inadequate availability of equipment.
D. Release of radiation and the need for a patient to be confined to a metal tube for up to 30 minutes.

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1.11: Applied Thinking Self - Assessment

Challenge Yourself

Extended response questions are assessment items that require students to construct written answers of substantial length—typically several sentences to multiple paragraphs—rather than selecting from predefined options. They represent a form of constructed response assessment designed to measure complex, higher-order thinking skills.

- Answer each question in complete sentences and in your own words.
- Use correct scientific vocabulary (e.g., hypothesis, variable, anterior, homeostasis, metabolism, tissue, organ system).
- Where appropriate, support your answer with a clear definition of key terms, a reasoned explanation ("because…", "therefore…"), a simple example or labeled sketch. do more than list facts; explain, compare, and apply concepts, use why and how in your answers to show your reasoning.
- Use proper anatomical terms of position and orientation (e.g., superior/inferior, medial/lateral, proximal/distal, superficial/deep, anterior/posterior) when describing locations in the human body.
- Write clearly and organize your answer: 1–2 sentences for short items, 1–2 paragraphs for extended items (with an introduction idea and supporting details).
- If you make an assumption (for example, about a body position or environment), state it clearly in your answer.

1. Explain how "form supports function" for one organ (e.g., heart, lungs, stomach, skin). Describe two or three specific structural features of that organ (for example: shape, size, surface area). Explain how each feature helps the organ do its job.
2. List and briefly define the six levels of organization in the human body, from smallest to largest. For each level, do both of the following:
    a. Give its name (for example, "cellular level").
    b. Write one simple sentence explaining what it means.
3. Can an organ belong to only one body system, or can it belong to more than one? Give the name of one specific organ that belongs to more than one system. Name each system this organ belongs to. Describe the organ's role in each system in one or two short sentences per system.
4. Give three different examples of how growth happens in the human body. For each example:
    a. Name the type of growth (for example: increase in cell size, increase in cell number, or increase in body materials between cells).
    b. Give one short, concrete example (for example: muscle fiber enlargement with exercise).
5. Atmospheric pressure and the body (sparkling water analogy). Consider what happens when you open a bottle of sparkling water: At first, carbon dioxide gas forms bubbles and escapes. If the bottle stays open, the water eventually "goes flat." Use this example to answer in your own words:
    a. What does this tell you about how gases move when pressure changes?
    b. Why is atmospheric pressure essential for the human body?
6. Dehydration in the desert (midsummer trek): Josh runs out of water during a midsummer hike in the desert. Explain three separate reasons why this is especially dangerous for his body. For each reason:
    a. Name a specific problem (for example: blood volume changes, overheating, or changes in cell function).
    b. Give one or two sentences explaining what could happen in the body and why it is harmful.
7. Homeostasis and a full negative feedback loop: Choose one variable (body temperature, blood glucose, blood pressure, or blood calcium). Define homeostasis and describe the full negative feedback loop for your chosen variable: stimulus, receptor(s), control center, effector(s), and response. Then predict what would happen if one component failed (e.g., receptor damage or effector fatigue) and describe the likely signs/symptoms.
8. Case: Head injury after a fall (imaging choice): Case: A 20-year-old falls from a bike. They have a severe headache and a brief loss of consciousness. Answer the following questions:
    a. Which imaging test should be done first for this patient (for example, CT or MRI), and why is it the best initial choice?
    b. Name at least two problems that this first test can detect well (for example, bleeding in the brain, skull fracture).
    c. Explain when and why another imaging test (for example, MRI) might be a better choice later in the patient's care.
9. Penetrating chest injury and thoracic cavities: Suppose a sharp object (such as a knife during surgery) enters the chest from the front and pierces a lung. Answer the following:
    a. Name the three thoracic spaces or cavities the object would pass through in order, from the body surface to the lung. Hint: Think about the space between the ribs, the pleural cavity, and the lung itself.
    b. Name the first layer of the pleura (serous membrane) that the object would contact on its way to the lung.

10. Why ultrasound is preferred in fetal imaging? Explain why ultrasound imaging is the technique of choice to study fetal growth and development. Include in your answer:
    a. How ultrasound works in simple terms (for example, what kind of waves it uses).
    b. At least two reasons why it is safer or better for the fetus and pregnant patient than imaging methods that use ionizing radiation (such as X-rays or CT).
    c. One example of the type of information about the fetus that ultrasound can provide.

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1.12: Alternative Text Descriptions

Figure 1.1.1: Bacteria

This figure is a scanning electron micrograph of rod-shaped bacteria. Several bacteria are clustered together in an arched, branching arrangement on a textured surface. A scale bar labeled “1 µm” indicates the structures are microscopic.

Figure 1.1.2: Scientific Method Flowchart

This figure is scientific method flowchart showing a step-by-step process. The flow begins at the top box labeled “Make an observation,” then moves down where an arrow points to the box labeled “Ask a question,” then moves down where an arrow points to the box labeled “Form a hypothesis that answers the question,” then moves down where an arrow points to the box labeled “Make a prediction based on the hypothesis,” then moves down where an arrow points to the box labeled “Do an experiment to test the prediction,” and then moves down where an arrow points to the box labeled “Analyze the results.” From “Analyze the results,” the chart branches into two outcomes to the left a box labeled “Hypothesis is supported” and to the right a box labeled “Hypothesis is not supported”. A box labeled “Try again…” indicates that if the hypothesis is not supported, the process loops back to revise the question or hypothesis and repeat the steps. Both outcome paths lead to the final step at the bottom to the box labeled “Report results.”

Figure 1.1.3: The Human Genome Project

This figure is a circular graphic representing an interdisciplinary STEM (Science, Technology, Engineering, Mathematics) focus. Around the outer ring, the words read (clockwise): “Biology” “Physics,” “Ethics,” “Informatics,” “Engineering,” and “Chemistry”. In the center is a stylized human-shaped silhouette over a DNA double helix background. A wide ribbon-like band wraps diagonally across the center, suggesting integration across the listed disciplines.

Figure 1.2.1: Gross and Microscopic Anatomy

This figure has two labeled panels comparing brain anatomy and brain tissue under magnification.

Panel (a) shows a photograph of an intact brain viewed from the outside. The surface has many folds and grooves, creating a wrinkled appearance typical of the cerebral cortex.

Panel (b) shows a microscopic view of brain tissue stained in shades of blue and purple. Several cell bodies are visible as darker, rounded or oval shapes within a lighter background. Two arrows point to larger, darker-stained cell bodies labeled “Neuron cells,” indicating examples of neurons within the tissue sample.

Figure 1.3.1: Levels of Structural Organization of the Human Body

This image is a pyramid-shaped overview of the levels of organization in the body, arranged from the smallest level at the top to the largest level at the bottom. Each tier includes a label, a short definition, and an example.

Top tier: Chemical level

- Shows individual hydrogen atoms and an oxygen atom.
- Text explains that atoms bond to form molecules with three-dimensional structures.

Second tier: Molecule example

- Shows a water molecule as an example of a molecule formed from atoms.

Third tier: Cellular level

- Labeled “Cellular level.”
- Text explains that a variety of molecules combine to form the fluid and organelles of a body cell.
- The example shown is a smooth muscle cell, with labels pointing to organelles and cell fluid.

Fourth tier: Tissue level

- Labeled “Tissue level.”
- Text states that a community of similar cells forms a body tissue.
- The example is smooth muscle tissue, shown as many elongated cells grouped together.

Fifth tier: Organ level

- Labeled “Organ level.”
- Text explains that two or more different tissues combine to form an organ.
- The example shown is the bladder, with a label indicating smooth muscle as part of the organ.

Sixth tier: Organ system level

- Labeled “Organ system level.”
- Text explains that two or more organs work closely together to perform the functions of a body system.
- The example is the urinary tract system, with labeled parts: kidney, ureter, bladder, and urethra.

Bottom tier: Organismal level

- Labeled “Organismal level.”
- Text explains that many organ systems work together to perform the functions of an independent organism.

Overall, the pyramid communicates that biological organization builds step-by-step from atoms, to molecules, to cells, to tissues, to organs, to organ systems, and finally to the whole organism

Figure 1.3.2: Major Body Systems

This figure is arranged in two vertical columns, with six human figures total, each illustrating a different organ system. Each figure is shown standing upright in a neutral position, facing forward. Labels point to key structures, and short descriptions explain each system’s function.

Top Left - Integumentary System: A full-body illustration of a human female with smooth skin and no visible muscles or organs.

- Labeled structures:
  - Hair on the head
  - Skin covering the entire body
  - Nails on the fingers and toes
- Description: The integumentary system encloses internal body structures, protects the body, and serves as the site of many sensory receptors. The skin forms a protective barrier that helps regulate temperature and prevents water loss.

Top Right - Skeletal System: A human figure showing the entire skeleton in light gray.

- Labeled structures:
  - Bones throughout the body
  - Joints at the shoulders, elbows, hips, knees, and ankles
  - Cartilage in specific joint areas
- Description: The skeletal system supports the entire body, protects internal organs, and enables movement when working together with the muscular system.

Middle Left - Muscular System: A human figure showing red skeletal muscles covering the body.

- Labeled structures:
  - Skeletal muscles in the arms, legs, chest, and abdomen

    - Tendons connecting muscles to bones
- Description: The muscular system enables movement, works with the skeletal system, and helps maintain body temperature through muscle activity.

Middle Right - Nervous System: A human figure showing the nervous system in yellow.

- Labeled structures:
    - Brain in the skull
    - Spinal cord running down the back
    - Peripheral nerves branching into the arms, torso, and legs
- Description: The nervous system detects and processes sensory information and activates bodily responses, allowing communication between the brain and the rest of the body.

Bottom Left - Endocrine System: A human figure showing glands throughout the body, with an inset for female reproductive glands.

- Labeled structures:
    - Pituitary gland in the brain
    - Thyroid gland in the neck
    - Pancreas in the abdomen
    - Adrenal glands on top of the kidneys
    - Testes (shown on the main figure)
    - Ovaries (shown in a separate inset image)
- Description: The endocrine system secretes hormones and regulates bodily processes such as growth, metabolism, reproduction, and stress responses through chemical signaling.

Bottom Right - Cardiovascular System: A human figure with red and blue blood vessels throughout the body.

- Labeled structures:
    - Heart in the chest
    - Blood vessels extending to all parts of the body
- Description: The cardiovascular system delivers oxygen and nutrients to tissues, removes waste products, and helps regulate body temperature by circulating blood.

Figure 1.3.3: Major Organ Systems

This figure contains six silhouettes of adult humans, arranged in three rows and two columns. Each silhouette represents a different organ system, with labels pointing to major organs. The figures are standing upright and facing forward.

Top Left - Lymphatic System: A human figure showing a network of thin vessels and small nodes distributed throughout the body.

- Labeled structures:
    - Thymus in the upper chest
    - Lymph nodes in the neck, underarms, and groin
    - Spleen in the upper left abdomen
    - Lymphatic vessels extending through the limbs and torso
- Description: The lymphatic system returns fluid to the blood and defends the body against pathogens. It plays a key role in immune function by filtering harmful substances and supporting the activity of immune cells.

Top Right - Respiratory System: A human figure showing the air-conducting passages and lungs.

- Labeled structures:
    - Nasal passages in the head
    - Trachea extending down the neck
    - Lungs within the chest
- Description: The respiratory system removes carbon dioxide from the body and delivers oxygen to the blood. Breathing allows gases to be exchanged between the air and the bloodstream.

Middle Left - Digestive System: A human figure with abdominal organs visible.

- Labeled structures:
  - Stomach
  - Liver
  - Gall bladder
  - Small intestine
  - Large intestine
- Description: The digestive system processes food for use by the body, absorbs nutrients, and removes wastes from undigested material.

Middle Right - Urinary System: A human figure showing the organs involved in urine production and storage.

- Labeled structures:
  - Kidneys
  - Urinary bladder
- Description: The urinary system controls water balance in the body, removes waste products from the blood, and excretes them as urine.

Bottom Left - Male Reproductive System: A male human figure showing reproductive organs.

- Labeled structures:
  - Testes
  - Epididymis
- Description: The male reproductive system produces sex hormones and gametes and delivers gametes to the female reproductive tract.

Bottom Right - Female Reproductive System: A female human figure showing reproductive and supportive structures.

- Labeled structures:
  - Ovaries
  - Uterus
  - Mammary glands
- Description: The female reproductive system produces sex hormones and gametes, supports the embryo and fetus until birth, and produces milk for the infant after birth.

Figure 1.4.1: Metabolism

This figure shows from the left food entering a cell. Above the arrow is labeled "Catabolism" and below the arrow is labeled "Releases energy". The entered food is being broken down into smaller particles. Different particles are combined with each other to form larger structures. Anabolism requires an energy input. To the right of the cell, above the arrow is labeled "Catabolism" and below the arrow is labeled "Releases energy"Anabolism.

Figure 1.6.1: Negative Feedback System

This figure contains two side-by-side flow diagrams, labeled A and B, that explain how a negative feedback system works in general and how it regulates human body temperature.

Left Diagram (A) - General Negative Feedback Loop: The left diagram shows the basic structure of a negative feedback system using a vertical sequence of labeled boxes connected by arrows. The process begins with an oval box labeled stimulus connected by an arrow to a rectangle box labeled sensor, connected by an arrow to a rectangle box labeled control, connected by an arrow to a rectangle box labeled effector, connected by an arrow to a rectangle box labeled response.

1. Stimulus - This represents a deviation from the normal set point of a body condition.
2. Sensor - The sensor detects the change caused by the stimulus and monitors the physiological condition.
3. Control - The control center receives information from the sensor and compares it to the normal range or set point.
4. Effector - The effector carries out a response directed by the control center.

5. Response - The response counteracts the original stimulus.

A return arrow leads back toward the stimulus, indicating that the response reduces or eliminates the original change, bringing the system back to homeostasis. This reversal of the stimulus is what defines negative feedback.

Right Diagram (B): - Negative Feedback Example is body temperature regulation: The right diagram applies the same negative feedback sequence to body temperature control.

1. Stimulus: Body temperature exceeds 37°C The process begins when body temperature rises above the normal set point of approximately 37 degrees Celsius.
2. Sensor: Nerve cells in skin and brain Specialized nerve cells detect the increased temperature and send signals to the brain.
3. Control: Temperature regulatory center in brain The brain's temperature control center receives the signals and determines that the temperature is too high.
4. Effector: Sweat glands throughout body The control center activates sweat glands across the skin.
5. Response: Increased heat loss Sweating increases heat loss as sweat evaporates from the skin, cooling the body.

This response lowers body temperature back toward the normal range, reducing the initial stimulus and restoring homeostasis.

Figure 1.6.2: Positive Feedback System

This figure illustrates a positive feedback loop that occurs during labor and childbirth. The diagram centers on a pregnant uterus shown in side view, with a full-term fetus positioned head-down inside the uterus. Surrounding the uterus is a circular sequence of arrows that represent the repeating steps of the feedback loop. Each step is labeled with text explaining the process.

Central Image (Uterus and Baby) - At the center of the diagram is a cross-section of the uterus containing a fetus.

- The baby is curled inside the uterus with the head positioned downward, pressing against the cervix, which is the lower opening of the uterus.
- The cervix appears stretched slightly due to the baby's head applying pressure.

Step-by-Step Feedback Loop (Clockwise)

1. Head of baby pushes against cervix The baby's head presses against the cervix, causing the cervix to stretch.
2. Nerve impulses from cervix transmitted to brain Stretch-sensitive nerve cells in the cervix detect the pressure and send nerve signals to the brain.
3. Brain stimulates pituitary gland to secrete oxytocin The brain responds to the nerve signals by signaling the pituitary gland to release the hormone oxytocin.
4. Oxytocin carried in bloodstream to uterus Oxytocin is released into the blood and travels through the bloodstream to the uterus.
5. Oxytocin stimulates uterine contractions and pushes baby toward cervix Oxytocin causes the smooth muscle of the uterus to contract more strongly and more frequently. These contractions push the baby further downward against the cervix.

Positive Feedback Explanation - As the baby is pushed harder against the cervix:

- Cervical stretching increases
- More nerve signals are sent to the brain
- More oxytocin is released
- Contractions become stronger and more frequent

This creates a self-reinforcing cycle, or positive feedback loop, that continues to intensify until the baby is born. The loop ends naturally at childbirth, when cervical stretching stops and oxytocin release decreases.

Figure 1.7.1: Regions of the Human Body

This figure shows the anatomical regional names used to identify specific locations on the human body. It includes two views: an anterior (front) view and a posterior (back) view. The figure labels major body regions and gives the corresponding anatomical adjectives commonly used in anatomy and physiology.

Major Body Divisions

- Head (cephalon or cephalic): Includes all structures of the head
- Neck (cervicis or cervical): Connects the head and trunk
- Trunk: Includes the chest, abdomen, pelvis, and back
- Upper limb: Includes the shoulder, arm, forearm, wrist, and hand
- Lower limb: Includes the hip, thigh, leg, ankle, and foot

Anterior (Front) View Labels

- Frons or forehead (frontal)
- Cranium or skull (cranial)
- Oculus or eye (orbital or ocular)
- Bucca or cheek (buccal)
- Auris or ear (otic)
- Facies or face (facial)
- Nasus or nose (nasal)
- Oris or mouth (oral)
- Mentis or chin (mental)
- Cervicis or neck (cervical)
- Thoracis or thorax, chest (thoracic)
- Mamma or breast (mammary)
- Abdomen (abdominal)
- Umbilicus or navel (umbilical)
- Axilla or armpit (axillary)
- Brachium or arm (brachial)
- Antecubitis or front of elbow (antecubital)
- Antebrachium or forearm (antebrachial)
- Carpus or wrist (carpal)
- Palma or palm (palmar)
- Pollex or thumb
- Digits (phalanges) or fingers (digital or phalangeal)
- Hip (coxal)
- Pelvis (pelvic)
- Inguen or groin (inguinal)
- Pubis (pubic)
- Femur or thigh (femoral)
- Patella or kneecap (patellar)
- Crus or leg (crural)
- Tarsus or ankle (tarsal)
- Pes or foot (pedal)
- Digits (phalanges) or toes (digital or phalangeal)
- Hallux or great toe

Posterior (Back) View Labels

- Cephalon or head (cephalic)
- Cervicis or neck (cervical)
- Shoulder (acromial)
- Dorsum or back (dorsal)

- Brachium or arm (brachial)
- Olecranon or back of elbow (olecranal)
- Antebrachium or forearm (antebrachial)
- Manus or hand (manual)
- Lumbus or loin (lumbar)
- Sacrum (sacral)
- Gluteus or buttock (gluteal)
- Femur or thigh (femoral)
- Popliteus or back of knee (popliteal)
- Sura or calf (sural)
- Calcaneus or heel of foot (calcaneal)
- Planta or sole of foot (plantar)

Body Region Groupings

Trunk

The trunk includes the following regions:

- Thoracic (chest)
- Mammary (breast)
- Abdominal (abdomen)
- Umbilical (navel)
- Pelvic
- Dorsal (back)
- Lumbar (loin)
- Sacral

Upper Limb

The upper limb includes the following regions:

- Acromial (shoulder)
- Axillary (armpit)
- Brachial (arm)
- Antecubital (front of elbow)
- Olecranal (back of elbow)
- Antebrachial (forearm)
- Carpal (wrist)
- Manual (hand)
- Palmar (palm)
- Pollex (thumb)
- Digital or phalangeal regions of the fingers

Lower Limb

The lower limb includes the following regions:

- Coxal (hip)
- Femoral (thigh)
- Patellar (kneecap)
- Popliteal (back of knee)
- Crural (leg)
- Sural (calf)
- Tarsal (ankle)
- Calcaneal (heel)

- Plantar (sole)
- Pedal (foot)
- Hallux (great toe)
- Digital or phalangeal regions of the toes

Educational Purpose

This figure provides standardized anatomical terminology used by healthcare professionals and scientists to identify and describe locations on the human body. Each region is labeled with both a common name and its corresponding anatomical adjective.

Figure 1.7.2: Anatomical Directional Terms

This image shows the standard anatomical directional terms used in human anatomy. It includes two illustrations of a female figure in the standard anatomical position against a white background.

Left Illustration: Lateral View (Side Profile)

This figure is shown in side profile, facing right. It illustrates vertical and front-to-back directional relationships.

- Superior / Inferior:
  Superior appears at the top of the image above both figures, and Inferior appears at the bottom. These terms indicate direction toward the head and toward the feet.

- Cranial / Caudal:
  A long green vertical arrow extends from the feet toward the head. The upper end near the head is labeled Cranial, and the lower end near the lower torso is labeled Caudal.

- Anterior / Posterior:
  A dashed horizontal line passes through the mid-chest area with arrows pointing in opposite directions:

  - The forward-pointing arrow, toward the right, is labeled Anterior or ventral
  - The backward-pointing arrow, toward the left, is labeled Posterior or dorsal

Right Illustration: Anterior View (Frontal View)

This figure faces forward with arms at the sides and palms facing forward. It illustrates side-to-side and limb-related directional relationships.

- Right / Left:
  The figure's right side, which appears on the viewer's left, is labeled Right. The figure's left side, which appears on the viewer's right, is labeled Left.

- Medial / Lateral:
  The word Medial appears at the center of the abdomen. A dashed horizontal line extends outward toward the arm with an arrow pointing away from the midline. This direction is labeled Lateral.

- Proximal / Distal (Upper Extremity):
  A long green arrow runs along the figure's left arm, shown on the viewer's right. The upper end near the shoulder is labeled Proximal, and the lower end near the fingers is labeled Distal.

- Proximal / Distal (Lower Extremity):
  A long green arrow runs along the figure's right leg, shown on the viewer's left. The upper end near the hip is labeled Proximal, and the lower end near the ankle and foot is labeled Distal.

Figure 1.7.3: Body Planes

This is a diagram of a human body with three labeled anatomical planes:

- Sagittal plane divides the body or an organ vertically into right and left sides. If this vertical plane runs directly down the middle of the body, it is called the mid-sagittal or median plane.
- Parasagittal plane is a vertical cut that is off-center that separates the left of the specimen from the right in unequal portions. It does not matter whether it is the left side or the right side that is larger, as long as they are not equal.
- Frontal plane divides the body or an organ into an anterior (front) portion and a posterior (rear) portion. The frontal plane is sometimes referred to as a coronal plane.
- Transverse plane divides the body or organ horizontally into upper and lower portions. Transverse planes produce images referred to as cross sections.
- Oblique plane is an anatomical plane that cuts the body at an angle, rather than in the coronal, sagittal, or transverse planes. Helps visualize structures like the spine and pelvis that are hard to see from other planes.

Figure 1.7.4: Dorsal and Ventral Body Cavities

This figure shows the major body cavities and their subdivisions in two views of the human body: a lateral (side) view and an anterior (front) view.

Major Body Cavities

The figure identifies two main body cavities:

- Dorsal body cavity
- Ventral body cavity

Lateral (Side) View

The dorsal body cavity is located along the posterior aspect of the body and includes:

- Cranial cavity: The space within the skull that contains the brain
- Vertebral cavity: The space within the vertebral column that contains the spinal cord

The ventral body cavity is located along the anterior aspect of the body and includes:

- Thoracic cavity
- Abdominal cavity
- Pelvic cavity

The diaphragm separates the thoracic cavity from the abdominal cavity.

Anterior (Front) View

In the anterior view:

- The cranial cavity is located within the skull
- The vertebral cavity extends through the vertebral column
- The ventral body cavity includes the thoracic cavity and the abdominopelvic cavity

The thoracic cavity contains:

- Superior mediastinum
- Right pleural cavity
- Left pleural cavity
- Pericardial cavity within the mediastinum

The diaphragm forms the boundary between the thoracic cavity and the abdominopelvic cavity.

The abdominopelvic cavity consists of:

- Abdominal cavity
- Pelvic cavity

Relationship of the Cavities

The dorsal body cavity includes:

- Cranial cavity
- Vertebral cavity

The ventral body cavity includes:

- Thoracic cavity
- Abdominopelvic cavity

The thoracic cavity contains:

- Superior mediastinum
- Right pleural cavity
- Left pleural cavity
- Pericardial cavity within the mediastinum

The abdominopelvic cavity contains:

- Abdominal cavity
- Pelvic cavity

Educational Purpose

The figure demonstrates how the major body cavities are organized and how they relate to one another.

- The dorsal body cavity is divided into the cranial cavity and the vertebral cavity
- The ventral body cavity is divided into the thoracic cavity and the abdominopelvic cavity
- The thoracic cavity contains the superior mediastinum, the right and left pleural cavities, and the pericardial cavity within the mediastinum
- The abdominopelvic cavity is further divided into the abdominal cavity and the pelvic cavity

Figure 1.7.5: Regions and Quadrants of the Peritoneal Cavity

The image compares two common systems used to describe abdominal locations. A dashed curved line near the top of both panels indicates the approximate level of the diaphragm.

Panel (a) divides the abdomen into a 3-by-3 grid with these labeled regions:

- Top row: right hypochondriac; epigastric; left hypochondriac
- Middle row: right lumbar; umbilical; left lumbar
- Bottom row: right iliac; hypogastric; left iliac

Panel (b) uses a cross to divide the abdomen into four labeled quadrants:

- Right upper quadrant (RUQ)
- Left upper quadrant (LUQ)
- Right lower quadrant (RLQ)
- Left lower quadrant (LLQ)

The more detailed regional approach subdivides the cavity with one horizontal line immediately inferior to the ribs and one immediately superior to the pelvis, and two vertical lines drawn as if dropped from the midpoint of each clavicle (collarbone). There are nine resulting regions. The simpler quadrants approach, which is more commonly used in medicine, subdivides the cavity with one horizontal and one vertical line that intersect at the patient's umbilicus (navel).

Figure 1.7.6:Serous Membrane

The image is divided into two side-by-side illustrations. The left illustration shows the anatomical structure of the heart and its surrounding membranes. The right illustration uses a hand-in-balloon analogy to explain how the pericardial layers surround the heart.

Left Illustration – Heart and Pericardium: The left side displays a detailed drawing of a human heart enclosed within protective layers called the pericardium. The heart is centrally positioned and includes visible blood vessels at the top. Surrounding the heart are three labeled layers:

- Visceral pericardium: The inner layer that lies directly on the surface of the heart.
- Pericardial cavity: A thin fluid-filled space surrounding the heart, located between the visceral and parietal layers.
- Parietal pericardium: The outer layer that forms a protective sac around the heart.

The pericardial cavity is depicted as a narrow space, indicating that it contains a small amount of fluid allowing the heart to move smoothly during beating.

Right Illustration – Balloon Analogy: The right side uses a simplified analogy to explain the structure of the pericardium:

- A human hand is shown pushing into a partially inflated balloon.
- The balloon surface represents the pericardial layers.
- The portion of the balloon touching the hand represents the visceral pericardium.
- The outer surface of the balloon represents the parietal pericardium.
- The small space between the layers of the balloon is labeled as the air space, representing the pericardial cavity.

The opening of the balloon is visible at the bottom, tied with a string.

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2: CHEMICAL FOUNDATIONS OF LIFE

Chapter Overview

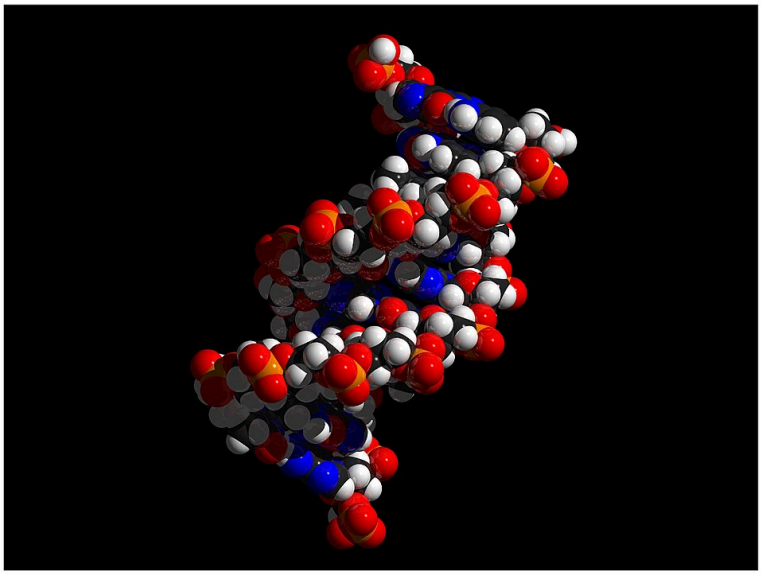


Figure 2.1: Human DNA is described as a double helix that resembles a molecular spiral staircase. In humans the DNA is organized into 46 chromosomes. (CC BY 4.0; via Wikimedia Commons).

Figure 2.1 displays a three-dimensional molecular model of DNA. The structure is shown as a cluster of spheres representing atoms in a ball-and-stick style. The DNA appears twisted in a double-helix formation, with red, white, blue, and gray spheres indicating different atomic elements. The background is solid black, highlighting the molecular details.

Introduction to Life's Chemical Foundations

Life's chemistry begins with a handful of familiar elements. Oxygen (O), carbon (C), hydrogen (H), and nitrogen (N) dominate the human body, arriving in us by way of the air we breathe and the foods we eat. Each element is defined by its atoms - the smallest units that still carry that element's identity. Atoms share a common architecture of protons, neutrons, and electrons; what distinguishes one element from another is how many protons it has (its atomic number), while its mass reflects protons plus neutrons. Even a single element can come in heavier or lighter "versions," or isotopes, when neutron counts vary.

Atomic Structure, Valence Electrons, and Bonding

An atom's willingness to mingle or remain aloof is written in its outermost electrons, the valence shell. Noble gases, with complete valence shells, are content to stay as they are; most other atoms strive for a stable configuration by giving up, taking on, or sharing electrons. The result is bonding. If an atom donates or accepts electrons it becomes an ion - positively charged cations and negatively charged anions that attract to form ionic bonds. If atoms share electrons they form covalent bonds, which can be even-handed (nonpolar) or unequal (polar) depending on how strongly each partner pulls. Water, made of one oxygen and two hydrogens, is a classic polar molecule whose partial charges let it form fleeting hydrogen bonds with neighbors. Those hydrogen bonds, though weak individually, in vast numbers give water its remarkable biological roles - solvent, cushion, lubricant, and heat buffer.

Energy, Chemical Reactions, and Enzymes

With bonds in place, chemistry becomes change. Chemical reactions break old bonds and create new ones, shuffling atoms from reactants to products. Doing so requires energy to get started and either consumes or releases energy along the way. The body trades among several forms: chemical energy stored in bonds, electrical energy carried by moving electrons and ions, radiant

energy from waves like sunlight, and mechanical energy that moves muscles and fluids. Synthesis reactions build larger structures and typically demand energy; decomposition reactions tear them down and often release energy; exchange reactions do both. How fast these transformations occur depends on temperature, the abundance and pressure of reactants, and the presence of catalysts. Enzymes—protein catalysts with exquisite shape and specificity - speed life's reactions under gentle, physiological conditions.

Inorganic Compounds, Ions, and pH Balance

Not all molecules in the body are built on carbon's versatile backbone. Inorganic compounds such as water, salts, acids, and bases are indispensable. Salts dissociate into ions that conduct electrical signals and drive fluid balance. Acids donate H^+ to a solution, bases accept it, and together they influence pH - the measure of hydrogen ion concentration. Because the pH scale is logarithmic, a one-unit shift reflects a tenfold change in H^+. Blood is tightly regulated near pH 7.4 by chemical buffers, pairs of weak acids and bases that soak up excess H^+ or release it when needed to keep physiology within safe limits.

Organic Molecules and Biological Macromolecules

Organic compounds - those containing both carbon and hydrogen - form the main structural and functional toolkit of cells. Carbon's ability to share electrons and to host functional groups (like hydroxyl, amino, carboxyl, and phosphate) allows limitless architectures. Small organic units (monomers) link together by dehydration synthesis to build polymers; those polymers can be trimmed back to monomers by hydrolysis. Carbohydrates supply ready fuel: simple sugars such as glucose feed directly into pathways that harvest energy as ATP, while longer chains like glycogen store glucose and fiber supports digestive health. Lipids, mostly hydrophobic, store energy densely and build membranes; triglycerides pack fatty acids onto glycerol, phospholipids assemble amphipathic bilayers that define cells, steroids like cholesterol shape membranes and serve as hormone precursors, and prostaglandins act as local signals. Proteins - chains of nitrogen-containing amino acids joined by peptide bonds - old into shapes that determine their tasks, from scaffolding tissues to catalyzing reactions as enzymes. Nucleotides, built from a sugar, phosphate group(s), and a nitrogenous base, assemble into DNA and RNA to store and transmit genetic information and to direct protein synthesis. One nucleotide, ATP, stands apart as the cell's chief energy currency: cleaving or adding its phosphate groups releases or invests energy to power nearly every process that keeps us alive.

From Chemical Structure to Biological Function

From atoms and bonds to buffers and biomolecules, the storyline is one of structure enabling function and energy flowing through transformations. The human body leverages simple physical principles to build complexity, maintain stability, and do work - an elegant chemistry in constant motion.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own.

By the end of this chapter, students should be able to:

- Describe the fundamental composition of matter by defining elements, atoms, molecules, and compounds, and by distinguishing atomic number, mass number, and isotopes.
- Identify the three subatomic particles—protons, neutrons, and electrons—stating their charge, relative mass, and location within the atom.
- Identify the four most abundant elements in the human body (C, H, O, N) and describe the importance of each.
- Explain how the number of valence electrons relates to atomic stability and reactivity, using the octet rule to predict whether atoms tend to gain, lose, or share electrons.
- Distinguish among ionic, covalent (nonpolar and polar), and hydrogen bonds by describing how each forms, predicting bond type from electronegativity/valence information, and citing biological examples (e.g., NaCl, O_2, H_2O, DNA base pairing).

- Explain how energy is invested, stored, and released via chemical reactions, particularly those reactions that are critical to life.
- Explain the importance of key inorganic compounds—water, salts, acids, and bases—by linking their properties to physiological functions (solvent, cushioning, electrolytes), interpreting the pH scale, and describing how buffers help maintain blood pH.
- Compare and contrast the four major classes of organic compounds—carbohydrates, lipids, proteins, and nucleic acids—by outlining their elemental composition, monomers/polymers and functional groups, principal functions in the body, and representative examples (for example: glucose/glycogen, triglycerides/phospholipids, amino acids/enzymes, DNA/RNA/ATP).

2.1: Elements and Atoms - The Building Blocks of Matter
2.2: Chemical Bonds
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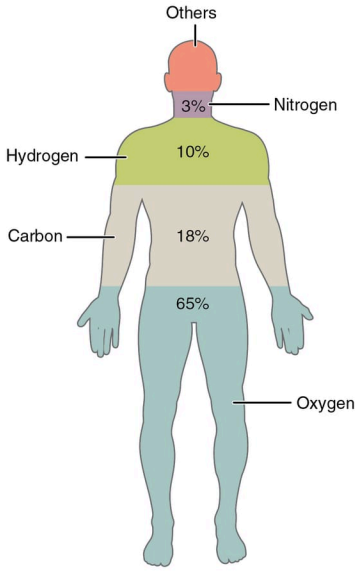
2.1: Elements and Atoms - The Building Blocks of Matter

Atomic Structure and Elements

The substance of the universe—from a grain of sand to a star—is called matter. Scientists define matter as anything that occupies space and has mass. An object's mass and its weight are related concepts, but not quite the same. An object's mass is the amount of matter contained in the object, and the object's mass is the same whether that object is on Earth or in the zero-gravity environment of outer space. An object's weight, on the other hand, is its mass as affected by the pull of gravity. Where gravity strongly pulls on an object's mass its weight is greater than it is where gravity is less strong. An object of a certain mass weighs less on the moon, for example, than it does on Earth because the gravity of the moon is less than that of Earth. In other words, weight is variable, and is influenced by gravity. A piece of cheese that weighs a pound on Earth weighs only a few ounces on the moon.

Elements and Compounds

All matter in the natural world is composed of one or more of the 92 fundamental substances called elements. An element is a pure substance that is distinguished from all other matter by the fact that it cannot be created or broken down by ordinary chemical means. While your body can assemble many of the chemical compounds needed for life from their constituent elements, it cannot make elements. They must come from the environment. A familiar example of an element that you must take in is calcium (Ca). Calcium is essential to the human body; it is absorbed and used for a number of processes, including strengthening bones. When you consume dairy products your digestive system breaks down the food into components small enough to cross into the bloodstream. Among these is calcium, which, because it is an element, cannot be broken down further. The elemental calcium in cheese, therefore, is the same as the calcium that forms your bones. Some other elements you might be familiar with are oxygen, sodium, and iron. The elements in the human body are shown in Figure 2.1.1, beginning with the most abundant: oxygen (O), carbon (C), hydrogen (H), and nitrogen (N). Each element's name can be replaced by a one- or two-letter symbol; you will become familiar with some of these during this course. All the elements in your body are derived from the foods you eat and the air you breathe.



Element	Symbol	Percentage in Body
Oxygen	O	65.0
Carbon	C	18.5
Hydrogen	H	9.5
Nitrogen	N	3.2
Calcium	Ca	1.5
Phosphorus	P	1.0
Potassium	K	0.4
Sulfur	S	0.3
Sodium	Na	0.2
Chlorine	Cl	0.2
Magnesium	Mg	0.1
Trace elements include boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).		less than 1.0

Figure 2.1.1: The main elements that compose the human body are shown from most abundant to least abundant. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.1.1.

In nature, elements rarely occur alone. Instead, they combine to form compounds. A compound is a substance composed of two or more elements joined by chemical bonds. For example, the compound glucose is an important body fuel. It is always composed of the same three elements: carbon, hydrogen, and oxygen. Moreover, the elements that make up any given compound always

occur in the same relative amounts. In glucose, there are always six carbon and six oxygen units for every twelve hydrogen units. But what, exactly, are these “units” of elements?

Atoms and Subatomic Particles

An atom is the smallest quantity of an element that retains the unique properties of that element. In other words, an atom of hydrogen is a unit of hydrogen—the smallest amount of hydrogen that can exist. As you might guess, atoms are almost unfathomably small. The period at the end of this sentence is millions of atoms wide.

Atomic Structure and Energy

Atoms are made up of even smaller subatomic particles, three types of which are important: the proton, neutron, and electron. The number of positively-charged protons and non-charged (“neutral”) neutrons, gives mass to the atom, and the number of protons determines the element. The number of negatively-charged electrons that “spin” around the nucleus at close to the speed of light equals the number of protons. An electron has about 1/2000th the mass of a proton or neutron.

Figure 2.1.2 shows two models that can help you imagine the structure of an atom—in this case, helium (He). In the planetary model, helium’s two electrons are shown circling the nucleus in a fixed orbit depicted as a ring. Although this model is helpful in visualizing atomic structure, in reality, electrons do not travel in fixed orbits, but whiz around the nucleus erratically in a so-called electron cloud.

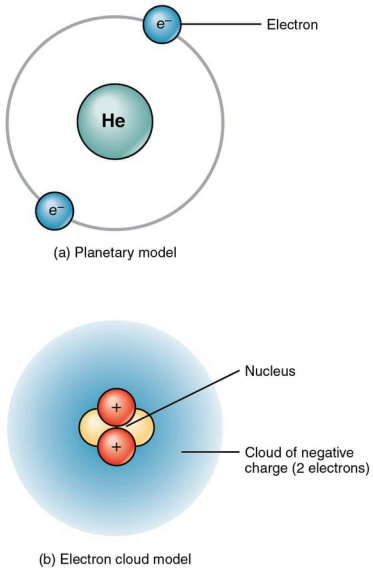


Figure 2.1.2: Two Models of Atomic Structure (a) In the planetary model, the electrons of helium are shown in fixed orbits, depicted as rings, at a precise distance from the nucleus, somewhat like planets orbiting the sun. (b) In the electron cloud model, the electrons of helium are shown in the variety of locations they would have at different distances from the nucleus over time. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.1.2.

An atom’s protons and electrons carry electrical charges. Protons, with their positive charge, are designated p^+. Electrons, which have a negative charge, are designated e^-. An atom’s neutrons have no charge: they are electrically neutral. Just as a magnet sticks to a steel refrigerator because their opposite charges attract, the positively charged protons attract the negatively charged electrons. This mutual attraction gives the atom some structural stability. The attraction by the positively charged nucleus helps keep electrons from straying far. The number of protons and electrons within a neutral atom are equal, thus, the atom’s overall charge is balanced.

Atomic Number and Mass Number

An atom of carbon is unique to carbon, but a proton of carbon is not. One proton is the same as another, whether it is found in an atom of carbon, sodium (Na), or iron (Fe). The same is true for neutrons and electrons. So, what gives an element its distinctive properties—what makes carbon so different from sodium or iron? The answer is the unique quantity of protons each contains.

Carbon by definition is an element whose atoms contain six protons. No other element has exactly six protons in its atoms. Moreover, *all* atoms of carbon, whether found in your liver or in a lump of coal, contain six protons. Thus, the atomic number, which is the number of protons in the nucleus of the atom, identifies the element. Because an atom usually has the same number of electrons as protons, the atomic number identifies the usual number of electrons as well.

In their most common form, many elements also contain the same number of neutrons as protons. The most common form of carbon, for example, has six neutrons as well as six protons, for a total of 12 subatomic particles in its nucleus. An element's mass number is the sum of the number of protons and neutrons in its nucleus. So the most common form of carbon's mass number is 12. (Electrons have so little mass that they do not appreciably contribute to the mass of an atom.) Carbon is a relatively light element. Uranium (U), in contrast, has a mass number of 238 and is referred to as a heavy metal. Its atomic number is 92 (it has 92 protons) but it contains 146 neutrons; it has the most mass of all the naturally occurring elements.

Periodic Table

The periodic table of the elements is a chart identifying the 92 elements found in nature, as well as several larger, unstable elements discovered experimentally. The elements are arranged in order of their atomic number, with hydrogen and helium at the top of the table, and the more massive elements below. The periodic table is a useful device because for each element, it identifies the chemical symbol, the atomic number, and the mass number, while organizing elements according to their propensity to react with other elements. The number of protons and electrons in an element are equal. The number of protons and neutrons may be equal for some elements, but are not equal for all.

The Ptable Properties view is an interactive periodic table that allows students to explore physical and chemical properties of elements and observe periodic trends across the table.

Key Features and Content:

- Each element in the periodic table can display different properties, such as:
  - Atomic mass
  - Atomic radius
  - Electronegativity
  - Ionization energy
  - Electron configuration
- Users can choose a specific property, and the table dynamically updates so that:
  - The selected property replaces standard values in each element box.
  - Color shading represents relative differences between elements.

Isotopes

Although each element has a unique number of protons, it can exist as different isotopes. An isotope is one of the different forms of an element, distinguished from one another by different numbers of neutrons. The standard isotope of carbon is ^{12}C, commonly called carbon twelve. ^{12}C has six protons and six neutrons, for a mass number of twelve. All of the isotopes of carbon have the same number of protons; therefore, ^{13}C has seven neutrons, and ^{14}C has eight neutrons. The different isotopes of an element can also be indicated with the mass number hyphenated (for example, C-12 instead of ^{12}C). Hydrogen has three common isotopes, shown in Figure 2.1.3.

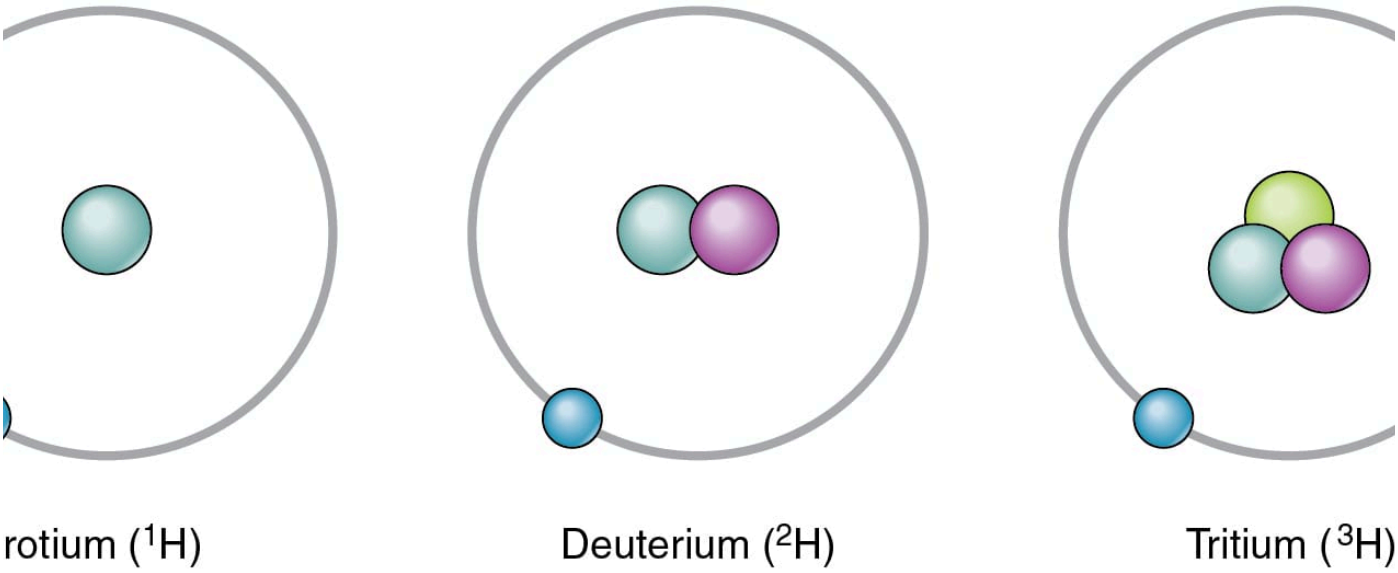


Figure 2.1.3: Protium, designated 1H, has one proton and no neutrons. It is by far the most abundant isotope of hydrogen in nature. Deuterium, designated 2H, has one proton and one neutron. Tritium, designated 3H, has two neutrons. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.1.3.

An isotope that contains more than the usual number of neutrons is referred to as a heavy isotope. An example is ^{14}C. Heavy isotopes tend to be unstable, and unstable isotopes are radioactive. A radioactive isotope is an isotope whose nucleus readily decays, giving off subatomic particles and electromagnetic energy. Different radioactive isotopes (also called radioisotopes) differ in their half-life, the time it takes for half of any size sample of an isotope to decay. For example, the half-life of tritium—a radioisotope of hydrogen—is about 12 years, indicating it takes 12 years for half of the tritium nuclei in a sample to decay. Excessive exposure to radioactive isotopes can damage human cells and even cause cancer and birth defects, but when exposure is controlled, some radioactive isotopes can be useful in medicine. For more information, see the Career Connections.

Career Connection

Interventional Radiologist

The controlled use of radioisotopes has advanced medical diagnosis and treatment of disease. Interventional radiologists are physicians who treat disease by using minimally invasive techniques involving radiation. Many conditions that could once only be treated with a lengthy and traumatic operation can now be treated non-surgically, reducing the cost, pain, length of hospital stay, and recovery time for patients. For example, in the past, the only options for a patient with one or more tumors in the liver were surgery and chemotherapy (the administration of drugs to treat cancer). Some liver tumors, however, are difficult to access surgically, and others could require the surgeon to remove too much of the liver. Moreover, chemotherapy is highly toxic to the liver, and certain tumors do not respond well to it anyway. In some such cases, an interventional radiologist can treat the tumors by disrupting their blood supply, which they need if they are to continue to grow. In this procedure, called radio embolization, the radiologist accesses the liver with a fine needle, threaded through one of the patient's blood vessels. The radiologist then inserts tiny radioactive "seeds" into the blood vessels that supply the tumors. In the days and weeks following the procedure, the radiation emitted from the seeds destroys the vessels and directly kills the tumor cells in the vicinity of the treatment.

Radioisotopes emit subatomic particles that can be detected and tracked by imaging technologies. One of the most advanced uses of radioisotopes in medicine is the positron emission tomography (PET) scanner, which detects the activity in the body of a very small injection of radioactive glucose, the simple sugar that cells use for energy. The PET camera reveals to the medical team which of the patient's tissues are taking up the most glucose. Thus, the most metabolically active tissues show up as bright "hot spots" on the images (Figure 2.1.4). PET can reveal some cancerous masses because cancer cells consume glucose at a high rate to fuel their rapid reproduction.

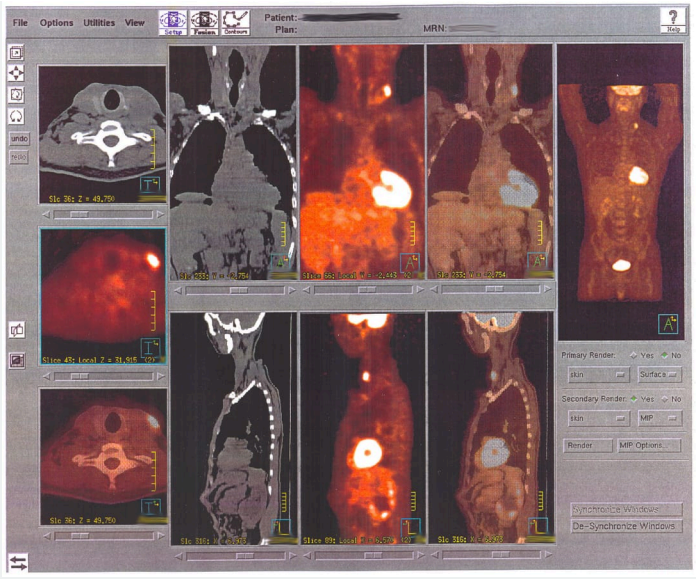


Figure 2.1.4: PET highlights areas in the body where there is relatively high glucose use, which is characteristic of cancerous tissue. This PET scan shows sites of the spread of a large primary tumor to other sites. (Public Domain; via Wikimedia Commons). Alternative text description of Figure 2.1.4.

The Behavior of Electrons

In the human body, atoms do not exist as independent entities. Rather, they are constantly reacting with other atoms to form and to break down more complex substances. To fully understand anatomy and physiology you must grasp how atoms participate in such reactions. The key is understanding the behavior of electrons.

Although electrons do not follow rigid orbits a set distance away from the atom's nucleus, they do tend to stay within certain regions of space called electron shells. An electron shell is a layer of electrons that encircle the nucleus at a distinct energy level.

The atoms of the elements found in the human body have from one to five electron shells, and all electron shells hold eight electrons except the first shell, which can only hold two. This configuration of electron shells is the same for all atoms. The precise number of shells depends on the number of electrons in the atom. Hydrogen and helium have just one and two electrons, respectively. If you take a look at the periodic table of the elements, you will notice that hydrogen and helium are placed alone on either sides of the top row; they are the only elements that have just one electron shell (Figure 2.1.5). A second shell is necessary to hold the electrons in all elements larger than hydrogen and helium.

Lithium (Li), whose atomic number is 3, has three electrons. Two of these fill the first electron shell, and the third spills over into a second shell. The second electron shell can accommodate as many as eight electrons. Carbon, with its six electrons, entirely fills its first shell, and half-fills its second. With ten electrons, neon (Ne) entirely fills its two electron shells. Again, a look at the periodic table reveals that all of the elements in the second row, from lithium to neon, have just two electron shells. Atoms with more than ten electrons require more than two shells. These elements occupy the third and subsequent rows of the periodic table.

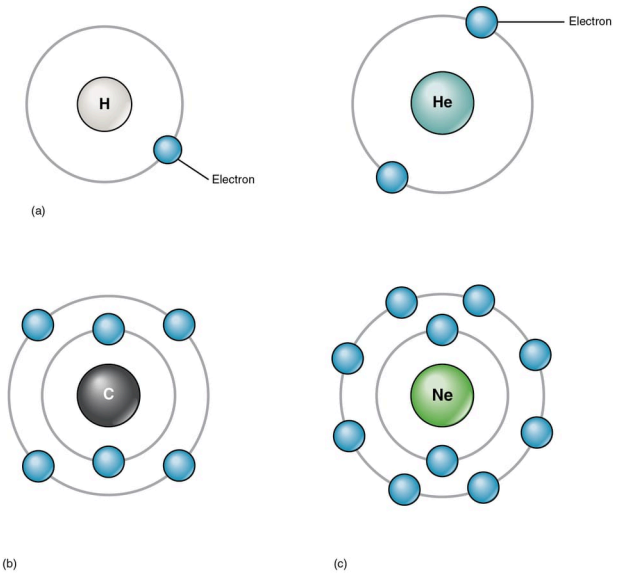


Figure 2.1.5: Electrons orbit the atomic nucleus at distinct levels of energy called electron shells. (a) With one electron, hydrogen only half-fills its electron shell. Helium also has a single shell, but its two electrons completely fill it. (b) The electrons of carbon completely fill its first electron shell, but only half-fills its second. (c) Neon, an element that does not occur in the body, has 10 electrons, filling both of its electron shells. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.1.5.

The factor that most strongly governs the tendency of an atom to participate in chemical reactions is the number of electrons in its valence shell. A valence shell is an atom's outermost electron shell. If the valence shell is full, the atom is stable; meaning its electrons are unlikely to be pulled away from the nucleus by the electrical charge of other atoms. If the valence shell is not full, the atom is reactive; meaning it will tend to react with other atoms in ways that make the valence shell full. Consider hydrogen, with its one electron only half-filling its valence shell. This single electron is likely to be drawn into relationships with the atoms of other elements, so that hydrogen's single valence shell can be stabilized.

All atoms (except hydrogen and helium with their single electron shells) are most stable when there are exactly eight electrons in their valence shell. This principle is referred to as the octet rule, and it states that an atom will give up, gain, or share electrons with another atom so that it ends up with eight electrons in its own valence shell. For example, oxygen, with six electrons in its valence shell, is likely to react with other atoms in a way that results in the addition of two electrons to oxygen's valence shell, bringing the number to eight. When two hydrogen atoms each share their single electron with oxygen, covalent bonds are formed, resulting in a molecule of water, H_2O.

In nature, atoms of one element tend to join with atoms of other elements in characteristic ways. For example, carbon commonly fills its valence shell by linking up with four atoms of hydrogen. In so doing, the two elements form the simplest of organic molecules, methane, which also is one of the most abundant and stable carbon-containing compounds on Earth. As stated above, another example is water; oxygen needs two electrons to fill its valence shell. It commonly interacts with two atoms of hydrogen, forming H_2O. Incidentally, the name "hydrogen" reflects its contribution to water (hydro- = "water"; -gen = "maker"). Thus, hydrogen is the "water maker."

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2.2: Chemical Bonds

Ionic, Covalent, and Hydrogen Bonds

Atoms separated by a great distance cannot link; rather, they must come close enough for the electrons in their valence shells to interact. But do atoms ever actually touch one another? Most physicists would say no, because the negatively charged electrons in their valence shells repel one another. No force within the human body—or anywhere in the natural world—is strong enough to overcome this electrical repulsion. So when you read about atoms linking together or colliding, bear in mind that the atoms are not merging in a physical sense.

Instead, atoms link by forming a chemical bond. A bond is a weak or strong electrical attraction that holds atoms in the same vicinity. The new grouping is typically more stable—less likely to react again—than its component atoms were when they were separate. A more or less stable grouping of two or more atoms held together by chemical bonds is called a molecule. The bonded atoms may be of the same element, as in the case of H_2, which is called molecular hydrogen or hydrogen gas. When a molecule is made up of two or more atoms of different elements, it is called a chemical compound. Thus, a unit of water, or H_2O, is a compound, as is a single molecule of the gas methane, or CH_4.

Three types of chemical bonds are important in human physiology, because they hold together substances that are used by the body for critical aspects of homeostasis, signaling, and energy production, to name just a few important processes. These are ionic bonds, covalent bonds, and hydrogen bonds.

Ions and Ionic Bonds

Recall that an atom typically has the same number of positively charged protons and negatively charged electrons. As long as this situation remains, the atom is electrically neutral. But when an atom participates in a chemical reaction that results in the donation or acceptance of one or more electrons, the atom will then become positively or negatively charged. This happens frequently for most atoms in order to have a full valence shell, as described previously. This can happen either by gaining electrons to fill a shell that is more than half-full, or by giving away electrons to empty a shell that is less than half-full, thereby leaving the next smaller electron shell as the new, full, valence shell. An atom that has an electrical charge—whether positive or negative—is an ion.

Potassium (K), for instance, is an important element in all body cells. Its atomic number is 19. It has just one electron in its valence shell. This characteristic makes potassium highly likely to participate in chemical reactions in which it donates one electron. (It is easier for potassium to donate one electron than to gain seven electrons.) The loss will cause the positive charge of potassium's protons to be more influential than the negative charge of potassium's electrons. In other words, the resulting potassium ion will be slightly positive. A potassium ion is written K^+, indicating that it has lost a single electron. A positively charged ion is known as a cation.

Now consider fluorine (F), a component of bones and teeth. Its atomic number is nine, and it has seven electrons in its valence shell. Thus, it is highly likely to bond with other atoms in such a way that fluorine accepts one electron (it is easier for fluorine to gain one electron than to donate seven electrons). When it does, its electrons will outnumber its protons by one, and it will have an overall negative charge. The ionized form of fluorine is called fluoride, and is written as F^-. A negatively charged ion is known as an anion.

Atoms that have more than one electron to donate or accept will end up with stronger positive or negative charges. A cation that has donated two electrons has a net charge of +2. Using magnesium (Mg) as an example, this can be written Mg^{++} or Mg^{2+}. An anion that has accepted two electrons has a net charge of –2. The ionic form of selenium (Se), for example, is typically written Se^{2-}.

The opposite charges of cations and anions exert a moderately strong mutual attraction that keeps the atoms in close proximity forming an ionic bond. An ionic bond is an ongoing, close association between ions of opposite charge. The table salt you sprinkle on your food owes its existence to ionic bonding. As shown in Figure 2.2.1, sodium commonly donates an electron to chlorine, becoming the cation Na^+. When chlorine accepts the electron, it becomes the chloride anion, Cl^-. With their opposing charges,

these two ions strongly attract each other.

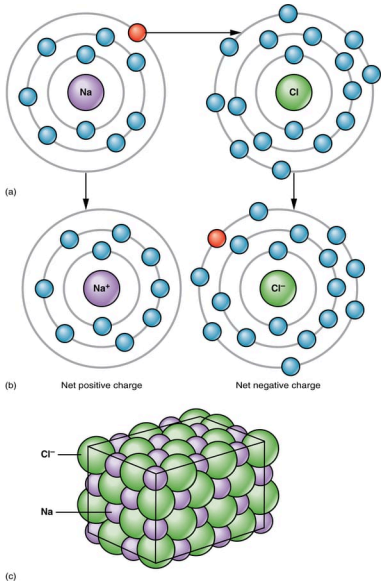


Figure 2.2.1: Formation of sodium and chloride ions through electron transfer and their arrangement in a crystal lattice. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.2.1.

Water is an essential component of life because it is able to break the ionic bonds in salts to free the ions. In fact, in biological fluids, most individual atoms exist as ions. These dissolved ions produce electrical charges within the body. The behavior of these ions produces the tracings of heart and brain function observed as waves on an electrocardiogram (EKG or ECG) or an electroencephalogram (EEG). The electrical activity that derives from the interactions of the charged ions is why they are also called electrolytes.

Covalent Bonds

Unlike ionic bonds formed by the attraction between a cation's positive charge and an anion's negative charge, molecules formed by a covalent bond share electrons in a mutually stabilizing relationship. Like next-door neighbors whose kids hang out first at one home and then at the other, the atoms do not lose or gain electrons permanently. Instead, the electrons move back and forth between the elements. Because of the close sharing of pairs of electrons (one electron from each of two atoms), covalent bonds are stronger than ionic bonds.

Nonpolar Covalent Bonds

Figure 2.2.2 shows several common types of covalent bonds. Notice that the two covalently bonded atoms typically share just one or two electron pairs, though larger sharings are possible. The important concept to take from this is that in covalent bonds, electrons in the two atoms' overlapping atomic orbitals are shared to fill the valence shells of both atoms, ultimately stabilizing both of the atoms involved. In a single covalent bond, a single electron pair is shared between two atoms, while in a double covalent bond, two pairs of electrons are shared between two atoms. There even are triple covalent bonds, where three electron pairs are shared between two atoms.

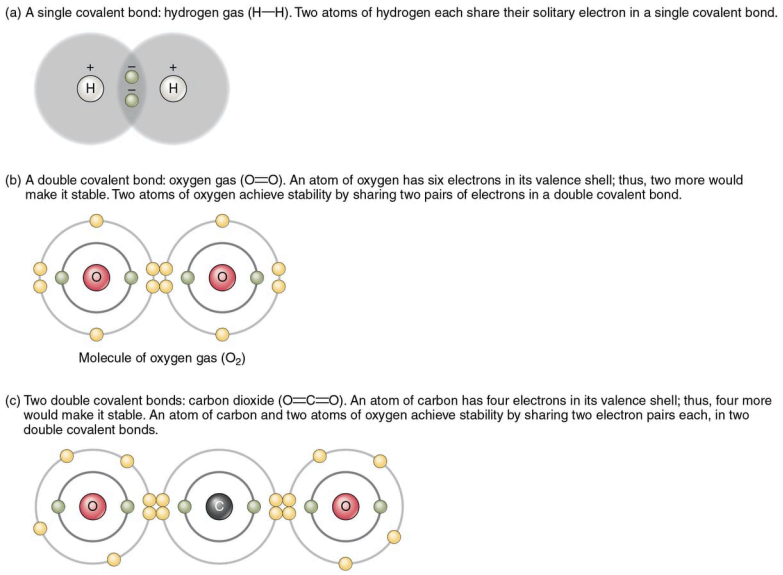


Figure 2.2.2: Examples of covalent bonding: single bond in hydrogen (H_2), double bond in oxygen (O_2), and two double bonds in carbon dioxide (CO_2). (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.2.2.

You can see that the covalent bonds shown in Figure 2.2.2 are balanced. The sharing of the negative electrons is relatively equal, as is the electrical pull of the positive protons in the nucleus of the atoms involved. This is why covalently bonded molecules that are electrically balanced in this way are described as nonpolar; that is, no region of the molecule is either more positive or more negative than any other.

Polar Covalent Bonds

Groups of legislators with completely opposite views on a particular issue are often described as “polarized” by news writers. In chemistry, a polar molecule is a molecule that contains regions that have opposite electrical charges. Polar molecules occur when atoms share electrons unequally, in polar covalent bonds.

The most familiar example of a polar molecule is water (Figure 2.2.3). The molecule has three parts: one atom of oxygen, the nucleus of which contains eight protons, and two hydrogen atoms, whose nuclei each contain only one proton. Because every proton exerts an identical positive charge, a nucleus that contains eight protons exerts a charge eight times greater than a nucleus that contains one proton. This means that the negatively charged electrons present in the water molecule are more strongly attracted to the oxygen nucleus than to the hydrogen nuclei. Each hydrogen atom’s single negative electron therefore migrates toward the oxygen atom, making the oxygen end of their bond slightly more negative than the hydrogen end of their bond.

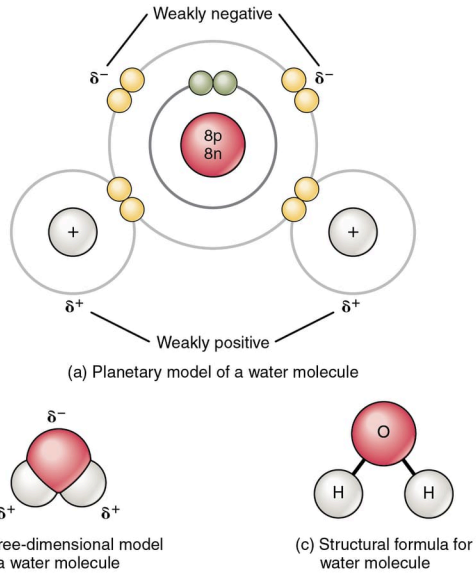


Figure 2.2.3: Three representations of a water molecule: (a) planetary model showing partial charges, (b) three-dimensional model, and (c) structural formula. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.2.3.

What is true for the bonds is true for the water molecule as a whole; that is, the oxygen region has a slightly negative charge and the regions of the hydrogen atoms have a slightly positive charge. These charges are often referred to as "partial charges" because the strength of the charge is less than one full electron, as would occur in an ionic bond. As depicted in Figure 2.2.3, regions of weak polarity are indicated with the Greek letter delta (δ) and a plus (+) or minus (–) sign.

Even though a single water molecule is unimaginably tiny, it has mass, and the opposing electrical charges on the molecule pull that mass in such a way that it creates a shape somewhat like a triangular tent (Figure 2.2.3(*b*)). This dipole, with the positive charges at one end formed by the hydrogen atoms at the "bottom" of the tent and the negative charge at the opposite end (the oxygen atom at the "top" of the tent) makes the charged regions highly likely to interact with charged regions of other polar molecules. For human physiology, the resulting bond is one of the most important formed by water—the hydrogen bond.

Hydrogen Bonds

A hydrogen bond is formed when a weakly positive hydrogen atom already bonded to one electronegative atom (for example, the oxygen in the water molecule) is attracted to another electronegative atom from another molecule. In other words, hydrogen bonds always include hydrogen that is already part of a polar molecule.

The most common example of hydrogen bonding in the natural world occurs between molecules of water. It happens before your eyes whenever two raindrops merge into a larger bead, or a creek spills into a river. Hydrogen bonding occurs because the weakly negative oxygen atom in one water molecule is attracted to the weakly positive hydrogen atoms of two other water molecules (Figure 2.2.4).

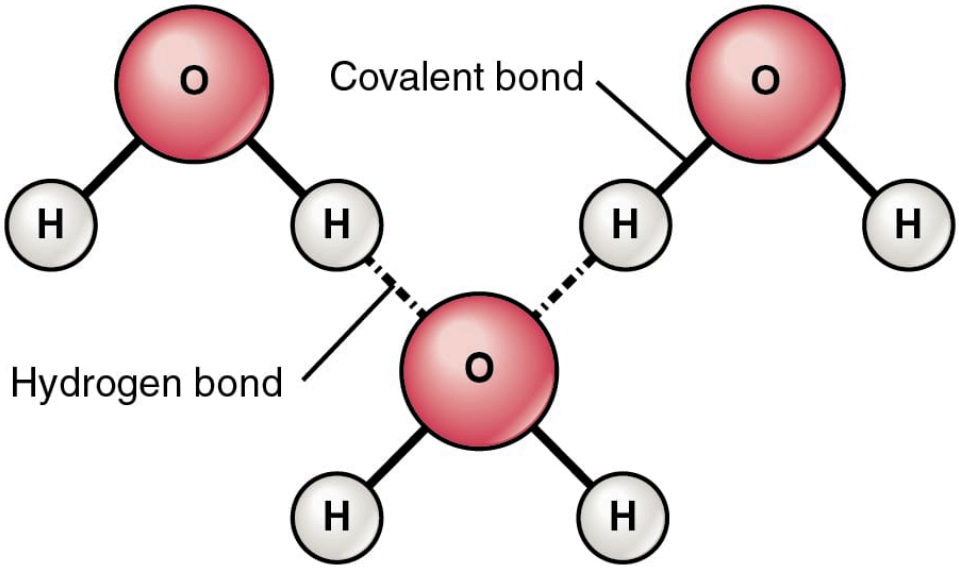


Figure 2.2.4: The bonds occur between the weakly positive charge on the hydrogen atoms and the weakly negative charge on the oxygen atoms. Hydrogen bonds are relatively weak, and therefore are indicated with a dotted (rather than a solid) line. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.2.4.

Water molecules also strongly attract other types of charged molecules as well as ions. This explains why "table salt," for example, actually is a molecule called a "salt" in chemistry, which consists of equal numbers of positively-charged sodium (Na^+) and negatively-charged chloride (Cl^-), dissolves so readily in water, in this case forming dipole-ion bonds between the water and the electrically-charged ions (electrolytes). Water molecules also repel molecules with nonpolar covalent bonds, like fats, lipids, and oils. You can demonstrate this with a simple kitchen experiment: pour a teaspoon of vegetable oil, a compound formed by nonpolar covalent bonds, into a glass of water. Instead of instantly dissolving in the water, the oil forms a distinct bead because the polar water molecules repel the nonpolar oil.

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2.3: Chemical Reactions in Human Physiology

How Energy and Enzymes Affect Chemical Reactions

One characteristic of a living organism is metabolism, which is the sum total of all of the chemical reactions that go on to maintain that organism's health and life. The bonding processes you have learned thus far are anabolic chemical reactions; that is, they form larger molecules from smaller molecules or atoms. But recall that metabolism can proceed in another direction: in catabolic chemical reactions, bonds between components of larger molecules break, releasing smaller molecules or atoms. Both types of reaction involve exchanges not only of matter, but of energy.

The Role of Energy in Chemical Reactions

Chemical reactions require a sufficient amount of energy to cause the matter to collide with enough precision and force that old chemical bonds can be broken and new ones formed. In general, kinetic energy is the form of energy powering any type of matter in motion. Imagine you are building a brick wall. The energy it takes to lift and place one brick atop another is kinetic energy—the energy matter possesses because of its motion. Once the wall is in place, it stores potential energy. Potential energy is the energy of position, or the energy matter possesses because of the positioning or structure of its components. If the brick wall collapses, the stored potential energy is released as kinetic energy as the bricks fall.

In the human body, potential energy is stored in the bonds between atoms and molecules. Chemical energy is the form of potential energy in which energy is stored in chemical bonds. When those bonds are formed, chemical energy is invested, and when they break, chemical energy is released. Notice that chemical energy, like all energy, is neither created nor destroyed; rather, it is converted from one form to another. When you eat an energy bar before heading out the door for a hike, the honey, nuts, and other foods the bar contains are broken down and rearranged by your body into molecules that your muscle cells convert to kinetic energy.

Chemical reactions that release more energy than they absorb are characterized as exergonic. The catabolism of the foods in your energy bar is an example. Some of the chemical energy stored in the bar is absorbed into molecules your body uses for fuel, but some of it is released—for example, as heat. In contrast, chemical reactions that absorb more energy than they release are endergonic. These reactions require energy input, and the resulting molecule stores not only the chemical energy in the original components, but also the energy that fueled the reaction. Because energy is neither created nor destroyed, where does the energy needed for endergonic reactions come from? In many cases, it comes from exergonic reactions.

Forms of Energy Important in Human Functioning

You have already learned that chemical energy is absorbed, stored, and released by chemical bonds. In addition to chemical energy, mechanical, radiant, and electrical energy are important in human functioning.

- Mechanical energy, which is stored in physical systems such as machines, engines, or the human body, directly powers the movement of matter. When you lift a brick into place on a wall, your muscles provide the mechanical energy that moves the brick.
- Radiant energy is energy emitted and transmitted as waves rather than matter. These waves vary in length from long radio waves and microwaves to short gamma waves emitted from decaying atomic nuclei. The full spectrum of radiant energy is referred to as the electromagnetic spectrum. The body uses the ultraviolet energy of sunlight to convert a compound in skin cells to vitamin D, which is essential to human functioning. The human eye evolved to see the wavelengths that comprise the colors of the rainbow, from red to violet, so that range in the spectrum is called "visible light."
- Electrical energy, supplied by electrolytes in cells and body fluids, contributes to the voltage changes that help transmit impulses in nerve and muscle cells.

Characteristics of Chemical Reactions

All chemical reactions begin with a reactant, the general term for the one or more substances that enter into the reaction. Sodium and chloride ions, for example, are the reactants in the production of table salt. The one or more substances produced by a

chemical reaction are called the product.

In chemical reactions, the components of the reactants—the elements involved and the number of atoms of each—are all present in the product(s). Similarly, there is nothing present in the products that are not present in the reactants. This is because chemical reactions are governed by the law of conservation of mass, which states that matter cannot be created or destroyed in a chemical reaction.

Just as you can express mathematical calculations in equations such as 2 + 7 = 9, you can use chemical equations to show how reactants become products. As in math, chemical equations proceed from left to right, but instead of an equal sign, they employ an arrow or arrows indicating the direction in which the chemical reaction proceeds. For example, the chemical reaction in which one atom of nitrogen and three atoms of hydrogen produce ammonia would be written as $\mathrm{N} + 3\mathrm{H} \rightarrow \mathrm{NH_3}$. Correspondingly, the breakdown of ammonia into its components would be written as $\mathrm{NH_3} \rightarrow \mathrm{N} + 3\mathrm{H}$.

Notice that, in the first example, a nitrogen (N) atom and three hydrogen (H) atoms bond to form a compound. This anabolic reaction requires energy, which is then stored within the compound's bonds. Such reactions are referred to as synthesis reactions. A synthesis reaction is a chemical reaction that results in the synthesis (joining) of components that were formerly separate (Figure $2.3.1a$). Again, nitrogen and hydrogen are reactants in a synthesis reaction that yields ammonia as the product. The general equation for a synthesis reaction is $\mathrm{A} + \mathrm{B} \rightarrow \mathrm{AB}$.

In the second example, ammonia is catabolized into its smaller components, and the potential energy that had been stored in its bonds is released. Such reactions are referred to as decomposition reactions. A decomposition reaction is a chemical reaction that breaks down or "de-composes" something larger into its constituent parts (see Figure $2.3.1b$. The general equation for a decomposition reaction is: $\mathrm{AB} \rightarrow \mathrm{A} + \mathrm{B}$.

An exchange reaction is a chemical reaction in which both synthesis and decomposition occur, chemical bonds are both formed and broken, and chemical energy is absorbed, stored, and released (see Figure $2.3.1c$). The simplest form of an exchange reaction might be: $\mathrm{A} + \mathrm{BC} \rightarrow \mathrm{AB} + \mathrm{C}$. Notice that, to produce these products, B and C had to break apart in a decomposition reaction, whereas A and B had to bond in a synthesis reaction. A more complex exchange reaction might be:$\mathrm{AB} + \mathrm{CD} \rightarrow \mathrm{AC} + \mathrm{BD}$. Another example might be: $\mathrm{AB} + \mathrm{CD} \rightarrow \mathrm{AD} + \mathrm{BC}$.

In theory, any chemical reaction can proceed in either direction under the right conditions. Reactants may synthesize into a product that is later decomposed. Reversibility is also a quality of exchange reactions. For instance, $\mathrm{A} + \mathrm{BC} \rightarrow \mathrm{AB} + \mathrm{C}$ could then reverse to $\mathrm{AB} + \mathrm{C} \rightarrow \mathrm{A} + \mathrm{BC}$. This reversibility of a chemical reaction is indicated with a double arrow: $\mathrm{A} + \mathrm{BC} \rightleftarrows \mathrm{AB} + \mathrm{C}$. Still, in the human body, many chemical reactions do proceed in a predictable direction, either one way or the other. You can think of this more predictable path as the path of least resistance because, typically, the alternate direction requires more energy.

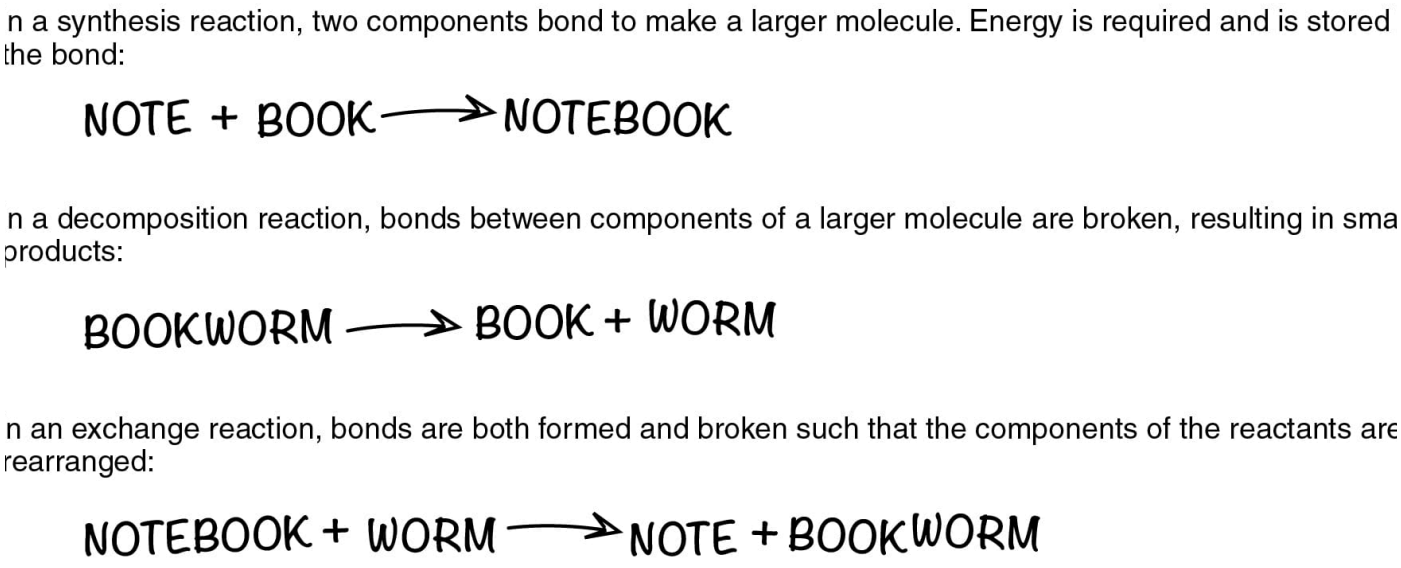


Figure $2.3.1$: The atoms and molecules involved in the three fundamental chemical reactions can be imagined as words. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure $2.3.1$.

Factors Influencing the Rate of Chemical Reactions

If you pour vinegar into baking soda, the reaction is instantaneous; the concoction will bubble and fizz. But many chemical reactions take time. A variety of factors influence the rate of chemical reactions. This section, however, will consider only the most important in human functioning.

Properties of the Reactants

If chemical reactions are to occur quickly, the atoms in the reactants have to have easy access to one another. Thus, the greater the surface area of the reactants, the more readily they will interact. When you pop a cube of cheese into your mouth, you chew it before you swallow it. Among other things, chewing increases the surface area of the food so that digestive chemicals can more easily get at it. As a general rule, gases tend to react faster than liquids or solids, again because it takes energy to separate particles of a substance, and gases by definition already have space between their particles. Similarly, the larger the molecule, the greater the number of total bonds, so reactions involving smaller molecules, with fewer total bonds, would be expected to proceed faster.

In addition, recall that some elements are more reactive than others. Reactions that involve highly reactive elements like hydrogen proceed more quickly than reactions that involve less reactive elements. Reactions involving stable elements like helium are not likely to happen at all.

Temperature

Nearly all chemical reactions occur at a faster rate at higher temperatures. Recall that kinetic energy is the energy of matter in motion. The kinetic energy of subatomic particles increases in response to increases in thermal energy. The higher the temperature, the faster the particles move, and the more likely they are to come in contact and react.

Concentration and Pressure

If just a few people are dancing at a club, they are unlikely to step on each other's toes. But as more and more people get up to dance—especially if the music is fast—collisions are likely to occur. It is the same with chemical reactions: the more particles present within a given space, the more likely those particles are to bump into one another. This means that chemists can speed up chemical reactions not only by increasing the concentration of particles—the number of particles in the space—but also by decreasing the volume of the space, which would correspondingly increase the pressure. If there were 100 dancers in that club, and the manager abruptly moved the party to a room half the size, the concentration of the dancers would double in the new space, and the likelihood of collisions would increase accordingly.

Enzymes and Other Catalysts

For two chemicals in nature to react with each other they first have to come into contact, and this occurs through random collisions. Because heat helps increase the kinetic energy of atoms, ions, and molecules, it promotes their collision. But in the body, extremely high heat—such as a very high fever—can damage body cells and be life-threatening. On the other hand, normal body temperature is not high enough to promote the chemical reactions that sustain life. That is where catalysts come in.

In chemistry, a catalyst is a substance that increases the rate of a chemical reaction without itself undergoing any change. You can think of a catalyst as a chemical change agent. They help increase the rate and force at which atoms, ions, and molecules collide, thereby increasing the probability that their valence shell electrons will interact.

The most important catalysts in the human body are enzymes. An enzyme is a catalyst composed of protein or ribonucleic acid (RNA), both of which will be discussed later in this chapter. Like all catalysts, enzymes work by lowering the level of energy that needs to be invested in a chemical reaction. A chemical reaction's activation energy is the "threshold" level of energy needed to break the bonds in the reactants. Once those bonds are broken, new arrangements can form. Without an enzyme to act as a catalyst, a much larger investment of energy is needed to ignite a chemical reaction (Figure 2.3.2).

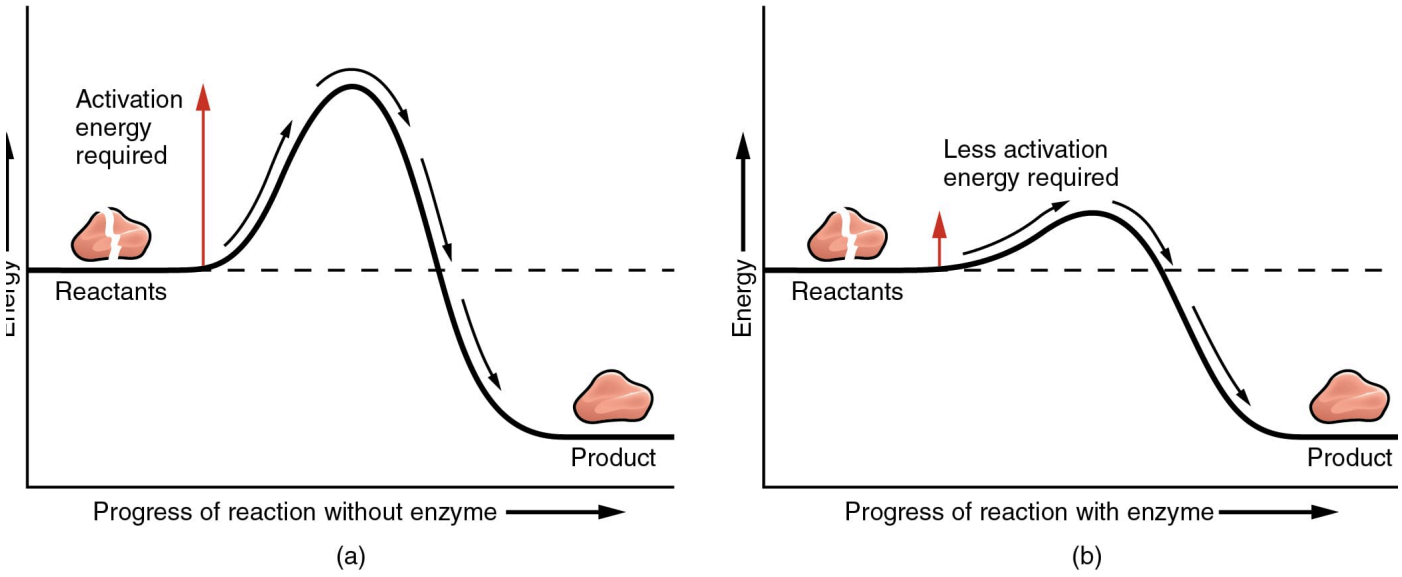


Figure 2.3.2: Enzymes decrease the activation energy required for a given chemical reaction to occur. (a) Without an enzyme, the energy input needed for a reaction to begin is high. (b) With the help of an enzyme, less energy is needed for a reaction to begin. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.3.2.

Enzymes are critical to the body's healthy functioning. They assist, for example, with the breakdown of food and its conversion to energy. In fact, most of the chemical reactions in the body are facilitated by enzymes.

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2.4: Inorganic Compounds Essential to Human Functioning

Essential Chemistry of Human Life

The concepts you have learned so far in this chapter govern all forms of matter, and would work as a foundation for geology as well as biology. This section of the chapter narrows the focus to the chemistry of human life; that is, the compounds important for the body's structure and function. In general, these compounds are either inorganic or organic.

- An inorganic compound is a substance that does not contain both carbon and hydrogen. A great many inorganic compounds do contain hydrogen atoms, such as water (H_2O) and the hydrochloric acid (HCl) produced by your stomach. In contrast, only a handful of inorganic compounds contain carbon atoms. Carbon dioxide (CO_2) is one of the few examples.
- An organic compound, then, is a substance that contains both carbon and hydrogen. Organic compounds are synthesized via covalent bonds within living organisms, including the human body. Recall that carbon and hydrogen are the second and third most abundant elements in your body. You will soon discover how these two elements combine in the foods you eat, in the compounds that make up your body structure, and in the chemicals that fuel your functioning.

The following section examines the three groups of inorganic compounds essential to life: water, salts, acids, and bases. Organic compounds are covered later in the chapter.

Water

As much as 70 percent of an adult's body weight is water. This water is contained both within the cells and between the cells that make up tissues and organs. Its several roles make water indispensable to human functioning.

Water as a Lubricant and Cushion

Water is a major component of many of the body's lubricating fluids. Just as oil lubricates the hinge on a door, water in synovial fluid lubricates the actions of body joints, and water in pleural fluid helps the lungs expand and recoil with breathing. Watery fluids help keep food flowing through the digestive tract, and ensure that the movement of adjacent abdominal organs is friction free.

Water also protects cells and organs from physical trauma, cushioning the brain within the skull, for example, and protecting the delicate nerve tissue of the eyes. Water cushions a developing fetus in the mother's womb as well.

Water as a Heat Sink

A heat sink is a substance or object that absorbs and dissipates heat but does not experience a corresponding increase in temperature. In the body, water absorbs the heat generated by chemical reactions without greatly increasing in temperature. Moreover, when the environmental temperature soars, the water stored in the body helps keep the body cool. This cooling effect happens as warm blood from the body's core flows to the blood vessels just under the skin and is transferred to the environment. At the same time, sweat glands release warm water in sweat. As the water evaporates into the air, it carries away heat, and then the cooler blood from the periphery circulates back to the body core.

Water as a Component of Liquid Mixtures

A mixture is a combination of two or more substances, each of which maintains its own chemical identity. In other words, the constituent substances are not chemically bonded into a new, larger chemical compound. The concept is easy to imagine if you think of powdery substances such as flour and sugar; when you stir them together in a bowl, they obviously do not bond to form a new compound. The room air you breathe is a gaseous mixture, containing three discrete elements—nitrogen, oxygen, and argon—and one compound, carbon dioxide. There are three types of liquid mixtures, all of which contain water as a key component. These are solutions, colloids, and suspensions.

For cells in the body to survive, they must be kept moist in a water-based liquid called a solution. In chemistry, a liquid solution consists of a solvent that dissolves a substance called a solute. An important characteristic of solutions is that they are

homogeneous; that is, the solute molecules are distributed evenly throughout the solution. If you were to stir a teaspoon of sugar into a glass of water, the sugar would dissolve into sugar molecules separated by water molecules. The ratio of sugar to water in the left side of the glass would be the same as the ratio of sugar to water in the right side of the glass. If you were to add more sugar, the ratio of sugar to water would change, but the distribution—provided you had stirred well—would still be even.

Water is considered the "universal solvent" and it is believed that life cannot exist without water because of this. Water is certainly the most abundant solvent in the body; essentially all of the body's chemical reactions occur among compounds dissolved in water. Because water molecules are polar, with regions of positive and negative electrical charge, water readily dissolves ionic compounds and polar covalent compounds. Such compounds are referred to as hydrophilic, or "water-loving." As mentioned above, sugar dissolves well in water. This is because sugar molecules contain regions of hydrogen-oxygen polar bonds, making it hydrophilic. Nonpolar molecules, which do not readily dissolve in water, are called hydrophobic, or "water-fearing."

Concentrations of Solutes

Various mixtures of solutes and water are described in chemistry. The concentration of a given solute is the number of particles of that solute in a given space (oxygen makes up about 21 percent of atmospheric air). In the bloodstream of humans, glucose concentration is usually measured in milligram (mg) per deciliter (dL), and in a healthy adult averages about 100 mg/dL. Another method of measuring the concentration of a solute is by its molarity—which is moles (M) of the molecules per liter (L). The mole of an element is its atomic weight, while a mole of a compound is the sum of the atomic weights of its components, called the molecular weight. An often-used example is calculating a mole of glucose, with the chemical formula $C_6H_{12}O_6$. Using the periodic table, the atomic weight of carbon (C) is 12.011 grams (g), and there are six carbons in glucose, for a total atomic weight of 72.066 g. Doing the same calculations for hydrogen (H) and oxygen (O), the molecular weight equals 180.156g (the "gram molecular weight" of glucose). When water is added to make one liter of solution, you have one mole (1M) of glucose. This is particularly useful in chemistry because of the relationship of moles to "Avogadro's number." A mole of any solution has the same number of particles in it: 6.02×10^{23}. Many substances in the bloodstream and other tissue of the body are measured in thousandths of a mole, or millimoles (mM).

A colloid is a mixture that is somewhat like a heavy solution. The solute particles consist of tiny clumps of molecules large enough to make the liquid mixture opaque (because the particles are large enough to scatter light). Familiar examples of colloids are milk and cream. In the thyroid glands, the thyroid hormone is stored as a thick protein mixture also called a colloid.

A suspension is a liquid mixture in which a heavier substance is suspended temporarily in a liquid, but over time, settles out. This separation of particles from a suspension is called sedimentation. An example of sedimentation occurs in the blood test that establishes sedimentation rate, or sed rate. The test measures how quickly red blood cells in a test tube settle out of the watery portion of blood (known as plasma) over a set period of time. Rapid sedimentation of blood cells does not normally happen in the healthy body, but aspects of certain diseases can cause blood cells to clump together, and these heavy clumps of blood cells settle to the bottom of the test tube more quickly than do normal blood cells.

The Role of Water in Chemical Reactions

Two types of chemical reactions involve the creation or the consumption of water: dehydration synthesis and hydrolysis.

- In dehydration synthesis, one reactant gives up an atom of hydrogen and another reactant gives up a hydroxyl group (OH) in the synthesis of a new product. In the formation of their covalent bond, a molecule of water is released as a byproduct Figure ({2{.}4{.}\eatSpaces{1} \endSpaces}\). This is also sometimes referred to as a condensation reaction.
- These reactions are reversible, and play an important role in the chemistry of organic compounds (which will be discussed shortly).

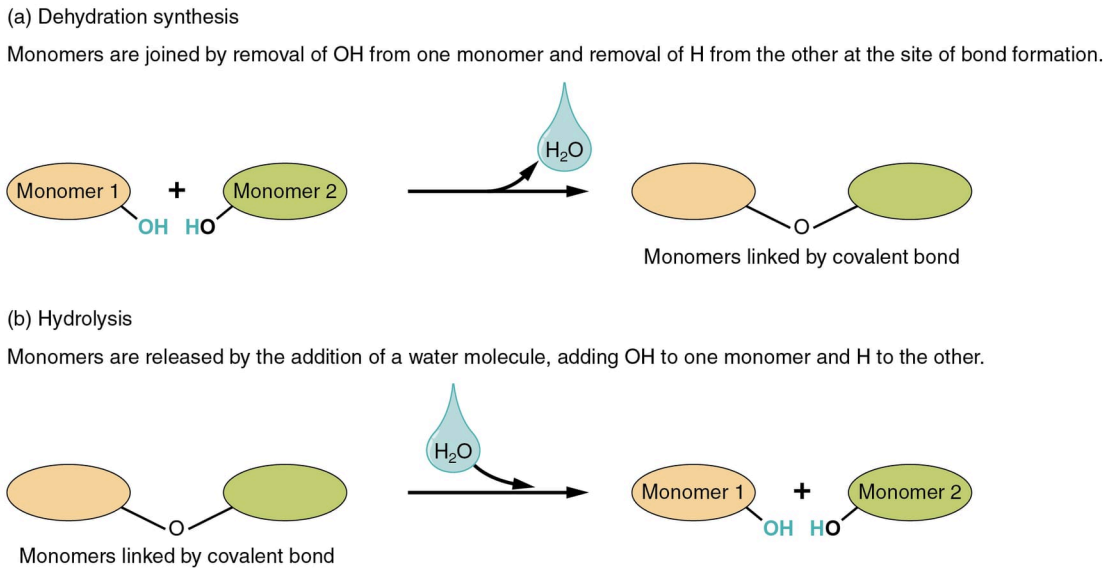


Figure 2.4.1: The basic units for building larger molecules, form polymers (two or more chemically-bonded monomers). (a) In dehydration synthesis, two monomers are covalently bonded in a reaction in which one gives up a hydroxyl group and the other a hydrogen atom. A molecule of water is released as a byproduct during dehydration reactions. (b) In hydrolysis, the covalent bond between two monomers is split by the addition of a hydrogen atom to one and a hydroxyl group to the other, which requires the contribution of one molecule of water. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.4.1.

Salts

Recall that salts are formed when ions form ionic bonds. In these reactions, one atom gives up one or more electrons, and thus becomes positively charged, whereas the other accepts one or more electrons and becomes negatively charged. You can now define a salt as a substance that, when dissolved in water, dissociates into ions other than H^+ or OH^-. This fact is important in distinguishing salts from acids and bases, discussed next.

A typical salt, NaCl, dissociates completely in water (Figure ({2{.}4{.}\eatSpaces{2} \endSpaces}\)). The positive and negative regions on the water molecule (the hydrogen and oxygen ends respectively) attract the negative chloride and positive sodium ions, pulling them away from each other. Again, whereas nonpolar and polar covalently bonded compounds break apart into molecules in solution, salts dissociate into ions. These ions are electrolytes; they are capable of conducting an electrical current in solution. This property is critical to the function of ions in transmitting nerve impulses and prompting muscle contraction.

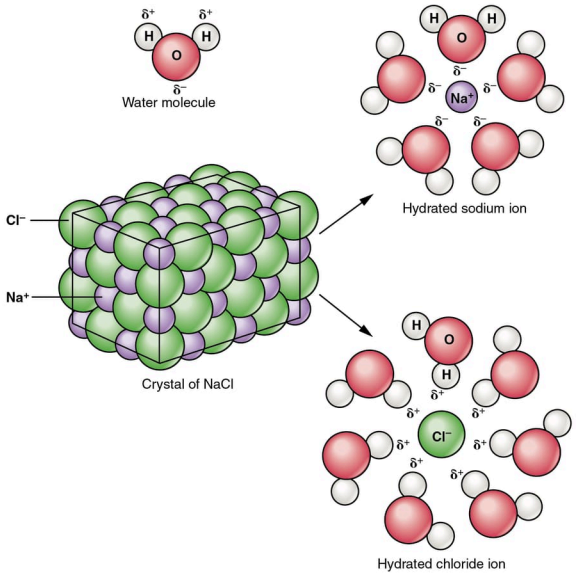


Figure 2.4.2: The crystals of sodium chloride dissociate not into molecules of NaCl, but into Na+ cations and Cl– anions, each completely surrounded by water molecules. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.4.2.

Acids and Bases

Acids and bases, like salts, dissociate in water into electrolytes. Acids and bases can very much change the properties of the solutions in which they are dissolved.

Acids

An acid is a substance that releases hydrogen ions (H^+) in solution (Figure ({2{.}4{.}\eatSpaces{3a} \endSpaces}\ ). Because an atom of hydrogen has just one proton and one electron, a positively charged hydrogen ion is simply a proton. This solitary proton is highly likely to participate in chemical reactions. Strong acids are compounds that release all of their H^+ in solution; that is, they ionize completely. Hydrochloric acid (HCl), which is released from cells in the lining of the stomach, is a strong acid because it releases all of its H^+ in the stomach's watery environment. This strong acid aids in digestion and kills ingested microbes. Weak acids do not ionize completely; that is, some of their hydrogen ions remain bonded within a compound in solution. An example of a weak acid is vinegar, or acetic acid; it is called acetate after it gives up a proton.

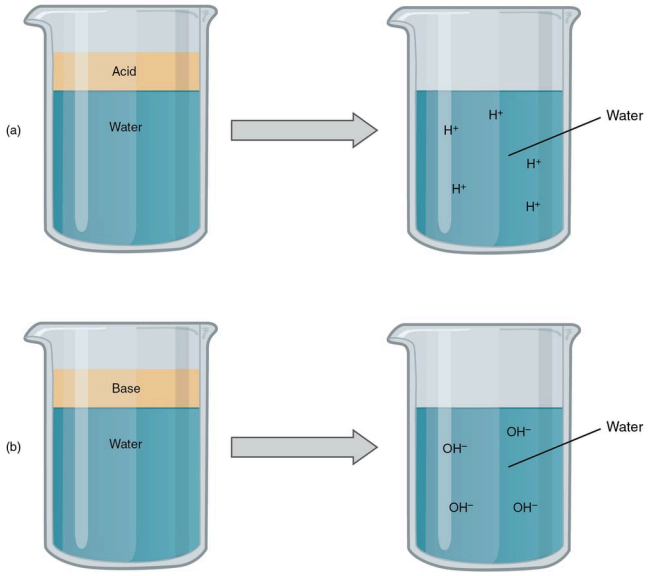


Figure 2.4.3: Acids and Bases (a) In aqueous solution, an acid dissociates into hydrogen ions (H+) and anions. Nearly every molecule of a strong acid dissociates, producing a high concentration of H+. (b) In aqueous solution, a base dissociates into hydroxyl ions (OH–) and cations. Nearly every molecule of a strong base dissociates, producing a high concentration of OH–. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.4.3.

Bases

A base is a substance that releases hydroxyl ions (OH^-) in solution, or one that accepts H^+ already present in solution. The hydroxyl ions (also known as hydroxide ions) or other basic substances combine with H^+ present to form a water molecule, thereby removing H^+ and reducing the solution's acidity. Strong bases release most or all of their hydroxyl ions; weak bases release only some hydroxyl ions or absorb only a few H^+. Food mixed with hydrochloric acid from the stomach would burn the small intestine, the next portion of the digestive tract after the stomach, if it were not for the release of bicarbonate (HCO_3^-), a weak base that attracts H^+. Bicarbonate accepts some of the H^+ protons, thereby reducing the acidity of the solution.

The Concept of pH

The relative acidity or alkalinity of a solution can be indicated by its pH. A solution's pH is the negative, base-10 logarithm of the hydrogen ion (H^+) concentration of the solution. As an example, a pH 4 solution has an H^+ concentration that is ten times greater than that of a pH 5 solution. That is, a solution with a pH of 4 is ten times more acidic than a solution with a pH of 5. The concept of pH will begin to make more sense when you study the pH scale, like that shown in Figure 2.4.4. The scale consists of a series of increments ranging from 0 to 14. A solution with a pH of 7 is considered neutral—neither acidic nor basic. Pure water has a pH of 7. The lower the number below 7, the more acidic the solution, or the greater the concentration of H^+. The concentration of hydrogen ions at each pH value is 10 times different than the next pH.

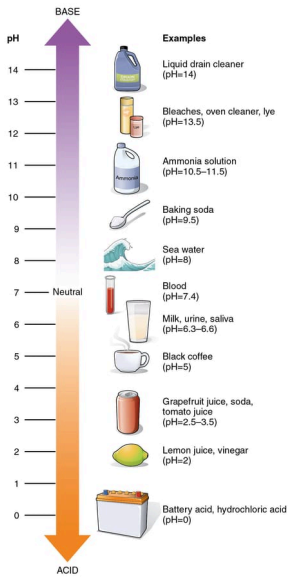


Figure 2.4.4: The image shows a pH scale ranging from 0 (most acidic) to 14 (most basic/alkaline), with 7 as neutral. Along this scale, common substances are placed according to their pH values: Lemon juice is near the acidic end, with a pH around 2.0–2.2, representing strong acidity. Milk is slightly acidic, close to neutral, with a pH of about 6.7–6.9. Human blood is slightly basic (alkaline), with a pH of approximately 7.4. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.4.4.

Buffers

The pH of human blood normally ranges from 7.35 to 7.45, although it is typically identified as pH 7.4. At this slightly basic pH, blood can reduce the acidity resulting from the carbon dioxide (CO_2) constantly being released into the bloodstream by the trillions of cells in the body. Homeostatic mechanisms (along with exhaling CO_2 while breathing) normally keep the pH of blood within this narrow range. This is critical, because fluctuations—either too acidic or too alkaline—can lead to life-threatening disorders.

All cells of the body depend on homeostatic regulation of acid–base balance at a pH of approximately 7.4. The body therefore has several mechanisms for this regulation, involving breathing, the excretion of chemicals in urine, and the internal release of chemicals collectively called buffers into body fluids. A buffer is a solution of a weak acid and its conjugate base. A buffer can neutralize small amounts of acids or bases in body fluids. For example, if there is even a slight decrease below 7.35 in the pH of a bodily fluid, the buffer in the fluid—in this case, acting as a weak base—will bind the excess hydrogen ions. In contrast, if pH rises above 7.45, the buffer will act as a weak acid and contribute hydrogen ions.

Homeostatic Imbalances

Acids and Bases

Excessive acidity of the blood and other body fluids is known as acidosis. Common causes of acidosis are situations and disorders that reduce the effectiveness of breathing, especially the person's ability to exhale fully, which causes a buildup of CO_2 (and H^+) in the bloodstream. Acidosis can also be caused by metabolic problems that reduce the level or function of buffers that act as bases, or that promote the production of acids. For instance, with severe diarrhea, too much bicarbonate can be lost from the body, allowing acids to build up in body fluids. In people with poorly managed diabetes (ineffective regulation of blood sugar), acids called ketones are produced as a form of body fuel. These can build up in the blood, causing a serious condition called diabetic ketoacidosis. Kidney failure, liver failure, heart failure, cancer, and other disorders also can prompt metabolic acidosis.

In contrast, alkalosis is a condition in which the blood and other body fluids are too alkaline (basic). As with acidosis, respiratory disorders are a major cause; however, in respiratory alkalosis, carbon dioxide levels fall too low. Lung disease, aspirin overdose, shock, and ordinary anxiety can cause respiratory alkalosis, which reduces the normal concentration of H^+.

Metabolic alkalosis often results from prolonged, severe vomiting, which causes a loss of hydrogen and chloride ions (as components of HCl). Medications also can prompt alkalosis. These include diuretics that cause the body to lose potassium ions, as well as antacids when taken in excessive amounts, for instance by someone with persistent heartburn or an ulcer.

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2.5: Organic Compounds Essential to Human Functioning

Foundations of Organic Compounds

Organic compounds typically consist of groups of carbon atoms covalently bonded to hydrogen, usually oxygen, and often other elements as well. They are found throughout the world, in soils and seas, commercial products, and every cell of the human body. The four types most important to human structure and function are carbohydrates, lipids, proteins, and nucleic acids. Before exploring these compounds, you need to first understand the chemistry of carbon.

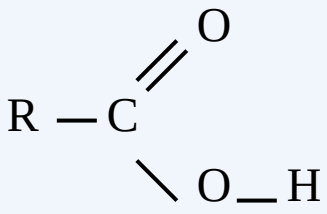
The Chemistry of Carbon

What makes organic compounds ubiquitous is the chemistry of their carbon core. Recall that carbon atoms have four electrons in their valence shell, and that the octet rule dictates that atoms tend to react in such a way as to complete their valence shell with eight electrons. Carbon atoms do not complete their valence shells by donating or accepting four electrons. Instead, they readily share electrons via covalent bonds.

Commonly, carbon atoms share with other carbon atoms, often forming a long carbon chain referred to as a carbon skeleton. When they do share, however, they do not share all their electrons exclusively with each other. Rather, carbon atoms tend to share electrons with a variety of other elements, one of which is always hydrogen. Carbon and hydrogen groupings are called hydrocarbons. If you study the figures of organic compounds in the remainder of this chapter, you will see several with chains of hydrocarbons in one region of the compound.

Many combinations are possible to fill carbon's four "vacancies." Carbon may share electrons with oxygen or nitrogen or other atoms in a particular region of an organic compound. Moreover, the atoms to which carbon atoms bond may also be part of a functional group. A functional group is a group of atoms linked by strong covalent bonds and tending to function in chemical reactions as a single unit. You can think of functional groups as tightly knit "cliques" whose members are unlikely to be parted. Five functional groups are important in human physiology; these are the hydroxyl, carboxyl, amino, methyl and phosphate groups Table 2.5.1.

Table 2.5.1: Functional Groups Important in Human Physiology

Functional group	Structural formula	Importance
Hydroxyl	—O—H	Hydroxyl groups are polar. They are components of all four types of organic compounds discussed in this chapter. They are involved in dehydration synthesis and hydrolysis reactions.
Carboxyl		Carboxyl groups are found within fatty acids, amino acids, and many other acids.
Amino	—N—H_2	Amino groups are found within amino acids, the building blocks of proteins.
Methyl	—C—H_3	Methyl groups are found within amino acids.
Phosphate	—P—O_4^{2-}	Phosphate groups are found within phospholipids and nucleotides.

Carbon's affinity for covalent bonding means that many distinct and relatively stable organic molecules nevertheless readily

form larger, more complex molecules. Any large molecule is referred to as macromolecule (macro- = “large”), and the organic compounds in this section all fit this description. However, some macromolecules are made up of several “copies” of single units called monomer (mono- = “one”; -mer = “part”). Like beads in a long necklace, these monomers link by covalent bonds to form long polymers (poly- = “many”). There are many examples of monomers and polymers among the organic compounds.

Monomers form polymers by engaging in dehydration synthesis. As was noted earlier, this reaction results in the release of a molecule of water. Each monomer contributes: One gives up a hydrogen atom and the other gives up a hydroxyl group. Polymers are split into monomers by hydrolysis (-lysis = “rupture”). The bonds between their monomers are broken, via the donation of a molecule of water, which contributes a hydrogen atom to one monomer and a hydroxyl group to the other.

Carbohydrates

The term carbohydrate means “hydrated carbon.” Recall that the root hydro- indicates water. A carbohydrate is a molecule composed of carbon, hydrogen, and oxygen; in most carbohydrates, hydrogen and oxygen are found in the same two-to-one relative proportions they have in water. In fact, the chemical formula for a “generic” molecule of carbohydrate is $(CH_2O)_n$.

Carbohydrates are referred to as saccharides, a word meaning “sugars.” Three forms are important in the body. Monosaccharides are the monomers of carbohydrates. Disaccharides (di- = “two”) are made up of two monomers. Polysaccharides are the polymers, and can consist of hundreds to thousands of monomers.

Monosaccharides

A monosaccharide is a monomer of carbohydrates. Five monosaccharides are important in the body. Three of these are the hexose sugars, so called because they each contain six atoms of carbon. These are glucose, fructose, and galactose, shown in Figure 2.5.1a. The remaining monosaccharides are the two pentose sugars, each of which contains five atoms of carbon. They are ribose and deoxyribose, shown in Figure 2.5.1b.

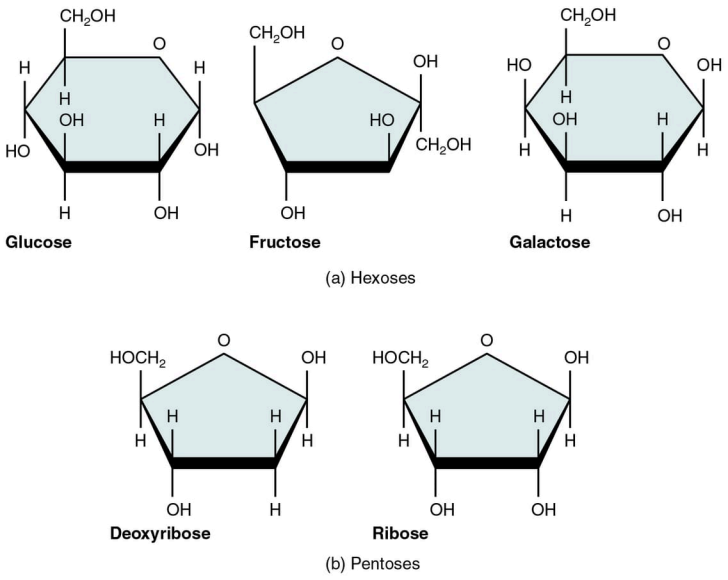


Figure 2.5.1: Comparison of monosaccharides: (a) hexoses—glucose, fructose, galactose; (b) pentoses—deoxyribose and ribose. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.1.

Disaccharides

A disaccharide is a pair of monosaccharides. Disaccharides are formed via dehydration synthesis, and the bond linking them is referred to as a glycosidic bond (glyco- = “sugar”). Three disaccharides (shown in Figure 2.5.2) are important to humans. These are sucrose, commonly referred to as table sugar; lactose, or milk sugar; and maltose, or malt sugar. As you can tell from their common names, you consume these in your diet; however, your body cannot use them directly. Instead, in the digestive tract, they are split into their component monosaccharides via hydrolysis.

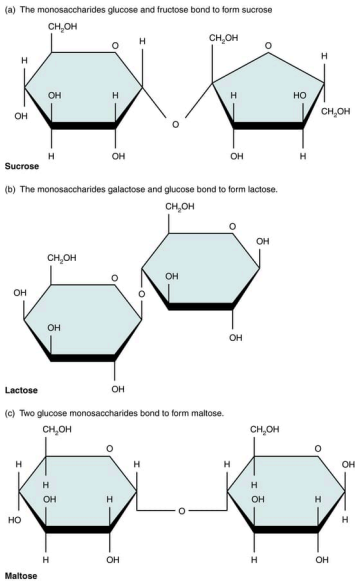


Figure 2.5.2: All three important disaccharides form by dehydration synthesis. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.2.

Polysaccharides

Polysaccharides can contain a few to a thousand or more monosaccharides. Three are important to the body (Figure 2.5.3):

- Starches are polymers of glucose. They occur in long chains called amylose or branched chains called amylopectin, both of which are stored in plant-based foods and are relatively easy to digest.
- Glycogen is also a polymer of glucose, but it is stored in the tissues of animals, especially in the muscles and liver. It is not considered a dietary carbohydrate because very little glycogen remains in animal tissues after slaughter; however, the human body stores excess glucose as glycogen, again, in the muscles and liver.
- Cellulose, a polysaccharide that is the primary component of the cell wall of green plants, is the component of plant food referred to as “fiber”. In humans, cellulose/fiber is not digestible; however, dietary fiber has many health benefits. It helps you feel full so you eat less, it promotes a healthy digestive tract, and a diet high in fiber is thought to reduce the risk of heart disease and possibly some forms of cancer.

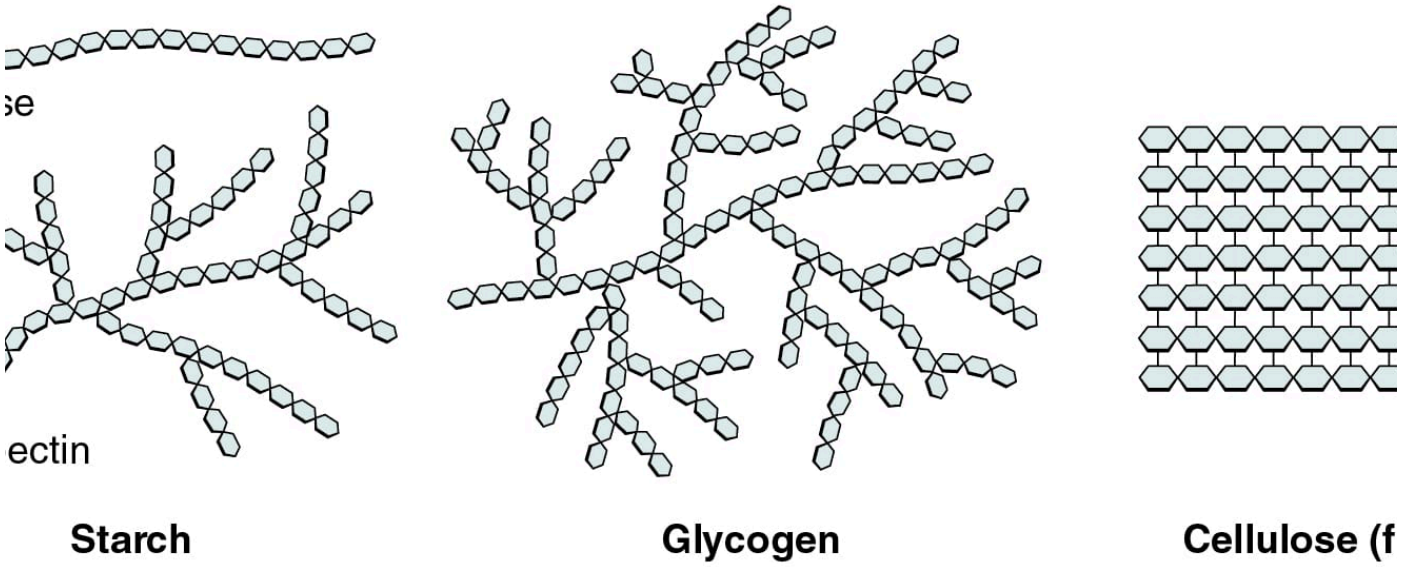


Figure 2.5.3: Three important polysaccharides are starches, glycogen, and fiber. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.3.

Functions of Carbohydrates

The body obtains carbohydrates from plant-based foods. Grains, fruits, and legumes and other vegetables provide most of the carbohydrate in the human diet, although lactose is found in dairy products.

Although most body cells can break down other organic compounds for fuel, all body cells can use glucose. Moreover, nerve cells (neurons) in the brain, spinal cord, and through the peripheral nervous system, as well as red blood cells, can use only glucose for fuel. In the breakdown of glucose for energy, molecules of adenosine triphosphate, better known as ATP, are produced. Adenosine triphosphate (ATP) is composed of a ribose sugar, an adenine base, and three phosphate groups. ATP releases free energy when its phosphate bonds are broken, and thus supplies ready energy to the cell. More ATP is produced in the presence of oxygen (O_2) than in pathways that do not use oxygen. The overall reaction for the conversion of the energy in glucose to energy stored in ATP can be written:

$$\mathrm{C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + ATP}$$

In addition to being a critical fuel source, carbohydrates are present in very small amounts in cells' structure. For instance, some carbohydrate molecules bind with proteins to produce glycoproteins, and others combine with lipids to produce glycolipids, both of which are found in the membrane that encloses the contents of body cells.

Lipids

A lipid is one of a highly diverse group of compounds made up mostly of hydrocarbons. The few oxygen atoms they contain are often at the periphery of the molecule. Their nonpolar hydrocarbons make all lipids hydrophobic. In water, lipids do not form a true solution, but they may form an emulsion, which is the term for a mixture of solutions that do not mix well.

Triglycerides

A triglyceride is one of the most common dietary lipid groups, and the type found most abundantly in body tissues. This compound, which is commonly referred to as a fat, is formed from the synthesis of two types of molecules (Figure 2.5.4):

- A glycerol backbone at the core of triglycerides, consists of three carbon atoms.
- Three fatty acids, long chains of hydrocarbons with a carboxyl group and a methyl group at opposite ends, extend from each of the carbons of the glycerol.

ains are bound to glycerol by dehydration synthesis.

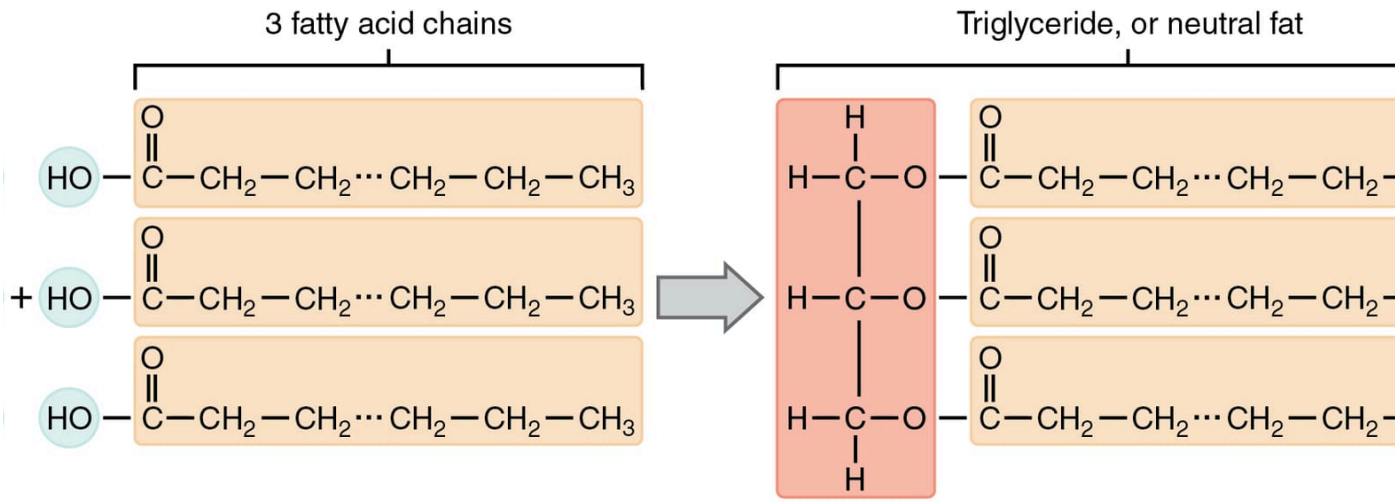


Figure 2.5.4: Triglycerides are composed of glycerol attached to three fatty acids via dehydration synthesis. Notice that glycerol gives up a hydrogen atom, and the carboxyl groups on the fatty acids each give up a hydroxyl group. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.4.

Triglycerides form via dehydration synthesis. Glycerol gives up hydrogen atoms from its hydroxyl groups at each bond, and the carboxyl group on each fatty acid chain gives up a hydroxyl group. A total of three water molecules are thereby released.

Fatty acid chains that have no double carbon bonds anywhere along their length and therefore contain the maximum number of hydrogen atoms are called saturated fatty acids. These straight, rigid chains pack tightly together and are solid or semi-solid at room temperature (Figure 2.5.5*a*). Butter and lard are examples, as is the fat found on a steak or in your own body. In contrast, fatty acids with one double carbon bond are kinked at that bond (Figure 2.5.5*b*). These monounsaturated fatty acids are therefore unable to pack together tightly, and are liquid at room temperature. Polyunsaturated fatty acids contain two or more double carbon bonds, and are also liquid at room temperature. Plant oils such as olive oil typically contain both mono- and polyunsaturated fatty acids.

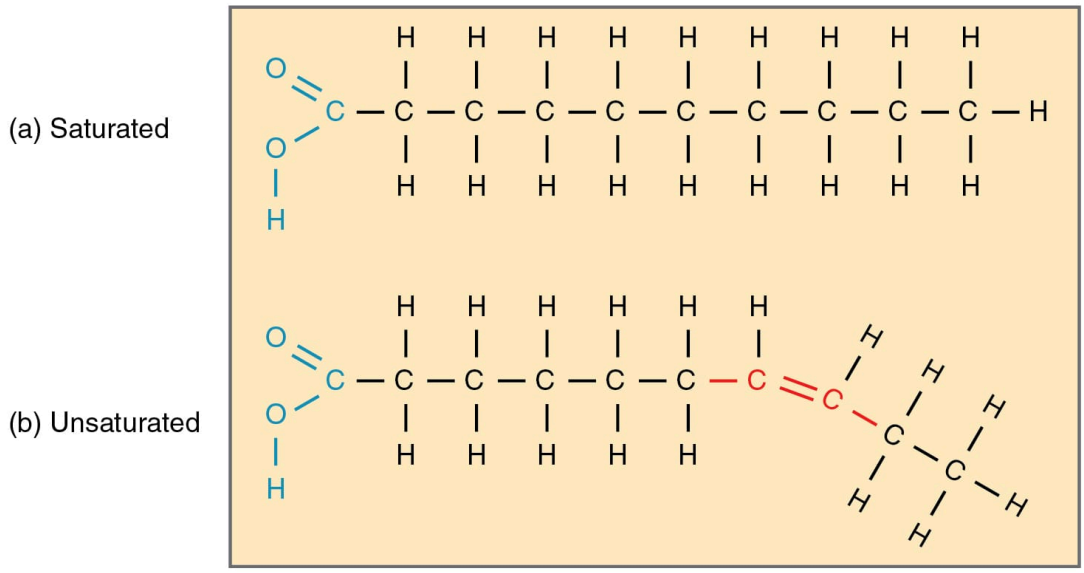


Figure 2.5.5: The level of saturation of a fatty acid affects its shape. (a) Saturated fatty acid chains are straight. (b) Unsaturated fatty acid chains are kinked.(CC BY 4.0 ; via OpenStax). Alternative text description of Figure 2.5.5.

Whereas a diet high in saturated fatty acids increases the risk of heart disease, a diet high in unsaturated fatty acids is thought

to reduce the risk. This is especially true for the omega-3 unsaturated fatty acids found in cold-water fish such as salmon. These fatty acids have their first double carbon bond at the third hydrocarbon from the methyl group (referred to as the omega end of the molecule).

Finally, *trans* fatty acids found in some processed foods, including some stick and tub margarines, are thought to be even more harmful to the heart and blood vessels than saturated fatty acids. *Trans* fats are created from unsaturated fatty acids (such as corn oil) when chemically treated to produce partially hydrogenated fats.

As a group, triglycerides are a major fuel source for the body. When you are resting or asleep, a majority of the energy used to keep you alive is derived from triglycerides stored in your fat (adipose) tissues. Triglycerides also fuel long, slow physical activity such as gardening or hiking, and contribute a modest percentage of energy for vigorous physical activity. Dietary fat also assists the absorption and transport of the nonpolar fat-soluble vitamins A, D, E, and K. Additionally, stored body fat protects and cushions the body's bones and internal organs, and acts as insulation to retain body heat.

Fatty acids are also components of glycolipids, which are sugar-fat compounds found in the cell membrane. Lipoproteins are compounds in which the hydrophobic triglycerides are packaged in protein envelopes for transport in body fluids.

Phospholipids

As its name suggests, a phospholipid is a bond between the glycerol component of a lipid and a phosphorous molecule. In fact, phospholipids are similar in structure to triglycerides. However, instead of having three fatty acids, a phospholipid is generated from a diglyceride, a glycerol with just two fatty acid chains (Figure 2.5.6). The third binding site on the glycerol is taken up by the phosphate group, which in turn is attached to a polar "head" region of the molecule. Recall that triglycerides are nonpolar and hydrophobic. This still holds for the fatty acid portion of a phospholipid compound. However, the head of a phospholipid contains charges on the phosphate groups, as well as on the nitrogen atom. These charges make the phospholipid head hydrophilic. Therefore, phospholipids are said to have hydrophobic tails, containing the neutral fatty acids, and hydrophilic heads, containing the charged phosphate groups and nitrogen atom.

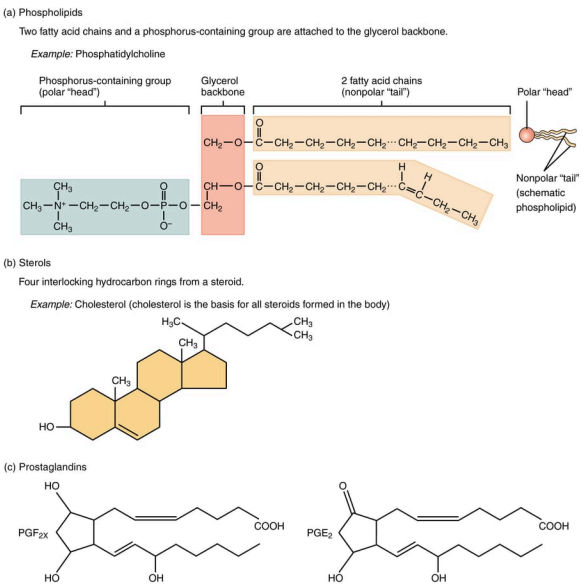


Figure 2.5.6: Other Important Lipids (a) Phospholipids are composed of two fatty acids, glycerol, and a phosphate group. (b) Sterols are ring-shaped lipids. Shown here is cholesterol. (c) Prostaglandins are derived from unsaturated fatty acids. Prostaglandin E2 (PGE2) includes hydroxyl and carboxyl groups. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.6.

Steroids

A steroid compound (referred to as a sterol) has as its foundation a set of four hydrocarbon rings bonded to a variety of other atoms and molecules. Although both plants and animals synthesize sterols, the type that makes the most important contribution to human structure and function is cholesterol, which is synthesized by the liver in humans and animals and is also present in most animal-based foods. Like other lipids, cholesterol's hydrocarbons make it hydrophobic; however, it has a polar hydroxyl head

that is hydrophilic. Cholesterol is an important component of bile acids, compounds that help emulsify dietary fats. In fact, the word root chole- refers to bile. Cholesterol is also a building block of many hormones, signaling molecules that the body releases to regulate processes at distant sites. Finally, like phospholipids, cholesterol molecules are found in the cell membrane, where their hydrophobic and hydrophilic regions help regulate the flow of substances into and out of the cell.

Prostaglandins

Like a hormone, a prostaglandin is one of a group of signaling molecules, but prostaglandins are derived from unsaturated fatty acids (see Figure 2.23**c**). One reason that the omega-3 fatty acids found in fish are beneficial is that they stimulate the production of certain prostaglandins that help regulate aspects of blood pressure and inflammation, and thereby reduce the risk for heart disease. Prostaglandins also sensitize nerves to pain. One class of pain-relieving medications called nonsteroidal anti-inflammatory drugs (NSAIDs) works by reducing the effects of prostaglandins.

Proteins

You might associate proteins with muscle tissue, but in fact, proteins are critical components of all tissues and organs. A protein is an organic molecule composed of amino acids linked by peptide bonds. Proteins include the keratin in the epidermis of skin that protects underlying tissues, the collagen found in the dermis of skin, in bones, and in the meninges that cover the brain and spinal cord. Proteins are also components of many of the body's functional chemicals, including digestive enzymes in the digestive tract, antibodies, the neurotransmitters that neurons use to communicate with other cells, and the peptide-based hormones that regulate certain body functions (for instance, growth hormone). While carbohydrates and lipids are composed of hydrocarbons and oxygen, all proteins also contain nitrogen (N), and many contain sulfur (S), in addition to carbon, hydrogen, and oxygen.

Microstructure of Proteins

Proteins are polymers made up of nitrogen-containing monomers called amino acids. An amino acid is a molecule composed of an amino group and a carboxyl group, together with a variable side chain. Just 20 different amino acids contribute to nearly all of the thousands of different proteins important in human structure and function. Body proteins contain a unique combination of a few dozen to a few hundred of these 20 amino acid monomers. All 20 of these amino acids share a similar structure (Figure 2.5.7). All consist of a central carbon atom to which the following are bonded:

- a hydrogen atom
- an alkaline (basic) amino group NH_2
- an acidic carboxyl group COOH
- a variable group

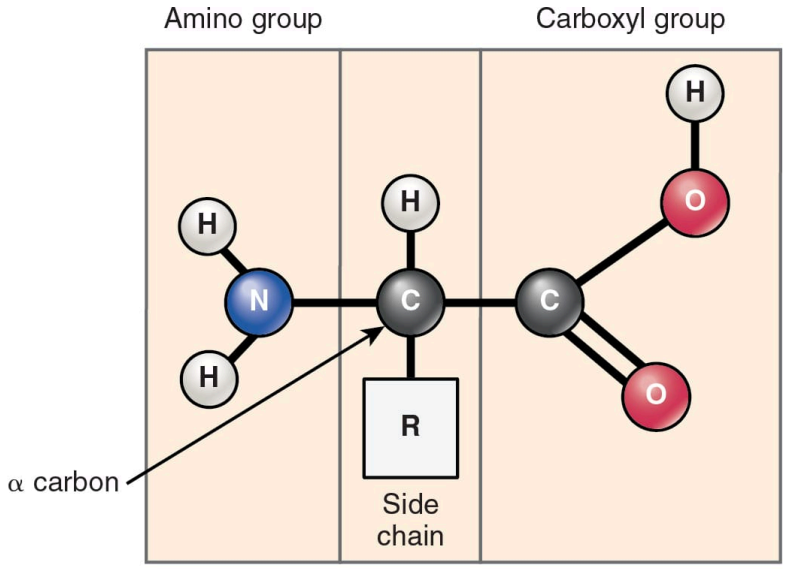


Figure 2.5.7: General structure of an amino acid with an amino group, carboxyl group, alpha carbon, and variable side chain (R group). (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.7.

Notice that all amino acids contain both an acid (the carboxyl group) and a base (the amino group) (amine = "nitrogen-containing"). For this reason, they make excellent buffers, helping the body regulate acid–base balance. What distinguishes the 20 amino acids from one another is their variable group, which is referred to as a side chain or an R-group. This group can vary in size and can be polar or nonpolar, giving each amino acid its unique characteristics. For example, the side chains of two amino acids—cysteine and methionine—contain sulfur. Sulfur does not readily participate in hydrogen bonds, whereas all other amino acids do. This variation influences the way that proteins containing cysteine and methionine are assembled.

Amino acids join via dehydration synthesis to form protein polymers (Figure 2.5.8). The unique bond holding amino acids together is called a peptide bond. A peptide bond is a covalent bond between two amino acids that forms by dehydration synthesis. A peptide, in fact, is a very short chain of amino acids. Strands containing fewer than about 100 amino acids are generally referred to as polypeptides rather than proteins.

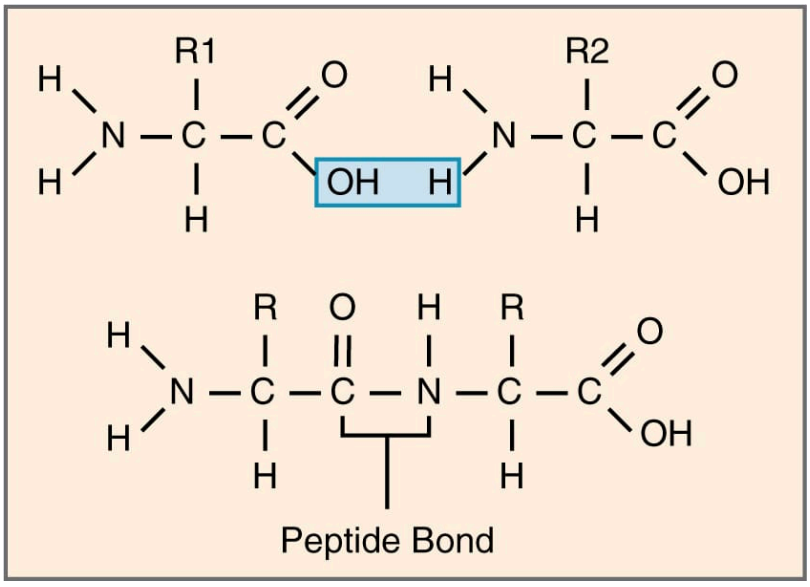


Figure 2.5.8: Different amino acids join together to form peptides, polypeptides, or proteins via dehydration synthesis. The bonds between the amino acids are peptide bonds R1 and R2 may be the same or different side chains. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.8.

The body is able to synthesize most of the amino acids from components of other molecules; however, nine cannot be synthesized and have to be consumed in the diet. These are known as the essential amino acids.

Free amino acids available for protein construction are said to reside in the amino acid pool within cells. Structures within cells use these amino acids when assembling proteins. If a particular essential amino acid is not available in sufficient quantities in the amino acid pool, however, synthesis of proteins containing it can slow or even cease.

Shape of Proteins

Just as a fork cannot be used to eat soup and a spoon cannot be used to spear meat, a protein's shape is essential to its function. A protein's shape is determined, most fundamentally, by the sequence of amino acids of which it is made (Figure $2.5.9a$). The sequence is called the primary structure of the protein.

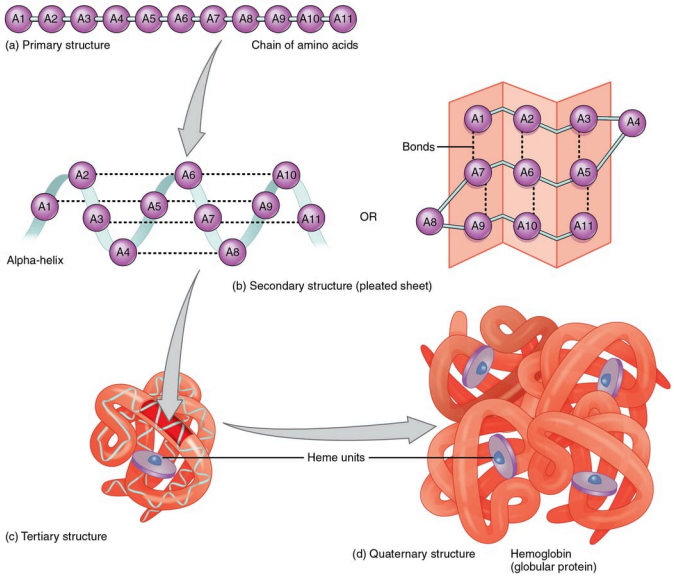


Figure $2.5.9$: Four levels of protein structure: (a) primary amino acid chain, (b) secondary alpha-helix or beta-sheet, (c) tertiary folded shape, (d) quaternary structure of hemoglobin with heme units. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure $2.5.9$.

Although some polypeptides exist as linear chains, most are twisted or folded into more complex secondary structures that form when bonding occurs between amino acids with different properties at different regions of the polypeptide. The most common secondary structure is a spiral called an alpha-helix. If you were to take a length of string and simply twist it into a spiral, it would not hold the shape. Similarly, a strand of amino acids could not maintain a stable spiral shape without the help of hydrogen bonds, which create bridges between different regions of the same strand (Figure $2.5.9$). Less commonly, a polypeptide chain can form a beta-pleated sheet, in which hydrogen bonds form bridges between different regions of a single polypeptide that has folded back upon itself, or between two or more adjacent polypeptide chains.

The secondary structure of proteins further folds into a compact three-dimensional shape, referred to as the protein's tertiary structure Figure $2.5.9$ In this configuration, amino acids that had been very distant in the primary chain can be brought quite close via hydrogen bonds or, in proteins containing cysteine, via disulfide bonds. A disulfide bond is a covalent bond between sulfur atoms in a polypeptide. Often, two or more separate polypeptides bond to form an even larger protein with a quaternary structure Figure $2.5.9$. The polypeptide subunits forming a quaternary structure can be identical or different. For instance, hemoglobin, the protein found in red blood cells is composed of four tertiary polypeptides, two of which are called alpha chains and two of which are called beta chains.

When they are exposed to extreme heat, acids, bases, and certain other substances, proteins will denature. Denaturation is a change in the structure of a molecule through physical or chemical means. Denatured proteins lose their functional shape and are no longer able to carry out their jobs. An everyday example of protein denaturation is the curdling of milk when acidic lemon juice is added.

The contribution of the shape of a protein to its function can hardly be exaggerated. For example, the long, slender shape of

protein strands that make up muscle tissue is essential to their ability to contract (shorten) and relax (lengthen). As another example, bones contain long threads of a protein called collagen that acts as scaffolding upon which bone minerals are deposited. These elongated proteins, called fibrous proteins, are strong and durable and typically hydrophobic.

In contrast, globular proteins are globes or spheres that tend to be highly reactive and are hydrophilic. The hemoglobin proteins packed into red blood cells are an example, however, globular proteins are abundant throughout the body, playing critical roles in most body functions. Enzymes, introduced earlier as protein catalysts, are examples of this. The next section takes a closer look at the action of enzymes.

Proteins Function as Enzymes

If you were trying to type a paper, and every time you hit a key on your laptop there was a delay of six or seven minutes before you got a response, you would probably get a new laptop. In a similar way, without enzymes to catalyze chemical reactions, the human body would be nonfunctional. It functions only because enzymes function.

Enzymatic reactions—chemical reactions catalyzed by enzymes—begin when substrates bind to the enzyme. A substrate is a reactant in an enzymatic reaction. This occurs on regions of the enzyme known as active sites (Figure 2.5.10). Any given enzyme catalyzes just one type of chemical reaction. This characteristic, called specificity, is due to the fact that a substrate with a particular shape and electrical charge can bind only to an active site corresponding to that substrate.

Due to this jigsaw puzzle-like match between an enzyme and its substrates, enzymes are known for their specificity. In fact, as an enzyme binds to its substrate(s), the enzyme structure changes slightly to find the best fit between the transition state (a structural intermediate between the substrate and product) and the active site, just as a rubber glove molds to a hand inserted into it. This active-site modification in the presence of substrate, along with the simultaneous formation of the transition state, is called induced fit. Overall, there is a specifically matched enzyme for each substrate and, thus, for each chemical reaction; however, there is some flexibility as well. Some enzymes have the ability to act on several different structurally related substrates.

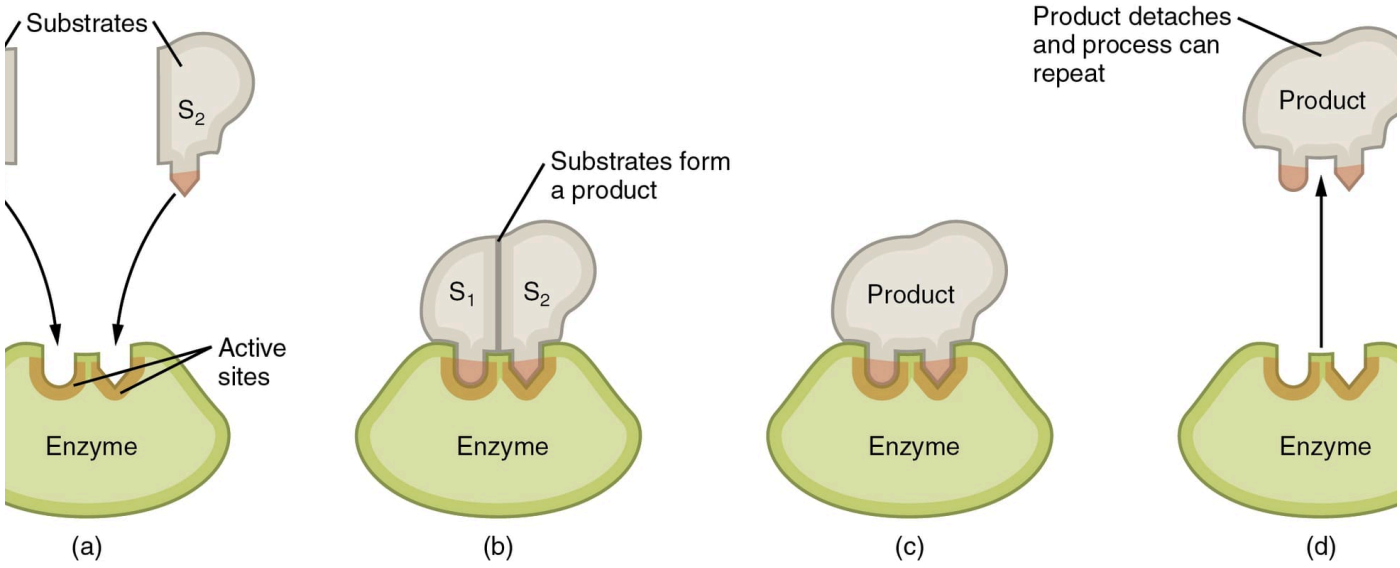


Figure 2.5.10: Enzyme action sequence: (a) substrates bind to active sites, (b) substrates form product, (c) product remains bound, (d) product detaches and enzyme is ready for reuse. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.10.

Binding of a substrate produces an enzyme–substrate complex. It is likely that enzymes speed up chemical reactions in part because the enzyme–substrate complex undergoes a set of temporary and reversible changes that cause the substrates to be oriented toward each other in an optimal position to facilitate their interaction. This promotes increased reaction speed. The enzyme then releases the product(s), and resumes its original shape. The enzyme is then free to engage in the process again, and will do so as long as substrate remains.

Other Functions of Proteins

Advertisements for protein bars, powders, and shakes all say that protein is important in building, repairing, and maintaining muscle tissue, but the truth is that proteins contribute to all body tissues, from the skin to the brain cells. Also, certain proteins act as hormones, chemical messengers that help regulate body functions, For example, growth hormone is important for skeletal growth, among other roles.

As was noted earlier, the basic and acidic components enable proteins to function as buffers in maintaining acid–base balance, but they also help regulate fluid–electrolyte balance. Proteins attract fluid, and a healthy concentration of proteins in the blood, the cells, and the spaces between cells helps ensure a balance of fluids in these various "compartments." Moreover, proteins in the cell membrane help to transport electrolytes in and out of the cell, keeping these ions in a healthy balance. Like lipids, proteins can bind with carbohydrates. They can thereby produce glycoproteins or proteoglycans, both of which have many functions in the body.

The body can use proteins for energy when carbohydrate and fat intake is inadequate, and stores of glycogen and adipose tissue become depleted. However, since there is no storage site for protein except functional tissues, using protein for energy causes tissue breakdown, and results in body wasting.

Nucleic acids

The fourth type of organic compound important to human structure and function are the nucleotides (Figure 2.5.11). A nucleotide is one of a class of organic compounds composed of three subunits:

- one or more phosphate groups
- a pentose sugar: either deoxyribose or ribose

Nucleotides can be assembled into nucleic acids (DNA or RNA) or the energy compound adenosine triphosphate.

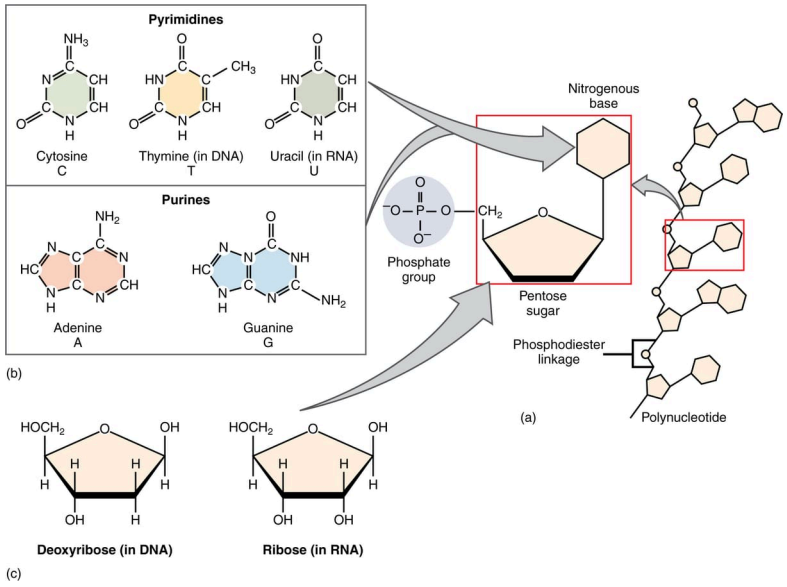


Figure 2.5.11: Nucleotides (a) The building blocks of all nucleotides are one or more phosphate groups, a pentose sugar, and a nitrogen-containing base. (b) The nitrogen-containing bases of nucleotides. (c) The two pentose sugars of DNA and RNA. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.11.

The nucleic acids differ in their type of pentose sugar. Deoxyribonucleic acid (DNA) is nucleotide that stores genetic information. DNA contains deoxyribose (so-called because it has one less atom of oxygen than ribose) plus one phosphate group and one nitrogen-containing base. The "choices" of base for DNA are adenine, cytosine, guanine, and thymine. Ribonucleic acid (RNA) is a ribose-containing nucleotide that helps manifest the genetic code as protein. RNA contains ribose, one phosphate group, and one nitrogen-containing base, but the "choices" of base for RNA are adenine, cytosine, guanine, and uracil.

The nitrogen-containing bases adenine and guanine are classified as purines. A purine is a nitrogen-containing molecule with a double ring structure, which accommodates several nitrogen atoms. The bases cytosine, thymine (found in DNA only) and uracil (found in RNA only) are pyramidines. A pyramidine is a nitrogen-containing base with a single ring structure

Bonds formed by dehydration synthesis between the pentose sugar of one nucleic acid monomer and the phosphate group of another form a “backbone,” from which the components’ nitrogen-containing bases protrude. In DNA, two such backbones attach at their protruding bases via hydrogen bonds. These twist to form a shape known as a double helix (Figure 2.5.12). The sequence of nitrogen-containing bases within a strand of DNA form the genes that act as a molecular code instructing cells in the assembly of amino acids into proteins. Humans have almost 22,000 genes in their DNA, locked up in the 46 chromosomes inside the nucleus of each cell (except red blood cells which lose their nuclei during development). These genes carry the genetic code to build one’s body, and are unique for each individual except identical twins.

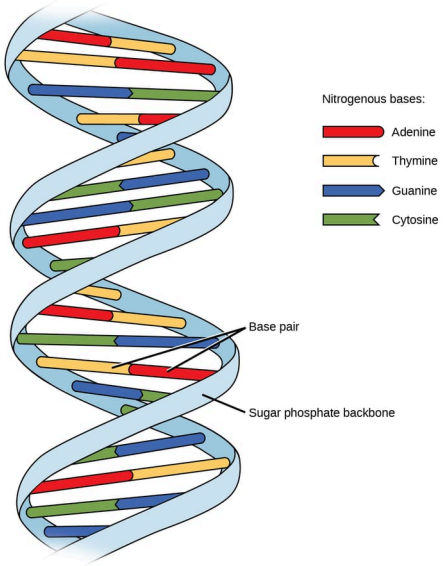


Figure 2.5.12: In the DNA double helix, two strands attach via hydrogen bonds between the bases of the component nucleotides. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.12.

In contrast, RNA consists of a single strand of sugar-phosphate backbone studded with bases. Messenger RNA (mRNA) is created during protein synthesis to carry the genetic instructions from the DNA to the cell’s protein manufacturing plants in the cytoplasm, the ribosomes.

Adenosine Triphosphate

The nucleotide adenosine triphosphate (ATP), is composed of a ribose sugar, an adenine base, and three phosphate groups (Figure 2.5.13). ATP is classified as a high energy compound because the two covalent bonds linking its three phosphates store a significant amount of potential energy. In the body, the energy released from these high energy bonds helps fuel the body’s activities, from muscle contraction to the transport of substances in and out of cells to anabolic chemical reactions.

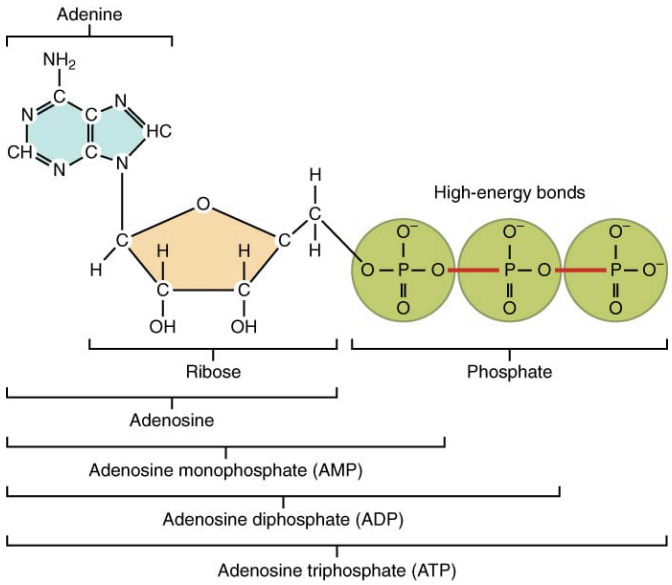


Figure 2.5.13: Components of adenosine triphosphate (ATP), including adenine, ribose, and phosphate groups. The diagram also shows the related molecules AMP and ADP and identifies the high-energy bonds between phosphate groups. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 2.5.13.

When a phosphate group is cleaved from ATP, the products are adenosine diphosphate (ADP) and inorganic phosphate (P_i). This hydrolysis reaction can be written:

$$\mathrm{ATP} + \mathrm{H_2O} \rightarrow \mathrm{ADP} + \mathrm{P_i} + \text{energy}$$

Removal of a second phosphate leaves adenosine monophosphate (AMP) and two phosphate groups. Again, these reactions also liberate the energy that had been stored in the phosphate-phosphate bonds. They are reversible, too, as when ADP undergoes phosphorylation. Phosphorylation is the addition of a phosphate group to an organic compound, in this case, resulting in ATP. In such cases, the same level of energy that had been released during hydrolysis must be reinvested to power dehydration synthesis. Cells can also transfer a phosphate group from ATP to another organic compound. For example, when glucose first enters a cell, a phosphate group is transferred from ATP, forming glucose phosphate ($C_6H_{12}O_6$—P) and ADP. Once glucose is phosphorylated in this way, it can be stored as glycogen or metabolized for immediate energy.

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2.6: Terms and Definitions

Key Terms

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Acid
compound that releases hydrogen ions (H^+) in solution

Activation energy
amount of energy greater than the energy contained in the reactants, which must be overcome for a reaction to proceed

Adenosine triphosphate (ATP)
nucleotide containing ribose and an adenine base that is essential in energy transfer

Amino acid
building block of proteins; characterized by an amino and carboxyl functional groups and a variable side-chain

Anion
atom with a negative charge

Atom
smallest unit of an element that retains the unique properties of that element

Atomic number
number of protons in the nucleus of an atom

Base
compound that accepts hydrogen ions (H^+) in solution

Bond
electrical force linking atoms

Buffer
solution containing a weak acid or a weak base that opposes wide fluctuations in the pH of body fluids

Carbohydrate
class of organic compounds built from sugars, molecules containing carbon, hydrogen, and oxygen in a 1-2-1 ratio

Catalyst
substance that increases the rate of a chemical reaction without itself being changed in the process

Cation
atom with a positive charge

Chemical energy
form of energy that is absorbed as chemical bonds form, stored as they are maintained, and released as they are broken

Colloid
liquid mixture in which the solute particles consist of clumps of molecules large enough to scatter light

Compound
substance composed of two or more different elements joined by chemical bonds

Concentration
number of particles within a given space

Covalent bond
chemical bond in which two atoms share electrons, thereby completing their valence shells

Decomposition reaction
type of catabolic reaction in which one or more bonds within a larger molecule are broken, resulting in the release of smaller molecules or atoms

Denaturation
change in the structure of a molecule through physical or chemical means

Deoxyribonucleic acid (DNA)
deoxyribose-containing nucleotide that stores genetic information

Disaccharide
pair of carbohydrate monomers bonded by dehydration synthesis via a glycosidic bond

Disulfide bond
covalent bond formed within a polypeptide between sulfide groups of sulfur-containing amino acids, for example, cysteine

Electron
subatomic particle having a negative charge and nearly no mass; found orbiting the atom's nucleus

Electron shell
area of space a given distance from an atom's nucleus in which electrons are grouped

Element
substance that cannot be created or broken down by ordinary chemical means

Enzyme
protein or RNA that catalyzes chemical reactions

Exchange reaction
type of chemical reaction in which bonds are both formed and broken, resulting in the transfer of components

Functional group
group of atoms linked by strong covalent bonds that tends to behave as a distinct unit in chemical reactions with other atoms

Hydrogen bond
dipole-dipole bond in which a hydrogen atom covalently bonded to an electronegative atom is weakly attracted to a second electronegative atom

Inorganic compound
substance that does not contain both carbon and hydrogen

Ion
atom with an overall positive or negative charge

Ionic bond
attraction between an anion and a cation

Isotope
one of the variations of an element in which the number of neutrons differ from each other

Kinetic energy
energy that matter possesses because of its motion

Lipid
class of nonpolar organic compounds built from hydrocarbons and distinguished by the fact that they are not soluble in water

Macromolecule
large molecule formed by covalent bonding

Mass number
sum of the number of protons and neutrons in the nucleus of an atom

Matter
physical substance; that which occupies space and has mass

Molecule
two or more atoms covalently bonded together

Monosaccharide
monomer of carbohydrate; also known as a simple sugar

Neutron
heavy subatomic particle having no electrical charge and found in the atom's nucleus

Nucleotide
class of organic compounds composed of one or more phosphate groups, a pentose sugar, and a base

Organic compound
substance that contains both carbon and hydrogen

Peptide bond
covalent bond formed by dehydration synthesis between two amino acids

Periodic table of the elements
arrangement of the elements in a table according to their atomic number; elements having similar properties because of their electron arrangements compose columns in the table, while elements having the same number of valence shells compose rows in the table

pH
negative logarithm of the hydrogen ion (H^+) concentration of a solution

Phospholipid
a lipid compound in which a phosphate group is combined with a diglyceride

Phosphorylation
addition of one or more phosphate groups to an organic compound

Polar molecule
molecule with regions that have opposite charges resulting from uneven numbers of electrons in the nuclei of the atoms participating in the covalent bond

Polysaccharide
compound consisting of more than two carbohydrate monomers bonded by dehydration synthesis via glycosidic bonds

Potential energy
stored energy matter possesses because of the positioning or structure of its components

Product
one or more substances produced by a chemical reaction

Prostaglandin
lipid compound derived from fatty acid chains and important in regulating several body processes

Protein
class of organic compounds that are composed of many amino acids linked together by peptide bonds

Proton
heavy subatomic particle having a positive charge and found in the atom's nucleus

Purine
nitrogen-containing base with a double ring structure; adenine and guanine

Pyrimidine
nitrogen-containing base with a single ring structure; cytosine, thiamine, and uracil

Radioactive isotope
unstable, heavy isotope that gives off subatomic particles, or electromagnetic energy, as it decays; also called radioisotopes

Reactant
one or more substances that enter into the reaction

Ribonucleic acid (RNA)
ribose-containing nucleotide that helps manifest the genetic code as protein

Solution
homogeneous liquid mixture in which a solute is dissolved into molecules within a solvent

Steroid
(also, sterol) lipid compound composed of four hydrocarbon rings bonded to a variety of other atoms and molecules

Substrate
reactant in an enzymatic reaction

Suspension
liquid mixture in which particles distributed in the liquid settle out over time

Synthesis reaction
type of anabolic reaction in which two or more atoms or molecules bond, resulting in the formation of a larger molecule

Triglyceride
lipid compound composed of a glycerol molecule bonded with three fatty acid chains

Valence shell
outermost electron shell of an atom

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2.7: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. A 70-kg adult human is composed mainly of just a few chemical elements. More than 95% of total body mass is made up of which four elements?
   A. Calcium, magnesium, iron, and carbon
   B. Oxygen, calcium, iron, and nitrogen
   C. Sodium, chlorine, carbon, and hydrogen
   D. Oxygen, carbon, hydrogen, and nitrogen
2. In a clinical lab, you are told that a sample contains “pure elemental oxygen.” The smallest unit of this element that still retains the chemical properties of oxygen is:
   A. An electron
   B. An atom
   C. An elemental particle
   D. An isotope
3. Two samples of the same element behave identically in chemical reactions, even though their masses are slightly different. This is because they have the same number of:
   A. Protons
   B. Neutrons
   C. Electrons
   D. Atoms
4. On the periodic table, mercury (Hg) has atomic number 80 and average atomic mass 200.59. It has several stable isotopes. The most abundant isotopes are likely to have:
   A. Mass numbers close to 200, with about 120 neutrons each
   B. Mass numbers close to 80, with about 80 neutrons each
   C. Mass numbers close to 200, with fewer than 80 neutrons each
   D. Mass numbers close to 200, with more electrons than neutrons
5. Which of the following is a molecule but not a compound?
   A. H_2O
   B. 2H
   C. H_2
   D. H◈
6. A nurse explains that ammonia (NH_3) is a small molecule that is very soluble in water because of the way its atoms share electrons. In NH_3, nitrogen and hydrogen are linked by:
   A. Ionic bonds
   B. Nonpolar covalent bonds
   C. Polar covalent bonds
   D. Hydrogen bonds
7. A sodium atom (Na) loses one electron and then interacts with a chlorine atom (Cl) that gains that electron, forming Na◈ and Cl◈. After this electron transfer, the sodium atom becomes:
   A. A positively charged ion (cation)
   B. A negatively charged ion (anion)

C. A nonpolar atom
D. An isotope of sodium

8. Solid sodium chloride (NaCl) consists of a regular three-dimensional arrangement of $Na^{\oplus}$ and $Cl^{\ominus}$ ions. A substance formed from crystals of equal numbers of cations and anions held together by ionic bonds is called a(n):
   A. Noble gas
   B. Salt
   C. Electrolyte
   D. Dipole
9. Consider the following statements about chemical bonds. Which is true in biological systems such as the human body?
   A. Covalent bonds are generally stronger than ionic bonds in aqueous solution.
   B. Hydrogen bonds occur between two atoms of hydrogen.
   C. Bonding readily occurs between strongly nonpolar and strongly polar molecules.
   D. A water molecule is unlikely to interact with an ion.
10. A heavy sheet of snow lies on a steep roof. Before it slides, the energy it possesses due to its elevated position is best classified as:
    A. Potential energy
    B. Kinetic energy
    C. Radiant energy
    D. Activation energy
11. During bone formation, calcium and phosphate ions react to form hydroxyapatite crystals, adding new mineral to bone matrix. This process is an example of a:
    A. Catabolic reaction
    B. Synthesis (anabolic) reaction
    C. Decomposition reaction
    D. Exchange reaction
12. In cellular metabolism, the breakdown of a large glycogen molecule into many glucose molecules is represented as AB → A + B. This notation describes a:
    A. Anabolic reaction
    B. Endergonic reaction
    C. Decomposition reaction
    D. Exchange reaction
13. A cell hydrolyzes ATP to ADP and inorganic phosphate, releasing usable energy. This reaction is:
    A. Catabolic
    B. Exergonic
    C. A decomposition reaction
    D. All of the above
14. Which of the following pairs of atoms is most likely to chemically react under normal physiological conditions?
    A. Hydrogen and hydrogen
    B. Hydrogen and helium
    C. Helium and helium
    D. Neon and helium
15. A patient is instructed to chew bread thoroughly before swallowing. This helps start chemical digestion in the mouth. The most important reason is that:
    A. The mouth temperature is very high
    B. Chewing stores potential energy
    C. Chewing facilitates synthesis reactions
    D. Saliva contains digestive enzymes
16. Methane (CH_4) is released in small amounts from the human gut by intestinal bacteria. CH_4 is:
    A. Inorganic
    B. Organic
    C. A salt
    D. A crystal
17. A 0.9% NaCl (saline) solution is commonly given intravenously. In this solution, which of the following is most likely to be evenly distributed throughout the water?
    A. Sodium ions and chloride ions
    B. NaCl molecules
    C. Solid salt crystals

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2.8: Applied Thinking Self - Assessment

Challenge Yourself

a. Critical thinking is essential in a time of endless information and AI, helping you move from passive memorizing to actively making sense of what you learn.

b. Use the short-essay, case-based prompts at the end of each chapter to check and deepen your understanding:

c. Extended response questions are assessment items that require students to construct written answers of substantial length - typically several sentences to multiple paragraphs - rather than selecting from predefined options. They represent a form of constructed response assessment designed to measure complex, higher-order thinking skills.

d. The following prompts ask you to apply chemistry concepts to biological contexts, justify your reasoning with mechanisms and data, and communicate clearly.

e. What your response must include:
   - Direct answer (1–2 sentences): State your conclusion up front.
   - Mechanistic explanation (4–8 sentences): Explain the "how/why" at the molecular level, linking cause to effect.
   - Use correct concepts (e.g., electronegativity → polarity → H-bonding → emergent property).
   - Diagram or equation (optional but encouraged).
   - Use precise terms and units; define symbols on first use.

1. Most of the mass of a human body and of typical foods comes from just four elements: carbon (C), hydrogen (H), oxygen (O), and nitrogen (N).
   a. For each element (C, H, O, N), name one major type of biological molecule (carbohydrate, lipid, protein, nucleic acid) or metabolic pathway (e.g., cellular respiration, ATP production) that depends strongly on it.
   b. For each example you chose, explain specifically how that element's chemical properties (e.g., ability to form 4 bonds, high electronegativity, role in functional groups like amino or carboxyl) support that molecule's structure or function.
2. Oxygen's atomic number is 8, and it has three common stable isotopes: ^{16}O, ^{17}O, and ^{18}O.
3. Work with both of the following:
   a. For each isotope (^{16}O, ^{17}O, ^{18}O), state the number of protons and neutrons in the nucleus of a neutral atom. Show how you calculate the number of neutrons from the mass number and atomic number.
   b. All three isotopes of oxygen participate in the same chemical reactions in the body (for example, in water and in cellular respiration). Explain why differences in neutron number do not change their basic chemical behavior, and identify which subatomic particle(s) matter most for chemical properties.
4. Magnesium atoms each have 12 electrons and are usually found in the body as the ion Mg^{2+}.
   a. Describe or draw the electron configuration of a neutral Mg atom and of Mg^{2+}. Use the idea of valence electrons and stable electron shells to explain why magnesium tends to lose two electrons rather than gain six.
   b. Explain how Mg's position in the periodic table (group and period) helps you predict that it will form a $2+$ ion.
   c. Choose one physiological role of Mg^{2+} (for example, as a cofactor for ATP-using enzymes or in bone mineralization). Describe how the charged ionic form Mg^{2+} is important for this role, and predict what might happen at the tissue or organ level if Mg^{2+} levels in the body become very low.
5. Methane (CH_4) is very common in nature and is produced by some gut bacteria in humans.
   a. What kind of bonds form between carbon and hydrogen in CH_4 (ionic or covalent, single or double)? Use electronegativity to explain why these C–H bonds are considered nonpolar.
   b. Describe the 3D shape of a CH_4 molecule and explain how this shape affects whether the molecule as a whole is polar or nonpolar.
   c. Many lipids (like fatty acids) are made mostly of C–H bonds. Using your answers above, explain why these hydrocarbons are hydrophobic and how this affects: their behavior in water-based body fluids (like blood) and their tendency to be stored in adipose (fat) tissue rather than dissolved in cytosol.
6. After making a salad with olive oil, rinsing the bowl with plain water leaves a greasy film, but adding dish soap removes it.
   a. Use the concept of polarity to explain why water alone cannot easily dissolve or remove the oil from the bowl.
   b. Describe the basic structure of a soap or detergent molecule (a "water-loving" head and an "oil-loving" tail).
   c. Explain how this structure allows soap molecules to attach to oil and water at the same time, form micelles, and help wash the oil off the bowl.
7. Classify chemical reactions relevant to physiology. Look at this reaction: $HCl + NaHCO_3 \rightarrow NaCl + H_2CO_3 \rightarrow CO_2 + H_2O$ (First,

hydrochloric acid reacts with sodium bicarbonate. Then carbonic acid breaks down into carbon dioxide and water.)

a. Look only at the first part: $HCl + NaHCO_3 \rightarrow NaCl + H_2CO_3$:
   - What type of reaction is this? (For example: synthesis, decomposition, exchange/double replacement, or acid–base neutralization.). Explain your answer in simple words. What is swapping places in this reaction?

b. Now look at the second part: $H_2CO_3 \rightarrow CO_2 + H_2O$
   - What type of reaction is this? (For example: decomposition or synthesis.) Explain what is happening to H_2CO_3 in this step.

c. Overall, do you think the first part $HCl + NaHCO_3 \rightarrow NaCl + H_2CO_3$, is an exchange (double replacement) reaction? Answer **yes or no** and give a short reason using the **ions** that change partners.

8. Lemon juice has pH 2 and orange juice has pH 4.
   a. Which liquid is more acidic? Explain how you know this from the pH values.
   b. The pH scale is logarithmic: each 1-unit change in pH represents a 10-fold change in hydrogen ion concentration [H⊕].

      Using this idea, calculate how many times greater the [H⊕] is in lemon juice than in orange juice. Show your reasoning.
   c. A student says, “Lemon juice (pH 2) is only twice as acidic as orange juice (pH 4) because 4 – 2 = 2.” Explain why this reasoning is incorrect, and correct it using numbers.
9. Eli drinks a whole bottle of strong lemon juice (very acidic). Soon he feels dizzy and has trouble breathing. In the hospital, the nurse gives him IV sodium bicarbonate ($NaHCO_3$).
   a. Lemon juice adds a lot of acid (H⊕ ions) to Eli’s body.
      - Explain in simple words what happens to his blood pH when there is too much acid.
      - How does the body try to fix this by changing breathing rate (faster or slower)?
   b. In the blood, bicarbonate (HCO_3⊕) is part of this buffer system: H⊕ + HCO_3⊕ ⊕ H_2CO_3 ⊕ $CO_2 + H_2O$
      - Using this equation, explain how adding bicarbonate (HCO_3⊕) from the IV can help remove extra H⊕ and bring the blood pH closer to normal.
   c. The lungs breathe out CO_2.
   d. Explain how breathing out more CO_2 (faster or deeper breathing) also helps correct the acid problem in Eli’s blood.
10. Two glucose (sugar) molecules join together to make one maltose molecule. Each glucose has the formula: $C_6H_{12}O_6$. So we start with: Glucose + Glucose → Maltose + Water
    a. First, add the atoms before water is removed: Total C (carbon) atoms = 6 + 6 = ?; Total H (hydrogen) atoms = 12 + 12 = ?; Total O (oxygen) atoms = 6 + 6 = ?
    b. In dehydration synthesis, the two glucose molecules lose one water molecule (H_2O) to form a bond. Subtract the atoms in water (H_2O) from your totals in part Write the final chemical formula for maltose. State the number of C, H, and O atoms in one maltose molecule.
    c. In your own words, explain why water is produced in this reaction. Hint: One glucose gives an H and the other gives an OH (O–H). Together they form H_2O, and the remaining parts of the glucose molecules join together.
11. There are different types of lipids (fats) in the body, such as: Phospholipids, Triglycerides, Cholesterol. Choose two types of lipids from the list above. For each lipid you choose:
    a. Describe its structure in simple words. For example, you may mention:
       - Phospholipids: a “water-loving” (hydrophilic) head and two “water-fearing” (hydrophobic) fatty acid tails
       - Triglycerides: one glycerol backbone with three fatty acid chains; chains can be more or less saturated (with or without double bonds) and can be short or long
       - Cholesterol: a small molecule with a rigid ring structure (four fused rings) and a short tail
    b. Explain how this structure helps it do its job in the body. For example, you may link it to:
       - Phospholipids: forming cell membranes (bilayers), controlling what can pass in or out, affecting membrane fluidity
       - Triglycerides: long-term energy storage, cushioning and insulation of organs and under the skin
       - Cholesterol: helping to stabilize cell membranes and acting as a starting material (precursor) for steroid hormones like cortisol, estrogen, and testosterone
    c. Give one example of what might happen in the body if this lipid is: Very low (deficient), or Very high (excessive). Explain how the problem is related to its structure and function.

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2.9: Alternative Text Descriptions

Figure 2.1.1: Elements and Compounds

This figure combines a simplified body diagram and a table to show the elemental composition of the human body. The body diagram highlights the four most abundant elements:

- Oxygen: 65 percent
- Carbon: 18 percent
- Hydrogen: 10 percent
- Nitrogen: 3 percent

A small remaining category labeled "Others" represents the rest of the body's elements.

The table lists the elements, their chemical symbols, and their percentage in the body:

- Oxygen, **O**, 65.0
- Carbon, **C**, 18.5
- Hydrogen, **H**, 9.5
- Nitrogen, **N**, 3.2
- Calcium, **Ca**, 1.5
- Phosphorus, **P**, 1.0
- Potassium, **K**, 0.4
- Sulfur, **S**, 0.3
- Sodium, **Na**, 0.2
- Chlorine, **Cl**, 0.2
- Magnesium, **Mg**, 0.1

The table also notes that trace elements, each present in amounts less than 1.0 percent, include: boron, chromium, cobalt, copper, fluorine, iodine, iron, manganese, molybdenum, selenium, silicon, tin, vanadium, and zinc.

Figure 2.1.2: Two Models of Atomic Structure

This image contains two vertically arranged diagrams comparing two models of a helium atom: the planetary model at the top and the electron cloud model at the bottom. Labels identify key components in each model.

a. Planetary Model - The top diagram shows a simplified representation of a helium atom based on the planetary model. This model suggests that electrons move in fixed circular paths around the nucleus, similar to planets orbiting the sun.
   - At the center is a circular nucleus labeled **"**He", representing helium.
   - Surrounding the nucleus is a single circular orbit path drawn as a thin gray ring.
   - Two small spheres labeled "e" (electrons) are positioned on opposite sides of the orbit.
   - One electron includes a label reading "Electron," with a line pointing to the particle.
b. Electron Cloud Model: The bottom diagram illustrates a more modern representation of the helium atom using the electron cloud model. This model emphasizes that the exact position of electrons cannot be precisely determined; instead, electrons are likely to be found within a region of space.
   - At the center is the **nucleus**, consisting of clustered particles:
     - Two red spheres marked with plus signs represent **positively charged protons**.
     - Two neutral-colored spheres represent **neutrons**.
     - A label reading **"Nucleus"** points to this central cluster.
   - Surrounding the nucleus is a large, diffuse blue shaded region labeled **"Cloud of negative charge (2 electrons)"**.
   - The blue region gradually fades outward, indicating that electrons are not in fixed paths but exist in a probability-based distribution around the nucleus.

Figure 2.1.3: Isotopes of Hydrogen

The image compares the three isotopes of hydrogen: protium, deuterium, and tritium. The image is arranged in three side-by-side atom diagrams.

- On the left, protium, labeled 1H, shows a nucleus with one proton and no neutrons, with one electron shown outside the nucleus.
- In the center, deuterium, labeled 2H, shows a nucleus with one proton and one neutron, with one electron outside the nucleus.
- On the right, tritium, labeled 3H, shows a nucleus with one proton and two neutrons, with one electron outside the nucleus.

Each diagram uses a large circular orbit line around the nucleus to represent the electron shell. In all three isotopes, the atom has one electron, but the number of neutrons increases from left to right. The main concept illustrated is that all hydrogen isotopes have one proton and one electron, but they differ in the number of neutrons:

- protium: 0 neutrons
- deuterium: 1 neutron
- tritium: 2 neutrons

Figure 2.1.4: PET Scan

This image shows a medical imaging interface with multiple panels of PET/CT scans. The left column includes axial slices, while the center and right columns display coronal and sagittal views. Bright white and orange areas indicate regions of high metabolic activity, likely corresponding to tracer uptake. The scans reveal anatomical structures such as the spine, chest, and abdomen, with highlighted spots suggesting possible abnormal activity. The interface includes patient information fields, slice indicators, and imaging options.

Figure 2.1.5: Electron Shells

This image displays four Bohr models of atoms. Top left: hydrogen with one electron orbiting a nucleus labeled H. Top right: helium with two electrons around a nucleus labeled He. Bottom left: carbon with six electrons in two shells around a nucleus labeled C. Bottom right: neon with ten electrons in two shells around a nucleus labeled Ne. Each electron is shown as a blue sphere, and shells are represented by gray circles.

Figure 2.2.1: Sodium Chloride Formation

This image explains how ionic bonding forms between sodium and chlorine and how those ions arrange into a crystal structure. The image has three parts labeled (a), (b), and (c).

Part (a) - At the top, two atom diagrams are shown:

- on the left is a sodium atom, Na
- on the right is a chlorine atom, Cl

A single outer electron is shown moving from sodium to chlorine. This transfer is indicated by an arrow from the outer shell of sodium to the outer shell of chlorine.

Part (b) - In the middle, the result of the electron transfer is shown:

- sodium becomes Na+, meaning it has lost one electron and now has a net positive charge
- chlorine becomes Cl-, meaning it has gained one electron and now has a net negative charge

This part illustrates that ionic bonding forms when one atom loses an electron and another atom gains it, producing oppositely charged ions that attract each other.

Part (c) - At the bottom, a three-dimensional crystal lattice is shown.

- The lattice contains alternating sodium ions and chloride ions arranged in a repeating pattern. This represents the structure of an ionic solid, such as sodium chloride.
- The main idea of the image is that sodium transfers one electron to chlorine, forming Na+ and Cl-, and these oppositely charged ions then arrange in a repeating crystal lattice.

Figure 2.2.2: Covalent Bond

This image illustrates examples of covalent bonding, where atoms become stable by sharing electrons. The diagram has three labeled parts: (a), (b), and (c).

Part (a): Single covalent bond in hydrogen gas - Two hydrogen atoms are shown forming hydrogen gas, H2. Each hydrogen atom contributes one electron, and the two atoms share this pair of electrons. This creates one shared pair, which is a single covalent bond.

Part (b): Double covalent bond in oxygen gas - Two oxygen atoms are shown forming oxygen gas, O2. Each oxygen atom has six electrons in its valence shells and needs two more to become stable. The two oxygen atoms share two pairs of electrons, creating a double covalent bond.

Part (c): Two double covalent bonds in carbon dioxide - One carbon atom is shown between two oxygen atoms, forming carbon dioxide, CO2. Carbon has four valence electrons and needs four more to become stable. Each oxygen atom shares two pairs of electrons with carbon. This creates two double covalent bonds, one between carbon and each oxygen, often written as O=C=O.

Figure 2.2.3: Polar Covalent Bond

This image illustrates three representations of a water molecule, H2O, and highlights its uneven charge distribution.The image has three labeled parts:

Part (a): Planetary model of a water molecule

The top diagram shows one oxygen atom bonded to two hydrogen atoms. The oxygen atom is in the center, and the two hydrogen atoms are positioned at an angle rather than in a straight line.

The oxygen region is labeled weakly negative, marked with delta minus, δ–. Each hydrogen region is labeled weakly positive, marked with delta plus, δ+.

This part shows that electrons are drawn more strongly toward oxygen, making the oxygen end of the molecule partially negative and the hydrogen ends partially positive.

Part (b): Three-dimensional model

The lower left diagram shows a three-dimensional view of the same water molecule. The oxygen atom is larger and centered above the two hydrogen atoms, creating a bent shape. The oxygen side is labeled δ–, and the hydrogen sides are labeled δ+. This part emphasizes the molecule's shape and polarity.

Part (c): Structural formula

The lower right diagram shows a simplified structural formula with oxygen in the center connected to two hydrogen atoms. This is the standard structural representation of water.

Figure 2.2.4: Hydrogen Bonds

This image shows hydrogen bonding between water molecules. Solid lines represent covalent bonds within each water molecule between oxygen and hydrogen. Dashed lines represent hydrogen bonds between the hydrogen of one water molecule and the oxygen of another water molecule. The image's main idea is that water molecules are linked to one another by hydrogen bonds, while the atoms within each water molecule are held together by covalent bonds.

Figure 2.3.1: The Three Fundamental Chemical Reactions

This figure is a three-part diagram labeled a, b, and c. It uses word examples to illustrate three types of chemical reactions: synthesis, decomposition, and exchange. Each part includes a short sentence explanation and a word “equation” with an arrow showing what changes.

(a) Synthesis reaction

Text states: In a synthesis reaction, two components bond to make a larger molecule. Energy is required and is stored in the bond.
Below the text is the example:
Note + Book → Notebook
This shows two smaller parts combining into one larger product.

(b) Decomposition reaction

Text states: In a decomposition reaction, bonds between components of a larger molecule are broken, resulting in smaller products.
Below the text is the example:
Bookwork → Book + Worm
This shows one larger item breaking into two smaller parts.

(c) Exchange reaction

Text states: In an exchange reaction, bonds are both formed and broken so that the components of the reactants are rearranged.
Below the text is the example:
Notebook + Worm → Note + Bookworm
This shows parts being rearranged between two starting items to form two new products.

Figure 2.3.2: Enzymes

This figure compares the energy changes in the same chemical reaction without an enzyme and with an enzyme.

The image has two side-by-side graphs. In both graphs, the vertical axis is energy and the horizontal axis is progress of reaction. In each case, the reaction starts with reactants and ends with products, and the products are shown at a lower energy level than the reactants.

Left graph, labeled (a) - This graph shows the reaction without an enzyme. The energy curve rises to a high peak before dropping to the products. A label indicates that activation energy is required. This means the reaction needs a larger energy input to begin.

Right graph, labeled (b) - This graph shows the reaction with an enzyme. The energy curve still rises and then falls, but the peak is lower than in the left graph. A label indicates that less activation energy is required. This means the enzyme lowers the energy barrier needed to start the reaction.

Figure 2.4.1: Dehydration Synthesis and Hydrolysis Monomers

This image is a two-part diagram labeled (a) and (b) that compares dehydration synthesis and hydrolysis. Both parts use simplified shapes to represent two monomers and show how a covalent bond forms or breaks, along with the role of water

(a) Dehydration synthesis - Monomers are joined by removal of OH from one monomer and removal of H from the other at the site of bond formation. What the diagram shows:

- On the left are two separate ovals labeled Monomer 1 and Monomer 2, separated by a plus sign.
- Near the end of Monomer 1 is the label OH.
- Near the end of Monomer 2 is the label H (shown as part of an HO/H notation near the bonding site).
- An arrow points to the right, showing the reaction proceeding.
- Above the arrow is a water droplet labeled H2O, indicating that water is produced.
- On the right, the two monomers are now connected by a line with an O in the middle, representing a covalent bond linking

the monomers.
- Text beneath the O reads: “Monomers linked by covalent bond.”

(b) Hydrolysis - Monomers are released by the addition of a water molecule, adding OH to one monomer and H to the other. What the diagram shows:

- On the left, two monomers are already connected by a line with an O in the middle, labeled “Monomers linked by covalent bond.”
- An arrow points to the right, showing the reaction proceeding.
- Above the arrow is a water droplet labeled H2O, indicating that water is added as a reactant.
- On the right, the bond is broken and the diagram shows two separate ovals labeled Monomer 1 and Monomer 2, separated by a plus sign.
- The end of Monomer 1 is labeled OH, and the end of Monomer 2 is labeled H, showing that water has been split and its parts added to the two monomers.

Figure 2.4.2: Dissociation of Sodium Chloride in Water

This image illustrates the process by which water dissolves sodium chloride (NaCl) into ions and how water molecules surround those ions. The diagram is divided into three main visual sections: a single water molecule, a crystal lattice of sodium chloride, and hydrated ions in solution.

1. Top Left – Water Molecule: A single water molecule (H_2O) is shown. This indicates that water is a polar molecule, with uneven charge distribution.
   - One oxygen atom (O) is at the center.
   - Two hydrogen atoms (H) are attached at an angle.
   - The hydrogens are labeled with partial positive charges (δ⊕).
   - The oxygen is labeled with a partial negative charge (δ⊖).
2. Bottom Left – Sodium Chloride Crystal: A cubic structure labeled “Crystal of NaCl” shows a repeating arrangement of ions. This structure represents the solid form before dissolution.
   - Sodium ions (Na⊕) and chloride ions (Cl⊖) are arranged in an alternating pattern.
   - The ions form a regular lattice structure, representing solid table salt.
   - Labels indicate:
     - Na⊕ (positively charged sodium ions)
     - Cl⊖ (negatively charged chloride ions)
3. Right Side – Hydrated Ions in Solution
   - Two separate clusters show how water molecules surround ions after dissolution:
4. Hydrated Sodium Ion (Na⊕)
   - A central Na⊕ ion is surrounded by several water molecules.
   - The oxygen ends (δ⊖) of water molecules point toward the sodium ion.
   - This orientation occurs because the oxygen is negatively polarized and is attracted to the positive sodium ion.
   - The structure is labeled “Hydrated sodium ion.”
5. Hydrated Chloride Ion (Cl⊖)
   - A central Cl⊖ ion is surrounded by multiple water molecules.
   - The hydrogen ends (δ⊕) of water molecules point toward the chloride ion.
   - This orientation occurs because the hydrogens are positively polarized and are attracted to the negatively charged chloride ion.
   - The structure is labeled “Hydrated chloride ion.”
6. Arrows and Process
   - Arrows connect the NaCl crystal to the hydrated ions, indicating the dissolution process:
   - Solid NaCl separates into individual Na⊕ and Cl⊖ ions.
   - Water molecules reorganize around each ion to stabilize them in solution.

Figure 2.4.3: Acids and Bases

This image shows two pairs of beakers demonstrating how acids and bases behave in water. In the top pair, labeled (a), the first beaker contains acid layered above water. After mixing, the second beaker shows water with hydrogen ions (H⊕) dispersed throughout, indicating acid dissociation. In the bottom pair, labeled (b), the first beaker contains base above water. After mixing,

the second beaker shows water with hydroxide ions (OH^-), indicating base dissociation. Arrows between the beakers represent the process of mixing and ion formation.

Figure 2.4.4: pH scale

The figure shows a vertical pH scale ranging from 0 to 14. The lower end of the scale is labeled **Acid**, pH 7 is labeled **Neutral**, and the upper end is labeled **Base**. An arrow points downward toward increasing acidity and upward toward increasing basicity. Examples are placed along the scale as follows:

- pH 14: Liquid drain cleaner
- pH 13.5: Bleaches, oven cleaner, lye
- pH 10.5-11.5: Ammonia solution
- pH 9.5: Baking soda
- pH 8: Sea water
- pH 7.4: Blood
- pH 7: Neutral
- pH 6.3-6.6: Milk, urine, saliva
- pH 5: Black coffee
- pH 2.5-3.5: Grapefruit juice, soda, tomato juice
- pH 2: Lemon juice, vinegar
- pH 0: Battery acid, hydrochloric acid

The figure illustrates that substances with lower pH values are more acidic, substances with higher pH values are more basic (alkaline), and neutral substances are near pH 7.

Figure 2.5.1: Comparison of Monosaccharides

This image presents structural diagrams of five monosaccharides (simple sugars) arranged in two groups: hexoses (six-carbon sugars) at the top and pentoses (five-carbon sugars) at the bottom. Each structure is shown as a ring with labeled atoms and functional groups.

1. Top Row – (a) Hexoses: Three six-carbon sugars are shown, each with a ring structure and labeled substituents:
   - Glucose
     - A six-membered ring (hexagon shape).
     - Contains one oxygen atom in the ring.
     - Several hydroxyl groups (–OH) and hydrogen atoms (H) are attached at different positions.
     - A CH_2OH group extends above the ring.
     - The arrangement of –OH groups distinguishes glucose from other sugars.
   - Fructose
     - A five-membered ring (pentagon shape).
     - Contains one oxygen atom in the ring.
     - Has two CH_2OH groups attached at different carbon positions.
     - Includes multiple hydroxyl groups.The structure differs from glucose in ring size and placement of functional groups.
   - Galactose
     - A six-membered ring, similar in shape to glucose.
     - Contains one oxygen atom in the ring and a CH_2OH group.
     - The arrangement of hydroxyl groups differs slightly from glucose, showing a structural variation.
2. Bottom Row – (b) Pentoses: Two five-carbon sugars are shown with smaller ring structures:
   - Deoxyribose
     - A five-membered ring (pentagon).
     - Contains one oxygen atom in the ring.
     - Includes hydroxyl groups and hydrogen atoms.
     - One carbon lacks an oxygen-containing group (labeled H instead of OH), indicating it is “deoxy” (missing an oxygen).
   - Ribose
     - Also a five-membered ring.
     - Contains one oxygen atom in the ring.
     - Has more hydroxyl groups (–OH) compared to deoxyribose.

- The extra hydroxyl group is the key structural difference from deoxyribose.

Figure 2.5.2: Three Important Disaccharides

This image presents three labeled diagrams demonstrating how monosaccharides (single sugars) bond together to form disaccharides (two-sugar molecules). Each section is labeled (a), (b), and (c), and shows the individual sugar structures connected by an oxygen bridge.

a. Formation of Sucrose
   - The diagram title states: “The monosaccharides glucose and fructose bond to form sucrose.”
   - On the left is glucose, shown as a six-membered ring with hydroxyl (–OH) groups and a CH_2OH group.
   - On the right is fructose, shown as a five-membered ring with hydroxyl groups and two CH_2OH groups.
   - The two molecules are connected by a single oxygen atom (O) forming a glycosidic bond between them.
   - The resulting molecule is labeled “Sucrose.”
b. Formation of Lactose
   - The diagram title states: “The monosaccharides galactose and glucose bond to form lactose.”
   - On the left is galactose, shown as a six-membered ring with hydroxyl groups.
   - On the right is glucose, also a six-membered ring.
   - The two monosaccharides are linked by an oxygen bridge, forming a glycosidic bond.
   - The combined molecule is labeled “Lactose.”
c. Formation of Maltose
   - The diagram title states: “Two glucose monosaccharides bond to form maltose.”
   - Two glucose molecules, each shown as six-membered rings, are displayed side by side.
   - The two glucose units are connected by a central oxygen atom, forming a glycosidic bond.
   - The resulting disaccharide is labeled “Maltose.”

Figure 2.5.3: Three Important Polysaccharides

This image shows four polysaccharide structures. On the left, starch is represented by two forms: amylose, a straight chain of glucose units, and amylopectin, a branched chain. In the center, glycogen is shown as a highly branched structure, more complex than amylopectin. On the right, cellulose is depicted as multiple straight chains aligned in parallel, forming a rigid fiber structure. These arrangements highlight the differences in branching and organization among starch, glycogen, and cellulose, which affect their biological roles and digestibility.

Figure 2.5.4: Triglycerides

This image illustrates the process of triglyceride formation through dehydration synthesis, showing how glycerol reacts with three fatty acid chains to form a triglyceride (neutral fat) and three water molecules. The diagram is arranged from left to right:

- Reactants on the left (glycerol and fatty acids)
- A right-pointing arrow indicating a chemical reaction
- Products on the right (triglyceride and water molecules)

Headings at the top label each section are labeled as “Glycerol”, “3 fatty acid chains”, “Triglyceride, or neutral fat” and “3 water molecules”

1. Left Side – Reactants
   a. Glycerol - This structure provides three bonding sites for fatty acids.
      - A vertical three-carbon molecule is shown.
      - Each carbon is bonded to:
        - A hydrogen atom (H)
        - A hydroxyl group (–OH)
2. Three Fatty Acid Chains
   - Three long hydrocarbon chains are shown side by side.
   - Each chain includes:
     - A carboxyl group (–COOH) at one end

    - A long chain of repeating CH_2 units ending in CH_3
3. The hydroxyl group (–OH) on each fatty acid is positioned to react with glycerol.
4. Reaction – Dehydration Synthesis
    - Small circles highlight hydrogen (H) from glycerol and hydroxyl (OH) from fatty acids.
    - These combine to form water (H_2O).
    - This removal of water is called dehydration synthesis.
    - The diagram shows this occurring three times, once for each fatty acid.
5. Right Side – Products
    - Triglyceride (Neutral Fat)
        - The resulting molecule shows glycerol bonded to three fatty acid chains.
        - Each fatty acid is attached to glycerol through an ester linkage (–O–C=O–).
        - The structure resembles a vertical glycerol backbone with three long chains extending outward.
6. Water Molecules
    - A label indicates "3 H_2O" (three water molecules).
    - These are produced as byproducts of the reaction.

Figure 2.5.5: Fatty Acid Shapes

This image shows two molecular diagrams comparing saturated and unsaturated fatty acids. Each structure includes a carboxyl group on the left and a long hydrocarbon chain extending to the right. The image contains two labeled sections labeled as (a) Saturated at the top and (b) Unsaturated at the bottom.

- Both structures are displayed horizontally from left (functional group) to right (carbon chain).
- Atoms are labeled using chemical symbols (C for carbon, H for hydrogen, O for oxygen).

a. Saturated Fatty Acid:
    - The structure begins on the left with a carboxyl group (–COOH):
        - A carbon atom double-bonded to one oxygen (C=O)
        - The same carbon bonded to a hydroxyl group (–OH)
    - To the right of this group is a long chain of carbon atoms.
    - Each carbon atom is connected by single bonds only.
    - Every carbon in the chain is bonded to the maximum number of hydrogen atoms.
    - The chain appears straight and linear, with no bends.

Key feature:

- No carbon–carbon double bonds
- Fully "saturated" with hydrogen atoms

b. Unsaturated Fatty Acid
    - The structure also starts with a carboxyl group (–COOH) on the left.
    - A carbon chain extends to the right, but includes a key difference:
    - One or more carbon–carbon double bonds (C=C) are present.
    - The location of a double bond is highlighted in the diagram.
    - The presence of the double bond causes the chain to **bend or kink**, changing its shape.
    - Some hydrogen atoms are missing compared to the saturated structure because of the double bond.

Key features:

- At least one carbon–carbon double bond
- The chain is not straight; it has a visible bend

Figure 2.5.6: Other Important Lipids

This image presents three categories of lipids labeled (a), (b), and (c): phospholipids, sterols, and prostaglandins. Each section includes both structural diagrams and descriptive labels. The image is divided into three horizontal sections (a) Phospholipids at the top, (b) Sterols in the middle and (c) Prostaglandins at the bottom Each section contains labeled molecular structures and

explanatory text.

a. Phospholipids: “Two fatty acid chains and a phosphorus-containing group are attached to the glycerol backbone. Example: Phosphatidylcholine.” Structure Components:
   1. A glycerol backbone (central vertical component)
   2. A phosphorus-containing group attached to one end:
      - Labeled as the polar “head”
      - Includes a phosphate group with additional chemical groups
   3. Two fatty acid chains attached to the glycerol:
      - Labeled as nonpolar “tails”
      - One chain is straight (saturated-like)
      - One chain contains a bend (unsaturated-like with a double bond)

Schematic Representation is a simplified diagram shows a round polar head and a two wavy nonpolar tails. Phospholipids are amphipathic molecules with both hydrophilic (water-attracting) and hydrophobic (water-repelling) regions.

b. Sterols: “Four interlocking hydrocarbon rings from a steroid. Example: Cholesterol (cholesterol is the basis for all steroids formed in the body).” Structure Components:
   - A molecule composed of four fused rings:
     - Three hexagon-shaped rings
     - One pentagon-shaped ring

   - Several attached groups, including:
     - A hydroxyl group (–OH) on one end
   - Multiple CH_3 (methyl): Sterols have a rigid ring structure and play structural and signaling roles in biological systems.

c. Prostaglandins: Two example molecules are shown: $PGF_2\alpha$ and PGE_2. Structure Components:
   - Each molecule contains:
     - A five-membered ring
     - Two extended hydrocarbon chains branching from the ring
     - Functional groups such as:
       - Hydroxyl (–OH) groups
       - Carbonyl (C=O) group
       - Carboxyl (–COOH) group

Figure 2.5.7: General structure of an amino acid

This image shows the general chemical structure of an amino acid, highlighting its key functional groups and how they are arranged around a central carbon atom. Overall layout is:

- The diagram is divided into two labeled regions across the top:
  - “Amino group” on the left
  - “Carboxyl group” on the right
- At the center is a carbon atom labeled as the alpha (α) carbon, which connects all parts of the molecule.

1. Central Structure – Alpha Carbon
   - A central carbon atom (C) is shown in the middle of the diagram.
   - This carbon is labeled as the α (alpha) carbon, indicated by an arrow and text.
   - The alpha carbon forms four bonds, connecting to:
     - An amino group on the left
     - A carboxyl group on the right
     - A hydrogen atom above
     - A variable side chain (R group) below
2. Left Side – Amino Group: The amino group is responsible for the basic (proton-accepting) properties of amino acids.
   - The amino group consists of:
     - One nitrogen atom (N)
     - Two hydrogen atoms (H) attached to the nitrogen
     - This group is commonly written as $–NH_2$.

3. Right Side – Carboxyl Group: The carboxyl group provides the acidic (proton-donating) properties.
    - The carboxyl group contains:
        - One carbon atom double-bonded to an oxygen (C=O)
        - The same carbon bonded to a hydroxyl group (–OH)
        - This group is commonly written as –COOH.
4. Bottom – Side Chain (R Group)
    - Below the alpha carbon is a box labeled “R”, representing the side chain.
    - The side chain can vary in:
        - Size
        - Structure
        - Chemical properties
    - This variation determines the identity and function of each amino acid.

Figure 2.5.8: Peptide Bond

This image illustrates how two amino acids join to form a peptide bond through a dehydration (condensation) reaction. The diagram is arranged in two parts: reactants at the top and the resulting bonded structure at the bottom.

1. Top Section – Separate Amino Acids
    - Two individual amino acids are shown side by side.
    - Each amino acid contains:
        - An amino group ($–NH_2$) on the left
        - A central carbon atom (C) bonded to hydrogen
        - A carboxyl group (–COOH) on the right
2. Highlighted Reaction Area:
    - A boxed region highlights:
        - An **–**OH group from the carboxyl group of one amino acid
        - A hydrogen atom (H) from the amino group of the second amino acid
3. Bottom Section – Peptide Bond Formation
    - The two amino acids are now connected into a dipeptide.
    - A new bond forms between:
        - The carbon atom of the first amino acid’s carboxyl group
        - The nitrogen atom of the second amino acid’s amino group
    - This connection is labeled “Peptide Bond.”
4. Structural Features:
    - The linkage is shown as **–C–N–** with a double-bonded oxygen still attached to the carbon (C=O).
    - Each amino acid retains its **R group (side chain)**, labeled above the central carbon atoms.

Figure 2.5.9: Four levels of protein structure

This image illustrates the four levels of protein structure: primary, secondary, tertiary, and quaternary. The diagram progresses from a simple chain of amino acids to a complex, folded protein composed of multiple subunits. Arrows indicate progression from simpler to more complex levels of organization. Amino acids are represented as labeled spheres (A1 through A11).

a. Primary Structure: The primary structure is the linear sequence of amino acids linked by peptide bonds.
    - A straight horizontal chain of connected spheres labeled A1 to A11.
    - Each sphere represents an amino acid.
    - The label “Chain of amino acids” appears near this section.
b. Secondary Structure: Secondary structure refers to local folding patterns stabilized by hydrogen bonds. Two alternative folding patterns are illustrated.
    - Alpha-helix (left side)
        - The amino acid chain coils into a spiral shape.
        - Dotted lines connect amino acids that are not adjacent, representing hydrogen bonds that stabilize the helix.
    - Beta-pleated sheet (right side)
        - The chain folds into a zigzag, sheet-like structure.
        - Multiple strands lie side by side.
        - Dotted vertical lines labeled “bonds” indicate hydrogen bonding between strands.

c. Tertiary Structure: The tertiary structure represents the overall three-dimensional shape of a single protein molecule, formed by interactions among side chains.
   - A single polypeptide chain is shown folded into a complex three-dimensional shape.
   - The structure appears compact and globular.
   - A labeled heme unit (a circular structure with a central component) is embedded within the folded protein.

d. Quaternary Structure
   - Multiple folded protein units are grouped together to form a larger structure.
   - The example shown is labeled “Hemoglobin (globular protein)”.
   - Several subunits, each containing a heme group, are clustered together.

Figure 2.5.10: Enzyme action sequence

This image shows a step-by-step process of enzyme activity involving two substrates combining to form a product. The sequence is divided into four labeled panels: (a), (b), (c), and (d), arranged from left to right. Overall layout:

- A large green shape represents the enzyme in each panel.
- The enzyme contains a recessed area labeled “Active sites.”
- Two smaller shapes labeled S_1 and S_2 represent substrates.
- Arrows and labels describe the progression from substrates to product.

a. Substrates Bind to the Enzyme: Substrates bind to the enzyme’s active site based on shape compatibility.
   - Two separate substrate molecules, labeled S_1 and S_2, are shown above the enzyme.
   - Arrows point downward from each substrate to the enzyme.
   - The enzyme has specifically shaped active sites that match the substrates.

b. Substrates Fit into Active Site: The enzyme brings substrates together and facilitates their interaction.
   - The two substrates are now positioned within the enzyme’s active site.
   - A label states: “Substrates form a product.”
   - The enzyme holds both substrates in close proximity.

c. Product Formation: The enzyme catalyzes the reaction, converting substrates into a product.
   - A single combined shape labeled “Product” is shown within the enzyme’s active site.
   - The substrates have chemically reacted to form one product.

d. Product Release: Enzymes are reusable and can catalyze the same reaction multiple times.
   - The product is shown moving away from the enzyme.
   - A label states: “Product detaches and process can repeat.”
   - The enzyme remains unchanged and ready to bind new substrates.

Figure 2.5.11: Nucleotides

This image explains the structure of nucleotides and how they combine to form nucleic acids (DNA and RNA). Each base is shown with detailed chemical structures including carbon (C), nitrogen (N), oxygen (O), and hydrogen (H) atoms. The diagram is divided into three labeled sections: (a), (b), and (c), each focusing on a different component of nucleic acid structure.

1. Nucleotide Structure and Polynucleotide Chain - Nucleotides link through the sugar and phosphate groups to form long chains, with bases projecting from the backbone.A nucleotide is shown as consisting of three main components:
   - Phosphate group
     - Displayed as a circular group containing phosphorus (P) bonded to oxygen atoms.
     - Positioned to the left of the sugar.
   - Pentose sugar
     - Shown as a five-sided ring labeled “Pentose sugar.”
     - Located in the center of the nucleotide.
   - Nitrogenous base
     - Shown as a hexagonal or ring-like structure attached to the sugar.
     - Highlighted with a box labeled “Nitrogenous base.”
   - Polynucleotide Formation
     - Arrows indicate how nucleotides connect to form a chain.
     - The connection between nucleotides is labeled “Phosphodiester linkage.”
     - A vertical chain on the right shows repeating sugar–phosphate units forming a polynucleotide backbone, with bases

extending outward.

2. Nitrogenous Bases- This section shows two categories of nitrogen-containing bases:
   - Pyrimidines (single-ring structures)
     - Cytosine (C)
     - Thymine (T) — labeled “in DNA”
     - Uracil (U) — labeled “in RNA”
   - Purines (double-ring structures)
     - Adenine (A)
     - Guanine (G)
3. Pentose Sugars - Two types of five-carbon sugars are shown:
   - Deoxyribose (in DNA): Contains one fewer oxygen atom (missing an –OH group compared to ribose)
   - Ribose (in RNA): Contains an additional hydroxyl (–OH) group
   - Both sugars are drawn as five-membered rings with labeled atoms.

Figure 2.5.12: DNA

This image depicts the DNA double helix structure. Two strands twist around each other forming a spiral, with a sugar-phosphate backbone on the outside and nitrogenous bases paired inside. The base pairs include adenine (red) paired with thymine (yellow) and guanine (blue) paired with cytosine (green). Labels indicate the sugar-phosphate backbone and base pairs. A color key identifies each base type. This arrangement illustrates the complementary pairing and the helical shape of DNA.

Figure 2.5.13: Structure of Adenosine Triphosphate (ATP)

This image illustrates the structure of adenosine triphosphate (ATP) and related molecules, showing how its components are organized and how energy is stored in its bonds. The diagram is arranged horizontally from left to right. It shows three main components: Adenine (nitrogenous base) on the far left, Ribose (five-carbon sugar) in the center and Phosphate groups on the right. Labels at the bottom identify related molecules: AMP, ADP, and ATP.

1. Left Section – Adenine
   - A complex double-ring nitrogenous base labeled “Adenine.”
   - The structure includes nitrogen (N) and carbon (C) atoms arranged in rings.
   - Adenine is part of a larger unit called adenosine when combined with ribose.
2. Middle Section – Ribose Sugar
   - A five-membered ring labeled “Ribose.”
   - Contains oxygen and carbon atoms with attached hydrogen (H) and hydroxyl (–OH) groups.
   - Ribose connects:
     - Adenine on the left
     - Phosphate groups on the right
     - The combination of adenine + ribose is labeled “Adenosine.”
3. Right Section – Phosphate Groups
   - Three circular groups labeled as phosphate are connected in a chain.
   - Each phosphate contains phosphorus (P) bonded to oxygen atoms (O).
   - Red lines between phosphates are labeled “High-energy bonds.”
4. Bottom Labels – Related Molecules: Three labeled lines show increasing numbers of phosphate groups:
   - Adenosine monophosphate (AMP) → one phosphate
   - Adenosine diphosphate (ADP) → two phosphates
   - Adenosine triphosphate (ATP) → three phosphates

Figure 2.5.13: ATP Structure

This figure shows the chemical structure of adenosine triphosphate (ATP) and identifies its major components. ATP is made of three parts arranged from left to right: adenine, ribose, and three phosphate groups.

Adenine

On the left side of the figure is adenine, a nitrogen-containing ring structure made of connected carbon and nitrogen atoms. A

bracket above this part labels it as Adenine.

Ribose

In the center is ribose, a five-carbon sugar shown as a five-membered ring containing one oxygen atom. Ribose is connected to adenine. A bracket below this part labels it as Ribose.

Adenosine

A larger bracket spanning both adenine and ribose labels the combined structure as Adenosine.

Phosphate Groups

To the right of ribose are three phosphate groups connected in a chain. Each phosphate group contains a phosphorus atom surrounded by oxygen atoms. A bracket below these three groups labels this portion as Phosphate.

High-Energy Bonds

The bonds connecting adjacent phosphate groups are highlighted in red and labeled High-energy bonds. These bonds are commonly associated with the storage and transfer of energy in ATP.

Related Compounds

Additional brackets below the molecule identify related compounds based on the number of attached phosphate groups:

- Adenosine monophosphate (AMP): Adenosine plus one phosphate group
- Adenosine diphosphate (ADP): Adenosine plus two phosphate groups
- Adenosine triphosphate (ATP): Adenosine plus three phosphate groups

Summary

The figure illustrates how ATP is built from adenine, ribose, and three phosphate groups. It also shows the structural relationship among ATP, ADP, and AMP.

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3: THE CELLULAR LEVEL OF ORGANIZATION

Overview

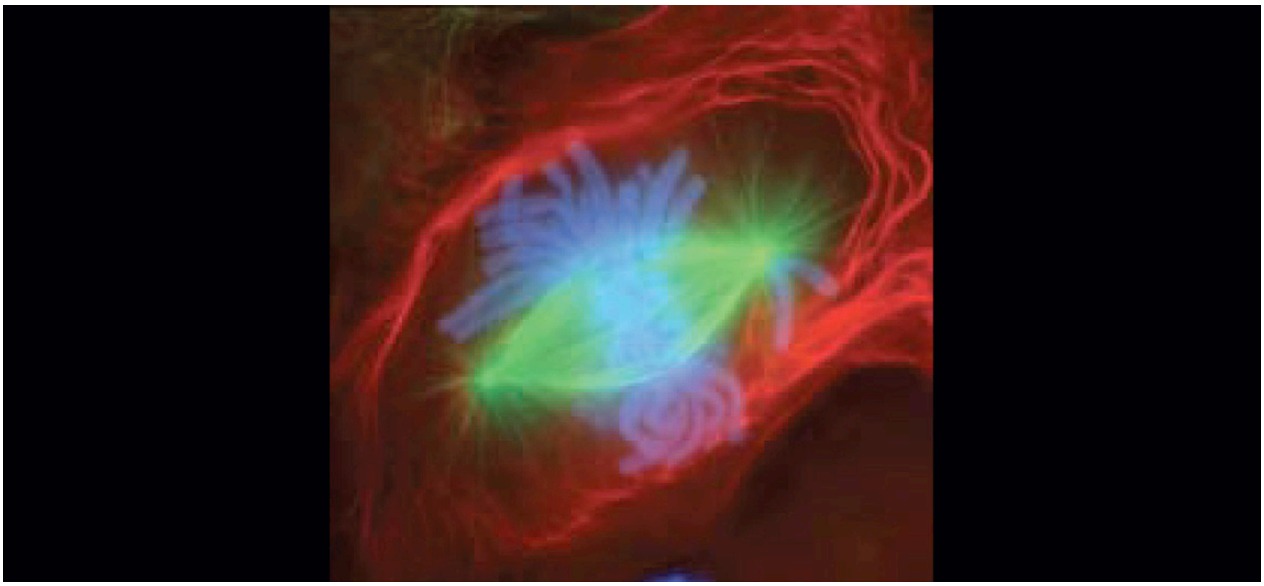


Figure 3.1: A lung cell from a newt, commonly studied for its similarity to human lung cells, is stained with fluorescent dyes. The green stain reveals mitotic spindles, red is the cell membrane and part of the cytoplasm, and the structures that appear light blue are chromosomes. This cell is in anaphase of mitosis. (CC BY-SA 4.0; via Wikimedia Commons).

Introduction to Eukaryotic Cells

Eukaryotes may be either single-celled or multicellular. In eukaryotes, the cell's genetic material, or DNA, is contained within an organelle called the nucleus, where it is organized in long molecules called chromosomes. Eukaryotic cells also contain other membrane-bound organelles (such as mitochondria, endoplasmic reticulum, Golgi apparatus) and non-membrane-bound organelles (such as ribosomes, cytoskeleton).

Structure and Function of the Cell Membrane

The cell membrane provides a barrier around the cell, separating its internal components from the extracellular environment. It is composed of a phospholipid bilayer, with hydrophobic internal lipid "tails" and hydrophilic external phosphate "heads." Various membrane proteins are scattered throughout the bilayer, both inserted within it and attached to it peripherally. The cell membrane is selectively permeable, allowing only a limited number of materials to diffuse through its lipid bilayer.

Passive and Active Transport Across the Membrane

All materials that cross the membrane do so using passive (non energy-requiring) or active (energy-requiring) transport processes. During passive transport, materials move by simple diffusion or by facilitated diffusion through the membrane, down their concentration gradient. Water passes through the membrane in a diffusion process called osmosis. During active transport, energy is expended to assist material movement across the membrane in a direction against their concentration gradient. Active transport may take place with the help of protein pumps or through the use of vesicles.

Cytosol, Cytoplasm, and the Endomembrane System

The internal environment of a living cell is made up of a jelly-like fluid, called cytosol, which consists mainly of water, but also contains various dissolved nutrients and other molecules. The cell contains an array of cellular organelles, each one performing a unique function and helping to maintain the health and activity of the cell. The cytosol and organelles together

compose the cell's cytoplasm. Most organelles are surrounded by a lipid membrane similar to the cell membrane of the cell. The endoplasmic reticulum (ER), Golgi apparatus, and lysosomes share a functional connectivity and are collectively referred to as the endomembrane system.

Endoplasmic Reticulum, Golgi Apparatus, and Lysosomes

There are two types of ER: smooth and rough. While the smooth ER performs many functions, including lipid synthesis and ion storage, the rough ER is mainly responsible for protein synthesis using its associated ribosomes. The rough ER sends newly made proteins to the Golgi apparatus where they are modified and packaged for delivery to various locations within or outside of the cell. Some of these protein products are enzymes destined to break down unwanted material and are packaged as lysosomes for use inside the cell.

Mitochondria, Peroxisomes, and the Cytoskeleton

Cells also contain mitochondria and peroxisomes, which are the organelles responsible for producing the cell's energy supply and detoxifying certain chemicals, respectively. Biochemical reactions within mitochondria transform energy-carrying molecules into the usable form of cellular energy known as ATP. Peroxisomes contain enzymes that transform harmful substances such as free radicals into oxygen and water. Cells also contain a miniaturized "skeleton" of protein filaments that extend throughout its interior. Three different kinds of filaments compose this cytoskeleton (in order of increasing thickness): microfilaments, intermediate filaments, and microtubules. Each cytoskeletal component performs unique functions as well as provides a supportive framework for the cell.

Nucleus and Nuclear Envelope

The nucleus is the command center of the cell, containing the genetic instructions for all of the materials a cell will make (and thus all of its functions it can perform). The nucleus is encased within a membrane of two interconnected lipid bilayers, side-by-side. This nuclear envelope is studded with protein-lined pores that allow materials to be trafficked into and out of the nucleus.

Nucleolus, Chromatin, and Chromosomes

The nucleus contains one or more nucleoli, which serve as sites for ribosome synthesis. The nucleus houses the genetic material of the cell: DNA. DNA is normally found as a loosely contained structure called chromatin within the nucleus, where it is wound up and associated with a variety of histone proteins. When a cell is about to divide, the chromatin coils tightly and condenses to form chromosomes.

DNA Replication Before Cell Division

There is a pool of cells constantly dividing within your body. The result is billions of new cells being created each day. Before any cell is ready to divide, it must replicate its DNA so that each new daughter cell will receive an exact copy of the organism's genome. A variety of enzymes are enlisted during DNA replication. These enzymes unwind the DNA molecule, separate the two strands, and assist with the building of complementary strands along each parent strand. The original DNA strands serve as templates from which the nucleotide sequence of the new strands are determined and synthesized. When replication is completed, two identical DNA molecules exist. Each one contains one original strand and one newly synthesized complementary strand.

From DNA to Protein: Transcription and Translation

DNA stores the information necessary for instructing the cell to perform all of its functions. Cells use the genetic code stored within DNA to build proteins, which ultimately determine the structure and function of the cell. This genetic code lies in the particular sequence of nucleotides that make up each gene along the DNA molecule. To "read" this code, the cell must perform two sequential steps. In the first step, transcription, the DNA code is converted into an RNA code. A molecule of messenger RNA that is complementary to a specific gene is synthesized in a process similar to DNA replication. The molecule of mRNA provides the code to synthesize a protein. In the process of translation, the mRNA attaches to a ribosome. Next, tRNA molecules shuttle the appropriate amino acids to the ribosome, one-by-one, coded by sequential triplet codons on the mRNA, until the protein is fully synthesized. When completed, the mRNA detaches from the ribosome, and the protein is released. Typically, multiple ribosomes

attach to a single mRNA molecule at once such that multiple proteins can be manufactured from the mRNA concurrently.

The Cell Cycle and Its Regulation

The life of cell consists of stages that make up the cell cycle. After a cell is born, it passes through an interphase before it is ready to replicate itself and produce daughter cells. This interphase includes two gap phases (G1 and G2), as well as an S phase, during which its DNA is replicated in preparation for cell division. The cell cycle is under precise regulation by chemical messengers both inside and outside the cell that provide “stop” and “go” signals for movement from one phase to the next. Failures of these signals can result in cells that continue to divide uncontrollably, which can lead to cancer.

Mitosis and Cytokinesis

Once a cell has completed interphase and is ready for cell division, it proceeds through four separate stages of mitosis (prophase, metaphase, anaphase, and telophase). Telophase is followed by the division of the cytoplasm (cytokinesis), which generates two daughter cells. This process takes place in all normally dividing cells of the body except for the germ cells that produce eggs and sperm.

Cell Differentiation and Stem Cells

One of the major areas of research in biology is that of how cells specialize to assume their unique structures and functions, since all cells essentially originate from a single fertilized egg. Cell differentiation is the process of cells becoming specialized as the body develops. A stem cell is an unspecialized cell that can divide without limit as needed and can, under specific conditions, differentiate into specialized cells. Stem cells are divided into several categories according to their potential to differentiate.

Gene Expression and Cellular Specialization

While all somatic cells contain the exact same genome, different cell types only express some of those genes at any given time. These differences in gene expression ultimately dictate a cell’s unique morphological and physiological characteristics. The primary mechanism that determines which genes will be expressed and which ones will not is through the use of different transcription factor proteins, which bind to DNA and promote or hinder the transcription of different genes. Through the action of these transcription factors, cells specialize into one of hundreds of different cell types in the human body.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own. By the end of this chapter, students should be able to:

- Investigate the cellular basis of life, explaining how normal cell structure and function support health, and relate basic cytology concepts to clinical and scientific examples of aging and disease,
- Describe the structure of the cell membrane and relate it to how materials move across the membrane, distinguishing and explaining passive (diffusion, osmosis, filtration, facilitated diffusion) and active (active transport, endocytosis, exocytosis) transport mechanism,
- Recognize and describe the roles of selected cytoplasmic organelles (e.g., ER, Golgi apparatus, lysosomes, mitochondria, peroxisomes, cytoskeleton) in performing specialized cell functions such as protein synthesis, secretion, energy production, and intracellular digestion,
- Summarize how genes code for proteins and thereby determine cell and tissue function, by outlining the key steps and players in transcription and translation,
- Explain the structure and contents of the nucleus, including chromatin, chromosomes, and nucleoli; describe the basic steps of DNA replication; and list and describe the phases of mitosis, relating each stage to its purpose in producing genetically identical daughter cells,
- Discuss the normal genetic and chromosomal control mechanisms that regulate cell replication (e.g., checkpoints, cell cycle regulators, tumor suppressor genes, proto-oncogenes)

- Discuss how alterations in normal chromosomal and genetic control of cell division contribute to cancer development and other disorders of aging, and describe, at an introductory level, how understanding these alterations is used or may be used to design current and emerging treatments.

3.1: The Cell Membrane
3.2: The Cytoplasm and Cellular Organelles
3.3: The Nucleus and DNA Replication
3.4: Protein Synthesis
3.5: Cell Growth and Division
3.6: Cellular Differentiation
3.7: Terms and Definitions
3.8: Chapter Review Questions
3.9: Applied Thinking - Self Assessment
3.10: Alternative Text Descriptions

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3.1: The Cell Membrane

Structure and Composition of the Cell Membrane

The cell membrane is an extremely pliable structure composed primarily of back-to-back phospholipids (a “bilayer”). Cholesterol is also present, which contributes to the fluidity of the membrane, and there are various proteins embedded within the membrane that have a variety of functions.

A single phospholipid molecule has a phosphate group on one end, called the “head,” and two side-by-side chains of fatty acids that make up the lipid tails (Figure 3.1.1). The phosphate group is negatively charged, making the head polar and hydrophilic—or “water loving.” A hydrophilic molecule (or region of a molecule) is one that is attracted to water. The phosphate heads are thus attracted to the water molecules of both the extracellular and intracellular environments. The lipid tails, on the other hand, are uncharged, or nonpolar, and are hydrophobic—or “water fearing.” A hydrophobic molecule (or region of a molecule) repels and is repelled by water. Some lipid tails consist of saturated fatty acids and some contain unsaturated fatty acids. This combination adds to the fluidity of the tails that are constantly in motion. Phospholipids are thus amphipathic molecules. An amphipathic molecule is one that contains both a hydrophilic and a hydrophobic region. In fact, soap works to remove oil and grease stains because it has amphipathic properties. The hydrophilic portion can dissolve in water while the hydrophobic portion can trap grease in micelles that then can be washed away.

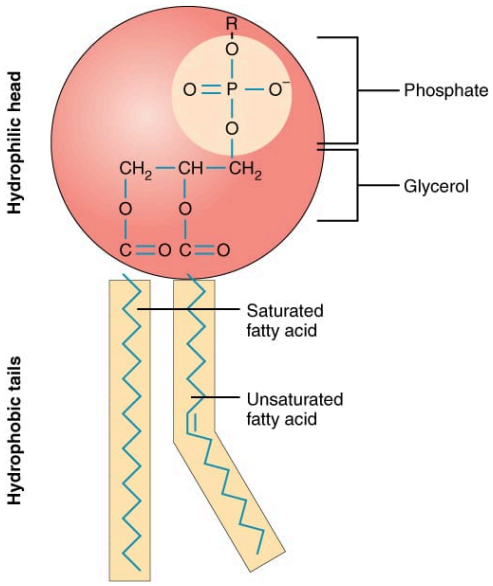


Figure 3.1.1: The molecule has a hydrophilic head made of phosphate and glycerol and two hydrophobic fatty acid tails. One tail is saturated and straight, and the other is unsaturated and bent. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.1.

The cell membrane consists of two adjacent layers of phospholipids. The lipid tails of one layer face the lipid tails of the other layer, meeting at the interface of the two layers. The phospholipid heads face outward, one layer exposed to the interior of the cell and one layer exposed to the exterior (Figure 3.1.2). Because the phosphate groups are polar and hydrophilic, they are attracted to water in the intracellular fluid. Intracellular fluid (ICF) is the fluid interior of the cell. The phosphate groups are also attracted to the extracellular fluid. Extracellular fluid (ECF) is the fluid environment outside the enclosure of the cell membrane. Interstitial fluid (IF) is the term given to extracellular fluid not contained within blood vessels. Because the lipid tails are hydrophobic, they meet in the inner region of the membrane, excluding watery intracellular and extracellular fluid from this space. The cell membrane has many proteins, as well as other lipids (such as cholesterol), that are associated with the phospholipid bilayer. An important feature of the membrane is that it remains fluid; the lipids and proteins in the cell membrane are not rigidly locked in place.

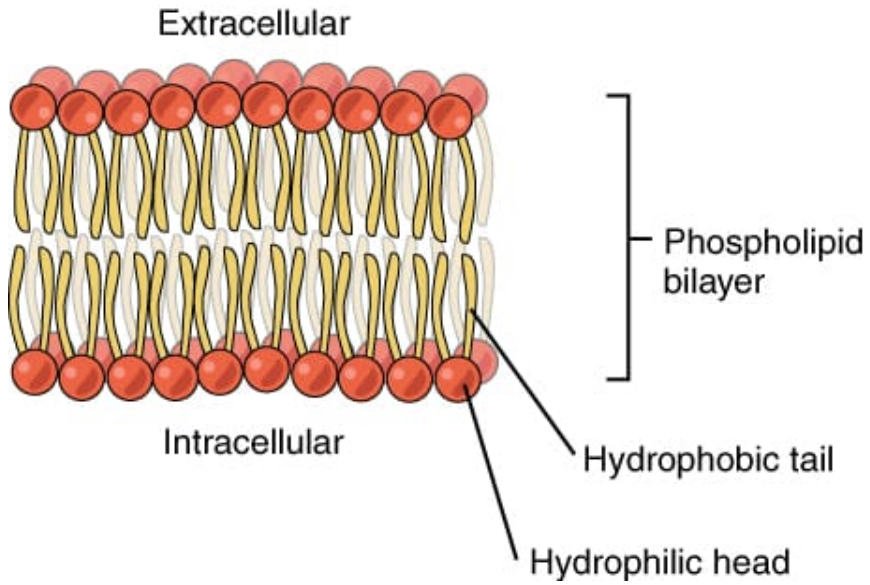


Figure 3.1.2: The phospholipid bilayer consists of two adjacent sheets of phospholipids, arranged tail to tail. The hydrophobic tails associate with one another, forming the interior of the membrane. The polar heads contact the fluid inside and outside of the cell. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.2.

Membrane Proteins

The lipid bilayer forms the basis of the cell membrane, but it is peppered throughout with various proteins. Two different types of proteins that are commonly associated with the cell membrane are the integral proteins and peripheral protein (Figure 3.1.3). As its name suggests, an integral protein is a protein that is embedded in the membrane. A channel protein is an example of an integral protein that selectively allows particular materials, such as certain ions, to pass into or out of the cell.

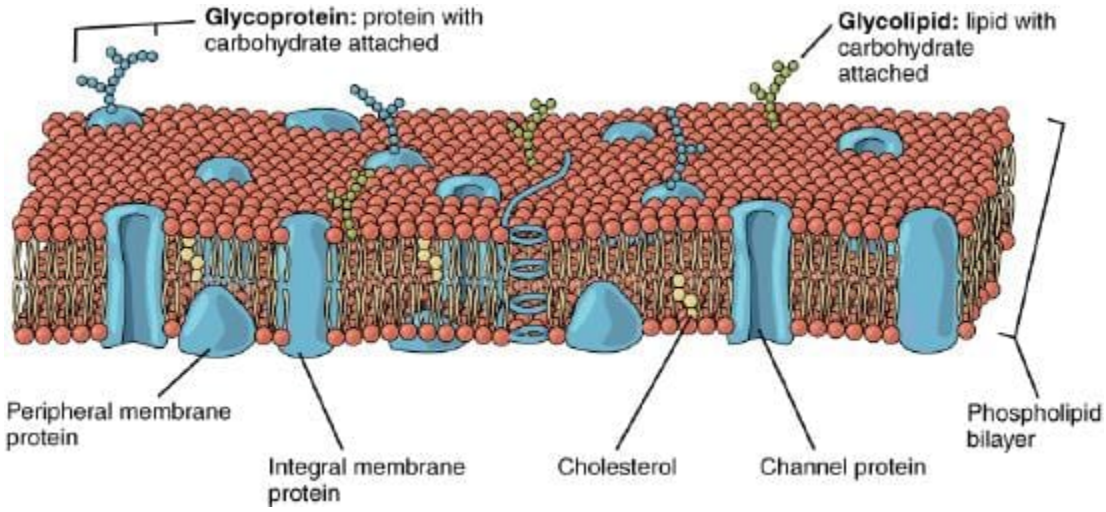


Figure 3.1.3: The cell membrane of the cell is a phospholipid bilayer containing many different molecular components, including proteins and cholesterol, some with carbohydrate groups attached. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.3.

Another important group of integral proteins are cell recognition proteins, which serve to mark a cell's identity so that it can be recognized by other cells. A receptor is a type of recognition protein that can selectively bind a specific molecule outside the cell, and this binding induces a chemical reaction within the cell. A ligand is the specific molecule that binds to and activates a receptor. Some integral proteins serve dual roles as both a receptor and an ion channel. One example of a receptor-ligand interaction is the receptors on nerve cells that bind neurotransmitters, such as dopamine. When a dopamine molecule binds to a dopamine receptor protein, a channel within the transmembrane protein opens to allow certain ions to flow into the cell.

Some integral membrane proteins are glycoproteins. A glycoprotein is a protein that has carbohydrate molecules attached, which extend into the extracellular matrix. The attached carbohydrate tags on glycoproteins aid in cell recognition. The carbohydrates that extend from membrane proteins and even from some membrane lipids collectively form the glycocalyx. The glycocalyx is a fuzzy-appearing coating around the cell formed from glycoproteins and other carbohydrates attached to the cell membrane. The glycocalyx can have various roles. For example, it may have molecules that allow the cell to bind to another cell, it may contain receptors for hormones, or it might have enzymes to break down nutrients. The glycocalyces found in a person's body are products of that person's genetic makeup. They give each of the individual's trillions of cells the "identity" of belonging in the person's body. This identity is the primary way that a person's immune defense cells "know" not to attack the person's own body cells, but it also is the reason organs donated by another person might be rejected.

Peripheral proteins are typically found on the inner or outer surface of the lipid bilayer but can also be attached to the internal or external surface of an integral protein. These proteins typically perform a specific function for the cell. Some peripheral proteins on the surface of intestinal cells, for example, act as digestive enzymes to break down nutrients to sizes that can pass through the cells and into the bloodstream.

Transport Across the Cell Membrane

One of the great wonders of the cell membrane is its ability to regulate the concentration of substances inside the cell. These substances include ions such as Ca^{++}, Na^{+}, K^{+}, and Cl^{-}; nutrients including sugars, fatty acids, and amino acids; and waste products, particularly carbon dioxide (CO_2), which must leave the cell.

The membrane's lipid bilayer structure provides the first level of control. The phospholipids are tightly packed together, and the membrane has a hydrophobic interior. This structure causes the membrane to be selectively permeable. A membrane that has selective permeability allows only substances meeting certain criteria to pass through it unaided. In the case of the cell membrane, only relatively small, nonpolar materials can move through the lipid bilayer (remember, the lipid tails of the membrane are nonpolar). Some examples of these are other lipids, oxygen and carbon dioxide gases, and alcohol. However, water-soluble materials—like glucose, amino acids, and electrolytes—need some assistance to cross the membrane because they are repelled by the hydrophobic tails of the phospholipid bilayer. All substances that move through the membrane do so by one of two general methods, which are categorized based on whether or not energy is required. Passive transport is the movement of substances across the membrane without the expenditure of cellular energy. In contrast, active transport is the movement of substances across the membrane using energy from adenosine triphosphate (ATP).

Passive Transport

In order to understand *how* substances move passively across a cell membrane, it is necessary to understand concentration gradients and diffusion. A concentration gradient is the difference in concentration of a substance across a space. Molecules (or ions) will spread/diffuse from where they are more concentrated to where they are less concentrated until they are equally distributed in that space. (When molecules move in this way, they are said to move *down* their concentration gradient.) Diffusion is the movement of particles from an area of higher concentration to an area of lower concentration. A couple of common examples will help to illustrate this concept. Imagine being inside a closed bathroom. If a bottle of perfume were sprayed, the scent molecules would naturally diffuse from the spot where they left the bottle to all corners of the bathroom, and this diffusion would go on until no more concentration gradient remains. Another example is a spoonful of sugar placed in a cup of tea. Eventually the sugar will diffuse throughout the tea until no concentration gradient remains. In both cases, if the room is warmer or the tea hotter, diffusion occurs even faster as the molecules are bumping into each other and spreading out faster than at cooler temperatures. Having an internal body temperature around 98.6° F thus also aids in diffusion of particles within the body.

Whenever a substance exists in greater concentration on one side of a semipermeable membrane, such as the cell membranes, any substance that can move down its concentration gradient across the membrane will do so. Consider substances that can easily diffuse through the lipid bilayer of the cell membrane, such as the gases oxygen (O_2) and CO_2. O_2 generally diffuses into cells because it is more concentrated outside of them, and CO_2 typically diffuses out of cells because it is more concentrated inside of them. Neither of these examples requires any energy on the part of the cell, and therefore they use passive transport to move across the membrane.

Before moving on, you need to review the gases that can diffuse across a cell membrane. Because cells rapidly use up oxygen during metabolism, there is typically a lower concentration of O_2 inside the cell than outside. As a result, oxygen will diffuse from the interstitial fluid directly through the lipid bilayer of the membrane and into the cytoplasm within the cell. On the other hand, because cells produce CO_2 as a byproduct of metabolism, CO_2 concentrations rise within the cytoplasm; therefore, CO_2 will move

from the cell through the lipid bilayer and into the interstitial fluid, where its concentration is lower. This mechanism of molecules moving across a cell membrane from the side where they are more concentrated to the side where they are less concentrated is a form of passive transport called simple diffusion (Figure 3.1.4).

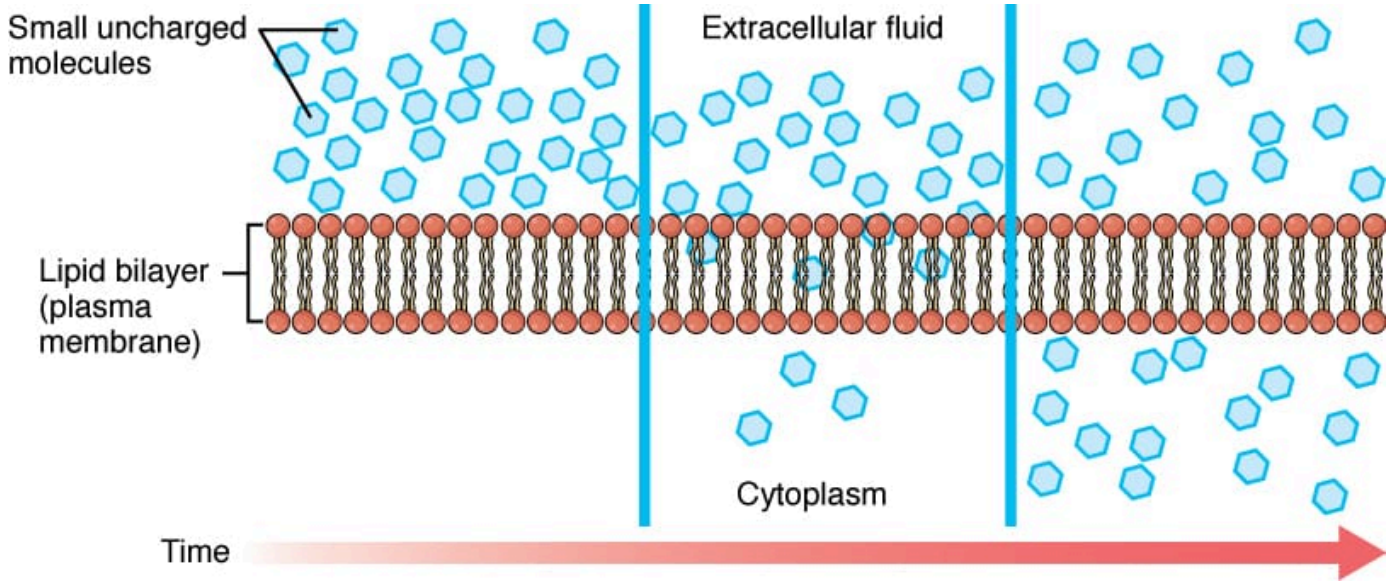


Figure 3.1.4: The structure of the lipid bilayer allows small, uncharged substances such as oxygen and carbon dioxide, and hydrophobic molecules such as lipids, to pass through the cell membrane, down their concentration gradient, by simple diffusion. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.4.

Large polar or ionic molecules, which are hydrophilic, cannot easily cross the phospholipid bilayer. Very small polar molecules, such as water, can cross via simple diffusion due to their small size. Charged atoms or molecules of any size cannot cross the cell membrane via simple diffusion as the charges are repelled by the hydrophobic tails in the interior of the phospholipid bilayer. Solutes dissolved in water on either side of the cell membrane will tend to diffuse down their concentration gradients, but because most substances cannot pass freely through the lipid bilayer of the cell membrane, their movement is restricted to protein channels and specialized transport mechanisms in the membrane. Facilitated diffusion is the diffusion process used for those substances that cannot cross the lipid bilayer due to their size, charge, and/or polarity (Figure 3.1.5). A common example of facilitated diffusion is the movement of glucose into the cell, where it is used to make ATP. Although glucose can be more concentrated outside of a cell, it cannot cross the lipid bilayer via simple diffusion because it is both large and polar. To resolve this, a specialized carrier protein called the glucose transporter will transfer glucose molecules into the cell to facilitate its inward diffusion.

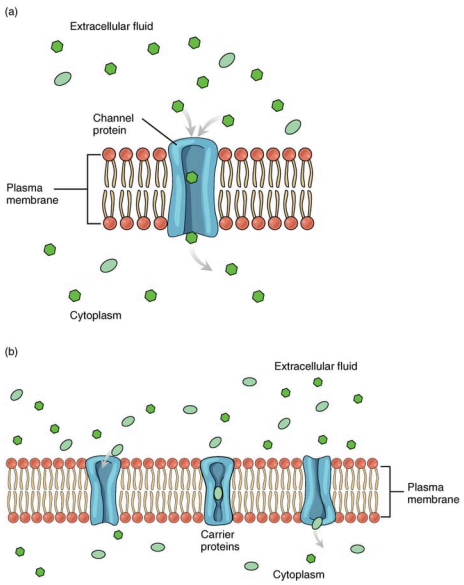


Figure 3.1.5: (a) Facilitated diffusion of substances crossing the cell (plasma) membrane takes place with the help of proteins such as channel proteins and carrier proteins. Channel proteins are less selective than carrier proteins, and usually mildly discriminate between their cargo based on size and charge. (b) Carrier proteins are more selective, often only allowing one particular type of molecule to cross. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.5.

As an example, even though sodium ions (Na^+) are highly concentrated outside of cells, these electrolytes are charged and cannot pass through the nonpolar lipid bilayer of the membrane. Their diffusion is facilitated by membrane proteins that form sodium channels (or "pores"), so that Na^+ ions can move down their concentration gradient from outside the cells to inside the cells. There are many other solutes that must undergo facilitated diffusion to move into a cell, such as amino acids, or to move out of a cell, such as wastes. Because facilitated diffusion is a passive process, it does not require energy expenditure by the cell.

Water also can move freely across the cell membrane of all cells, either through protein channels or by slipping between the lipid tails of the membrane itself. Osmosis is the diffusion of water through a semipermeable membrane (Figure 3.1.6).

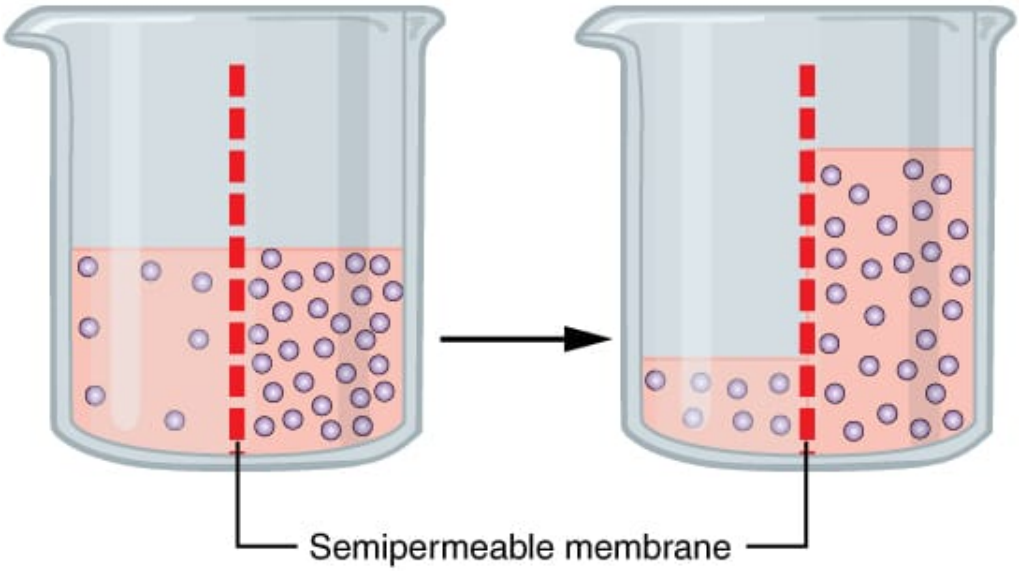


Figure 3.1.6: Osmosis is the diffusion of water through a semipermeable membrane down its concentration gradient. If a membrane is permeable to water, though not to a solute, water will equalize its own concentration by diffusing to the side of lower water concentration (and thus the side of higher solute concentration). In the beaker on the left, the solution on the right side of the membrane is hypertonic. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.6.

The movement of water molecules is not itself regulated by some cells, so it is important that these cells are exposed to an environment in which the concentration of solutes outside of the cells (in the extracellular fluid) is equal to the concentration of solutes inside the cells (in the cytoplasm). Two solutions that have the same concentration of solutes are said to be isotonic (equal tension). When cells and their extracellular environments are isotonic, the concentration of water molecules is the same outside and inside the cells, and the cells maintain their normal shape (and function).

Osmosis occurs when there is an imbalance of solutes outside of a cell versus inside the cell. A solution that has a higher concentration of solutes than another solution is said to be hypertonic, and water molecules tend to diffuse into a hypertonic solution (Figure 3.1.7). Cells in a hypertonic solution will shrivel as water leaves the cell via osmosis. In contrast, a solution that has a lower concentration of solutes than another solution is said to be hypotonic, and water molecules tend to diffuse out of a hypotonic solution. Cells in a hypotonic solution will take on too much water and swell, with the risk of eventually bursting. A critical aspect of homeostasis in living things is to create an internal environment in which all of the body's cells are in an isotonic solution. Various organ systems, particularly the kidneys, work to maintain this homeostasis.

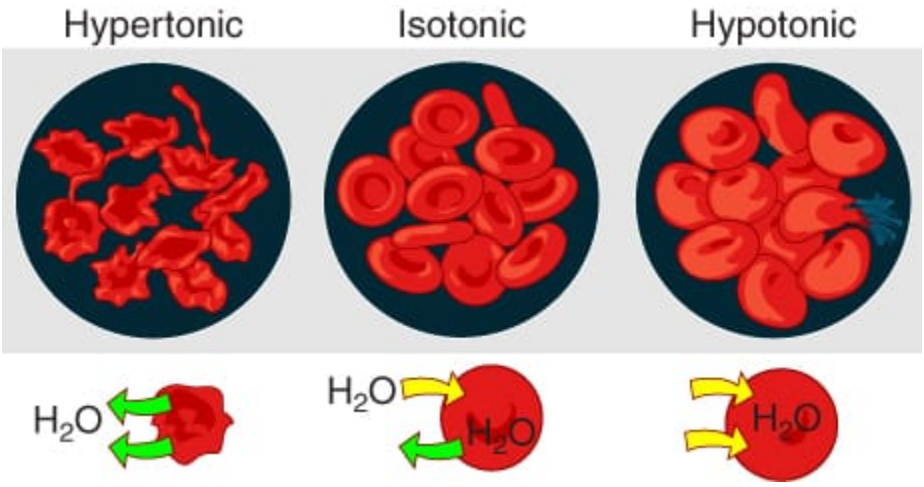


Figure 3.1.7: A hypertonic solution has a solute concentration higher than another solution. An isotonic solution has a solute concentration equal to another solution. A hypotonic solution has a solute concentration lower than another solution. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.7.

Another mechanism besides diffusion to passively transport materials between compartments is filtration. Unlike diffusion of a substance from where it is more concentrated to less concentrated, filtration uses a hydrostatic pressure gradient that pushes the fluid—and the solutes within it—from a higher pressure area to a lower pressure area. Filtration is an extremely important process in the body. For example, the circulatory system uses filtration to move plasma and substances across the endothelial lining of capillaries and into surrounding tissues, supplying cells with the nutrients. Filtration pressure in the kidneys provides the mechanism to remove wastes from the bloodstream.

Active Transport

For all of the transport methods described above, the cell expends no energy. Membrane proteins that aid in the passive transport of substances do so without the use of ATP. During active transport, ATP is required to move a substance across a membrane, often with the help of protein carriers, and usually *against* its concentration gradient.

One of the most common types of active transport involves proteins that serve as pumps. The word "pump" probably conjures up thoughts of using energy to pump up the tire of a bicycle or a basketball. Similarly, energy from ATP is required for these membrane proteins to transport substances—molecules or ions—across the membrane, usually against their concentration gradients (from an area of low concentration to an area of high concentration).

The sodium-potassium pump, which is also called Na^+/K^+ ATPase, transports sodium out of a cell while moving potassium into the cell. The Na^+/K^+ pump is an important ion pump found in the membranes of many types of cells. These pumps are particularly abundant in nerve cells, which are constantly pumping out sodium ions and pulling in potassium ions to maintain an electrical gradient across their cell membranes. An electrical gradient is a difference in electrical charge across a space. In the case of nerve cells, for example, the electrical gradient exists between the inside and outside of the cell, with the inside being negatively-charged (at around -70 mV) relative to the outside. The negative electrical gradient is maintained because each Na^+/K^+ pump

moves three Na^+ ions out of the cell and two K^+ ions into the cell for each ATP molecule that is used (Figure 3.1.8). This process is so important for nerve cells that it accounts for the majority of their ATP usage.

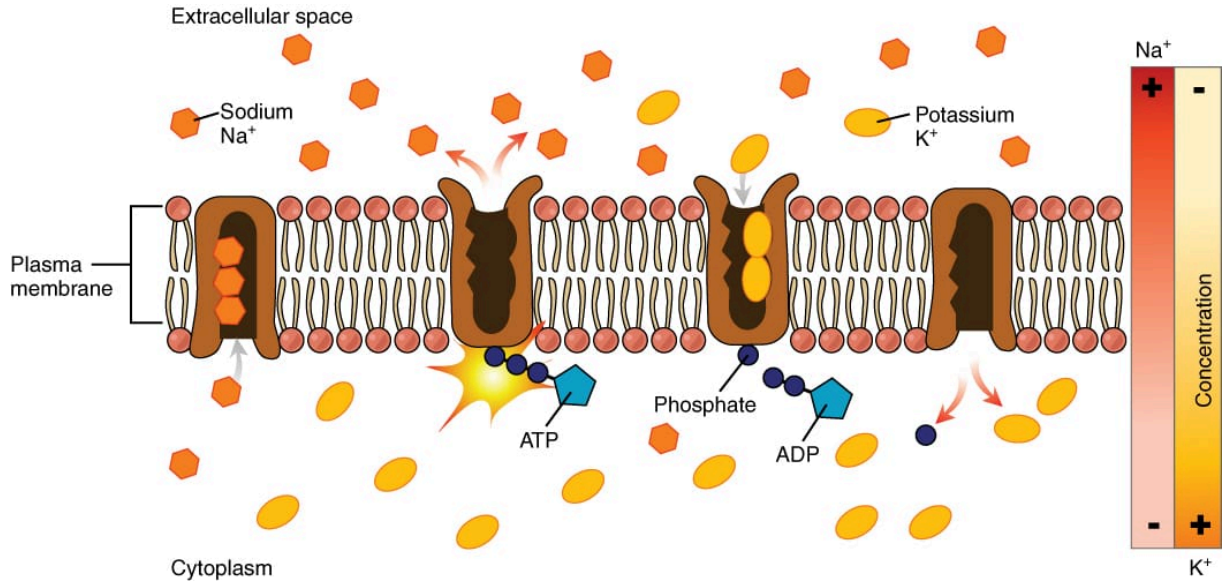


Figure 3.1.8: The sodium-potassium pump is found in many cell (plasma) membranes. Powered by ATP, the pump moves sodium and potassium ions in opposite directions, each against its concentration gradient. In a single cycle of the pump, three sodium ions are extruded from and two potassium ions are imported into the cell. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.8.

Active transport pumps can also work together with other active or passive transport systems to move substances across the membrane. For example, the sodium-potassium pump maintains a high concentration of sodium ions outside of the cell. Therefore, if the cell needs sodium ions, all it has to do is open a passive sodium channel, as the concentration gradient of the sodium ions will drive them to diffuse into the cell. In this way, the action of an active transport pump (the sodium-potassium pump) powers the passive transport of sodium ions by creating a concentration gradient. When active transport powers the transport of another substance in this way, it is called secondary active transport.

Symporters are secondary active transporters that move two substances in the same direction. For example, the sodium-glucose symporter uses sodium ions to “pull” glucose molecules into the cell. Because cells store glucose for energy, glucose is typically at a higher concentration inside of the cell than outside. However, due to the action of the sodium-potassium pump, sodium ions will easily diffuse into the cell when the symporter is opened. The flood of sodium ions through the symporter provides the energy that allows glucose to move through the symporter and into the cell, against its concentration gradient.

Conversely, antiporters are secondary active transport systems that transport substances in opposite directions. For example, the sodium-hydrogen ion antiporter uses the energy from the inward flood of sodium ions to move hydrogen ions (H+) out of the cell. The sodium-hydrogen antiporter is used to maintain the pH of the cell's interior.

Other forms of active transport do not involve membrane carriers. Endocytosis (bringing “into the cell”) is the process of a cell ingesting material by enveloping it in a portion of its cell membrane, and then pinching off that portion of membrane (Figure 3.1.9). Once pinched off, the portion of membrane and its contents becomes an independent, intracellular vesicle. A vesicle is a membranous sac—a spherical and hollow organelle bounded by a lipid bilayer membrane. Endocytosis often brings materials into the cell that must be broken down or digested. Phagocytosis (“cell eating”) is the endocytosis of large particles. Many immune cells engage in phagocytosis of invading pathogens. Like little Pac-men, their job is to patrol body tissues for unwanted matter, such as invading bacterial cells, phagocytize them, and digest them. In contrast to phagocytosis, pinocytosis (“cell drinking”) brings fluid containing dissolved substances into a cell through membrane vesicles.

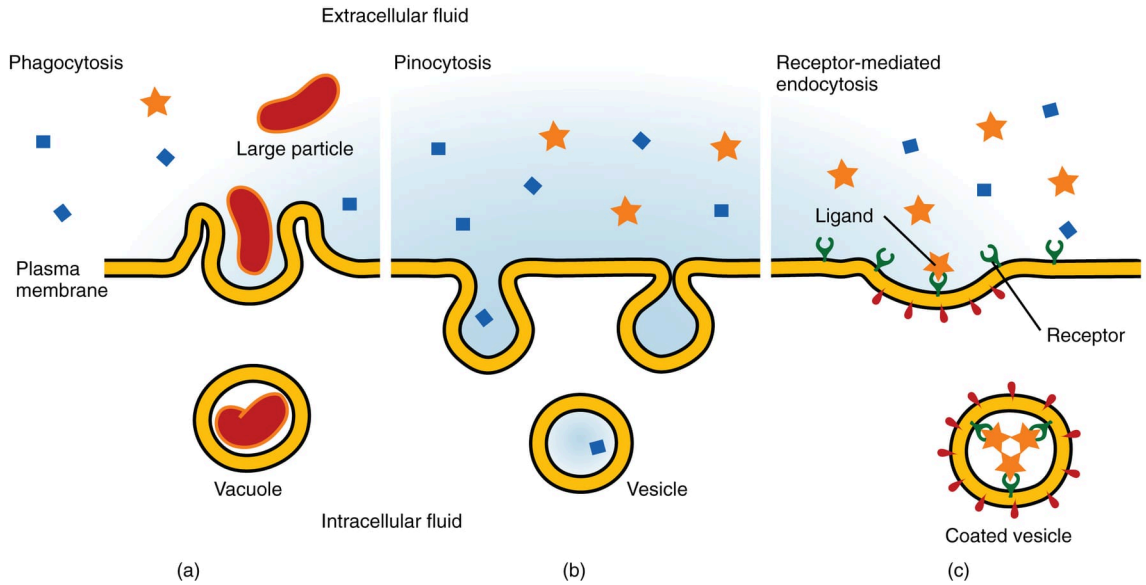


Figure 3.1.9: Endocytosis is an active transport process in which the cell membrane encloses extracellular material. In phagocytosis, the cell takes in a large particle; in pinocytosis, it takes in fluid and small dissolved substances; and in receptor-mediated endocytosis, specific ligands bind to receptors and are selectively brought into the cell. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.9.

Phagocytosis and pinocytosis take in large portions of extracellular material, and they are typically not highly selective in the substances they bring in. Cells regulate the endocytosis of specific substances via receptor-mediated endocytosis. Receptor-mediated endocytosis is endocytosis by a portion of the cell membrane that contains many receptors that are specific for a certain substance. Once the surface receptors have bound sufficient amounts of the specific substance (the receptor's ligand), the cell will endocytose the part of the cell membrane containing the receptor-ligand complexes. Iron, a required component of hemoglobin, is endocytosed by red blood cells in this way. Iron is bound to a protein called transferrin in the blood. Specific transferrin receptors on red blood cell surfaces bind the iron-transferrin molecules, and the cell endocytoses the receptor-ligand complexes.

In contrast with endocytosis, exocytosis (taking "out of the cell") is the process of a cell exporting material using vesicular transport (Figure 3.1.10). Many cells manufacture substances that must be secreted, like a factory manufacturing a product for export. These substances are typically packaged into membrane-bound vesicles within the cell. When the vesicle membrane fuses with the cell membrane, the vesicle releases it contents into the interstitial fluid. The vesicle membrane then becomes part of the cell membrane. Cells of the stomach and pancreas produce and secrete digestive enzymes through exocytosis (Figure 3.1.11). Endocrine cells produce and secrete hormones that are sent throughout the body, and certain immune cells produce and secrete large amounts of histamine, a chemical important for immune responses.

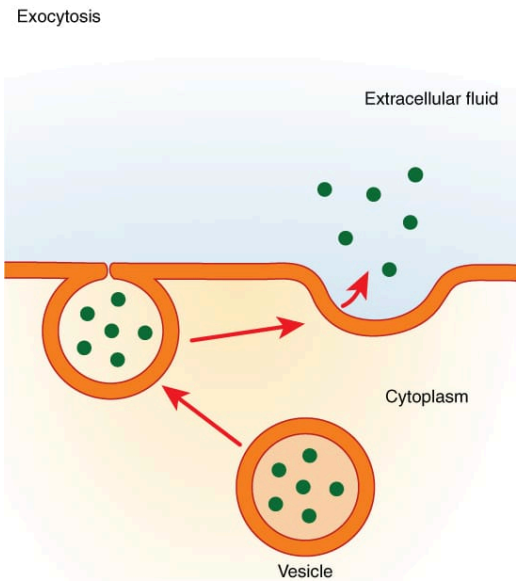


Figure 3.1.10: Exocytosis is much like endocytosis in reverse. Material destined for export is packaged into a vesicle inside the cell. The membrane of the vesicle fuses with the cell membrane, and the contents are released into the extracellular space. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.10.

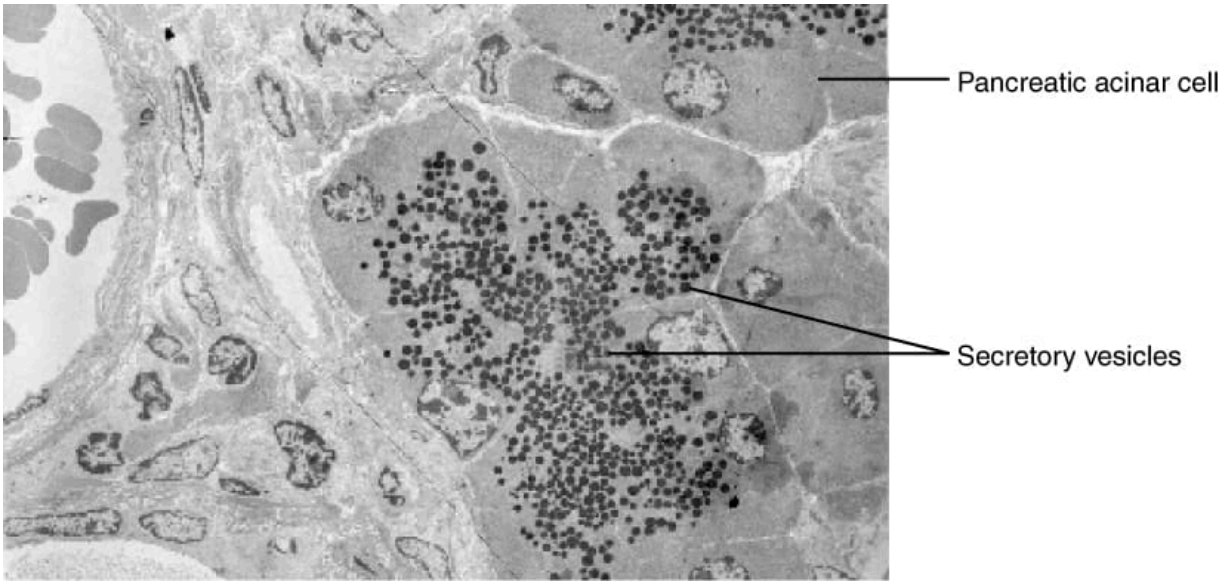


Figure 3.1.11: The pancreatic acinar cells produce and secrete many enzymes that digest food. The tiny black granules in this electron micrograph are secretory vesicles filled with enzymes that will be exported from the cells via exocytosis. LM × 2900. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.1.11.

Disease of the...

Cell: Cystic Fibrosis

Cystic fibrosis (CF) affects approximately 30,000 people in the United States, with about 1,000 new cases reported each year. The genetic disease is most well known for its damage to the lungs, causing breathing difficulties and chronic lung infections, but it also affects the liver, pancreas, and intestines. Only about 50 years ago, the prognosis for children born with CF was very grim—a life expectancy rarely over 10 years. Today, with advances in medical treatment, many CF patients live into their 30s.

The symptoms of CF result from a malfunctioning membrane ion channel called the cystic fibrosis trans-membrane conductance regulator, or CFTR. In healthy people, the CFTR protein is an integral membrane protein that transports Cl^- ions out of the cell. In a person who has CF, the gene for the CFTR is mutated, thus, the cell manufactures a defective channel protein that typically is not incorporated into the membrane, but is instead degraded by the cell.

The CFTR requires ATP in order to function, making its Cl^- transport a form of active transport. This characteristic puzzled researchers for a long time because the Cl^- ions are actually flowing *down* their concentration gradient when transported out of cells. Active transport generally pumps ions *against* their concentration gradient, but the CFTR presents an exception to this rule.

In normal lung tissue, the movement of Cl^- out of the cell maintains a Cl^--rich, negatively charged environment immediately outside of the cell. This is particularly important in the epithelial lining of the respiratory system. Respiratory epithelial cells secrete mucus, which serves to trap dust, bacteria, and other debris. A cilium (plural = cilia) is one of the hair-like appendages found on certain cells. Cilia on the epithelial cells move the mucus and its trapped particles up the airways away from the lungs and toward the outside. In order to be effectively moved upward, the mucus cannot be too viscous; rather it must have a thin, watery consistency. The transport of Cl^- and the maintenance of an electronegative environment outside of the cell attract positive ions such as Na^+ to the extracellular space. The accumulation of both Cl^- and Na^+ ions in the extracellular space creates solute-rich mucus, which has a low concentration of water molecules. As a result, through osmosis, water moves from cells and extracellular matrix into the mucus, “thinning” it out. This is how, in a normal respiratory system, the mucus is kept sufficiently watered-down to be propelled out of the respiratory system.

If the CFTR channel is absent, Cl^- ions are not transported out of the cell in adequate numbers, thus preventing them from drawing positive ions. The absence of ions in the secreted mucus results in the lack of a normal water concentration gradient. Thus, there is no osmotic pressure pulling water into the mucus. The resulting mucus is thick and sticky, and the ciliated epithelia cannot effectively remove it from the respiratory system. Passageways in the lungs become blocked with mucus, along with the debris it carries. Bacterial infections occur more easily because bacterial cells are not effectively carried away from the lungs.

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3.2: The Cytoplasm and Cellular Organelles

Introduction

Now that you have learned that the cell membrane surrounds all cells, you can dive inside of a prototypical human cell to learn about its internal components and their functions. All living cells in multicellular organisms contain an internal cytoplasmic compartment, and a nucleus within the cytoplasm. Cytosol, the jelly-like substance within the cell, provides the fluid medium necessary for biochemical reactions. Eukaryotic cells, including all animal cells, also contain various cellular organelles. An organelle ("little organ") is one of several different types of membrane-enclosed bodies in the cell, each performing a unique function. Just as the various bodily organs work together in harmony to perform all of a human's functions, the many different cellular organelles work together to keep the cell healthy and performing all of its important functions. The organelles and cytosol, taken together, compose the cell's cytoplasm. The nucleus is a cell's central organelle, which contains the cell's DNA (Figure 3.2.1).

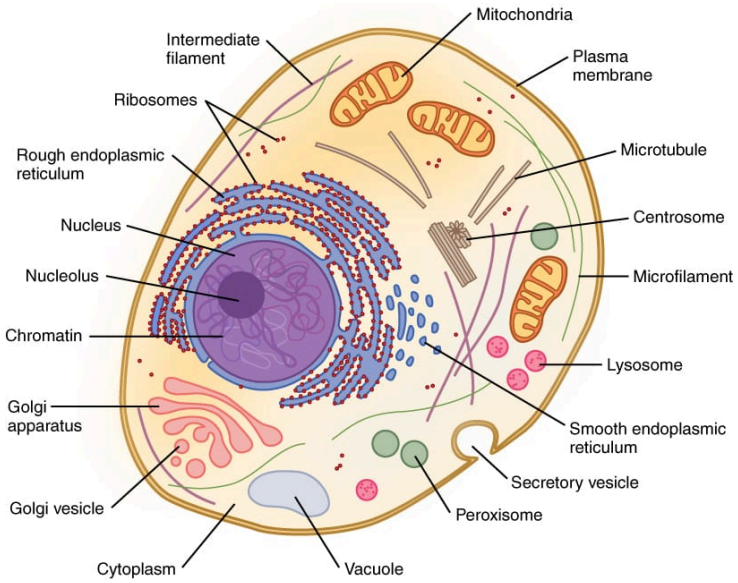


Figure 3.2.1: This illustration does not represent one specific cell type, but rather a generalized human cell showing the major organelles and internal structures commonly found in most cells. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.2.1.

Organelles of the Endomembrane System

A set of three major organelles together form a system within the cell called the endomembrane system. These organelles work together to perform various cellular jobs, including the task of producing, packaging, and exporting certain cellular products. The organelles of the endomembrane system include the endoplasmic reticulum, Golgi apparatus, and vesicles.

Endoplasmic Reticulum

The endoplasmic reticulum (ER) is a system of channels that is continuous with the nuclear membrane (or "envelope") covering the nucleus and composed of the same lipid bilayer material. The ER can be thought of as a series of winding thoroughfares similar to the waterway canals in Venice. The ER provides passages throughout much of the cell that function in transporting, synthesizing, and storing materials. The winding structure of the ER results in a large membranous surface area that supports its many functions.

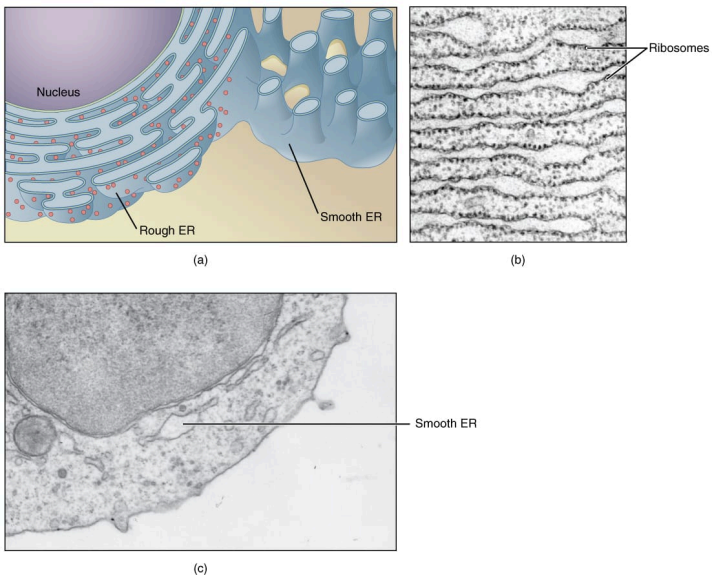


Figure 3.2.2: Illustration and electron micrographs showing rough and smooth endoplasmic reticulum. Rough ER appears as folded membranes studded with ribosomes, while smooth ER forms tubular membranes without ribosomes. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.2.2.

Endoplasmic reticulum can exist in two forms: rough ER and smooth ER. These two types of ER perform some very different functions and can be found in very different amounts depending on the type of cell. Rough ER (RER) is so-called because its membrane is dotted with embedded granules—organelles called ribosomes, giving the RER a bumpy appearance. A ribosome is an organelle that serves as the site of protein synthesis. It is composed of two ribosomal RNA subunits that wrap around mRNA to start the process of translation, followed by protein synthesis. Smooth ER (SER) lacks these ribosomes.

One of the main functions of the smooth ER is in the synthesis of lipids. The smooth ER synthesizes phospholipids, the main component of biological membranes, as well as steroid hormones. For this reason, cells that produce large quantities of such hormones, such as those of the female ovaries and male testes, contain large amounts of smooth ER. In addition to lipid synthesis, the smooth ER also sequesters (i.e., stores) and regulates the concentration of cellular Ca^{++}, a function extremely important in cells of the nervous system where Ca^{++} is the trigger for neurotransmitter release. The smooth ER additionally metabolizes some carbohydrates and performs a detoxification role, breaking down certain toxins.

In contrast with the smooth ER, the primary job of the rough ER is the synthesis and modification of proteins destined for the cell membrane or for export from the cell. For this protein synthesis, many ribosomes attach to the ER (giving it the studded appearance of rough ER). Typically, a protein is synthesized within the ribosome and released inside the channel of the rough ER, where sugars can be added to it (by a process called glycosylation) before it is transported within a vesicle to the next stage in the packaging and shipping process: the Golgi apparatus.

The Golgi Apparatus

The Golgi apparatus is responsible for sorting, modifying, and shipping off the products that come from the rough ER, much like a post-office. The Golgi apparatus looks like stacked flattened discs, almost like stacks of oddly shaped pancakes. Like the ER, these discs are membranous. The Golgi apparatus has two distinct sides, each with a different role. One side of the apparatus receives products in vesicles. These products are sorted through the apparatus, and then they are released from the opposite side after being repackaged into new vesicles. If the product is to be exported from the cell, the vesicle migrates to the cell surface and fuses to the cell membrane, and the cargo is secreted (Figure 3.2.3).

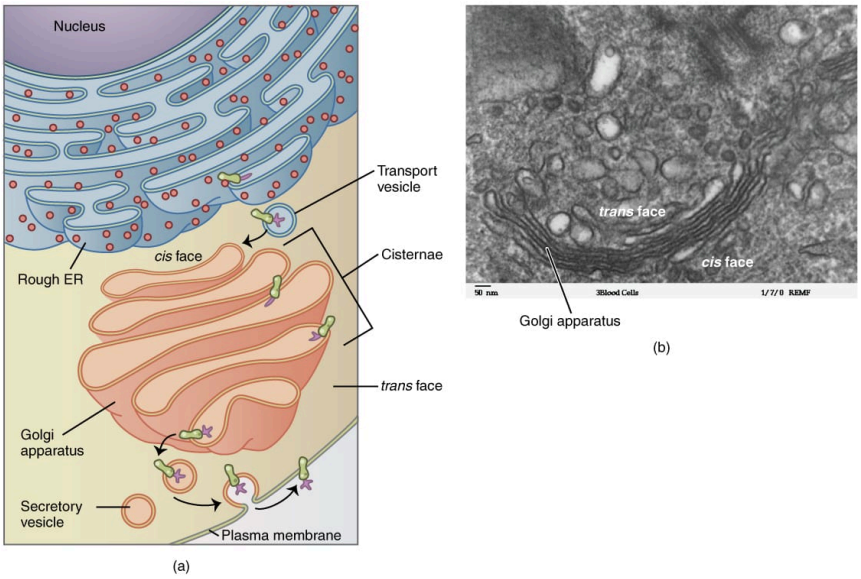


Figure 3.2.3: Diagram and electron micrograph of the Golgi apparatus showing its cis and trans faces, stacked cisternae, and the flow of transport and secretory vesicles between the rough ER and the plasma membrane. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.2.3.

Lysosomes

Some of the protein products packaged by the Golgi include digestive enzymes that are meant to remain inside the cell for use in breaking down certain materials. The enzyme-containing vesicles released by the Golgi may form new lysosomes, or fuse with existing, lysosomes. A lysosome is an organelle that contains enzymes that break down and digest unneeded cellular components, such as a damaged organelle. (A lysosome is similar to a wrecking crew that takes down old and unsound buildings in a neighborhood.) Autophagy ("self-eating") is the process of a cell digesting its own structures. Lysosomes are also important for breaking down foreign material. For example, when certain immune defense cells (white blood cells) phagocytize bacteria, the bacterial cell is transported into a lysosome and digested by the enzymes inside. As one might imagine, such phagocytic defense cells contain large numbers of lysosomes.

Under certain circumstances, lysosomes perform a more grand and dire function. In the case of damaged or unhealthy cells, lysosomes can be triggered to open up and release their digestive enzymes into the cytoplasm of the cell, killing the cell. This "self-destruct" mechanism is called autolysis, and makes the process of cell death controlled (a mechanism called "apoptosis").

Organelles for Energy Production and Detoxification

In addition to the jobs performed by the endomembrane system, the cell has many other important functions. Just as you must consume nutrients to provide yourself with energy, so must each of your cells take in nutrients, some of which convert to chemical energy that can be used to power biochemical reactions. Another important function of the cell is detoxification. Humans take in all sorts of toxins from the environment and also produce harmful chemicals as byproducts of cellular processes. Cells called hepatocytes in the liver detoxify many of these toxins.

Mitochondria

A mitochondrion (plural = mitochondria) is a membranous, bean-shaped organelle that is the "energy transformer" of the cell. Mitochondria consist of an outer lipid bilayer membrane as well as an additional inner lipid bilayer membrane (Figure 3.2.4). The inner membrane is highly folded into winding structures with a great deal of surface area, called cristae. It is along this inner membrane that a series of proteins, enzymes, and other molecules perform the biochemical reactions of cellular respiration. These reactions convert energy stored in nutrient molecules (such as glucose) into adenosine triphosphate (ATP), which provides usable cellular energy to the cell. Cells use ATP constantly, and so the mitochondria are constantly at work. Oxygen molecules are required during cellular respiration, which is why you must constantly breathe it in. One of the organ systems in the body that uses huge amounts of ATP is the muscular system because ATP is required to sustain muscle contraction. As a result, muscle cells are packed full of mitochondria. Nerve cells also need large quantities of ATP to run their sodium-potassium pumps. Therefore,

an individual neuron will be loaded with over a thousand mitochondria. On the other hand, a bone cell, which is not nearly as metabolically-active, might only have a couple hundred mitochondria.

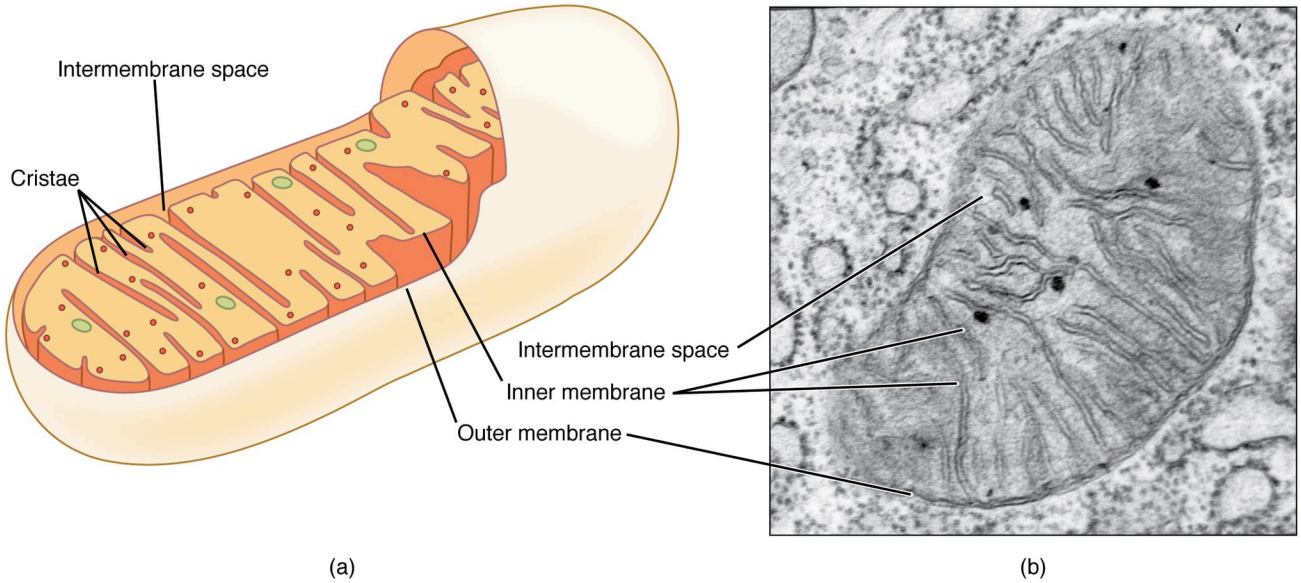


Figure 3.2.4: Diagram and electron micrograph of a mitochondrion showing the outer membrane, inner membrane, cristae, and intermembrane space. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.2.4.

Peroxisomes

Like lysosomes, a peroxisome is a membrane-bound cellular organelle that contains mostly enzymes (Figure 3.2.5). Peroxisomes perform a couple of different functions, including lipid metabolism and chemical detoxification. In contrast to the digestive enzymes found in lysosomes, the enzymes within peroxisomes serve to transfer hydrogen atoms from various molecules to oxygen, producing hydrogen peroxide (H_2O_2). In this way, peroxisomes neutralize poisons such as alcohol. In order to appreciate the importance of peroxisomes, it is necessary to understand the concept of reactive oxygen species.

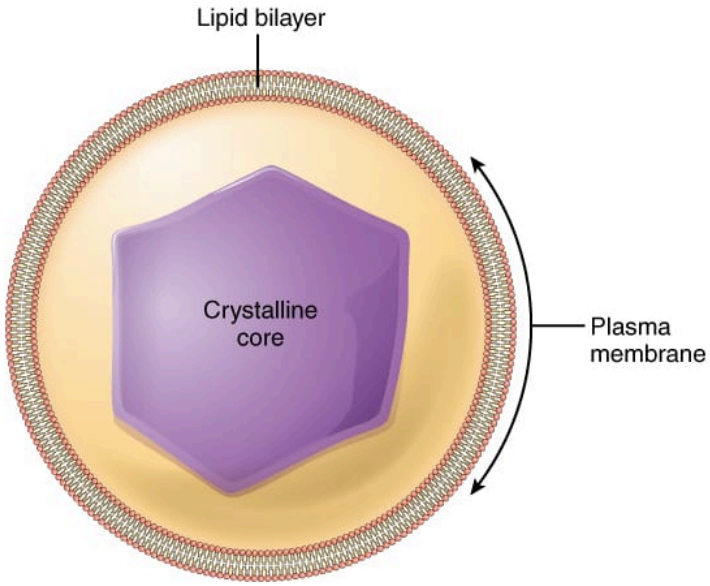


Figure 3.2.5: Peroxisomes are membrane-bound organelles that contain an abundance of enzymes for detoxifying harmful substances and lipid metabolism. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.2.5.

Reactive oxygen species (ROS) such as peroxides and free radicals are the highly reactive products of many normal cellular processes, including the mitochondrial reactions that produce ATP and oxygen metabolism. Examples of ROS include the hydroxyl radical OH, H_2O_2, and superoxide (O_2^-). Some ROS are important for certain cellular functions, such as cell signaling processes

and immune responses against foreign substances. Free radicals are reactive because they contain free unpaired electrons; they can easily oxidize other molecules throughout the cell, causing cellular damage and even cell death. Free radicals are thought to play a role in many destructive processes in the body, from cancer to coronary artery disease.

Peroxisomes, on the other hand, oversee reactions that neutralize free radicals. Peroxisomes produce large amounts of the toxic H_2O_2 in the process, but peroxisomes contain enzymes that convert H_2O_2 into water and oxygen. These byproducts are safely released into the cytoplasm. Like miniature sewage treatment plants, peroxisomes neutralize harmful toxins so that they do not wreak havoc in the cells. The liver is the organ primarily responsible for detoxifying the blood before it travels throughout the body, and liver cells contain an exceptionally high number of peroxisomes.

Defense mechanisms such as detoxification within the peroxisome and certain cellular antioxidants serve to neutralize many of these molecules. Some vitamins and other substances, found primarily in fruits and vegetables, have antioxidant properties. Antioxidants work by being oxidized themselves, halting the destructive reaction cascades initiated by the free radicals. Sometimes though, ROS accumulate beyond the capacity of such defenses.

Oxidative stress is the term used to describe damage to cellular components caused by ROS. Due to their characteristic unpaired electrons, ROS can set off chain reactions where they remove electrons from other molecules, which then become oxidized and reactive, and do the same to other molecules, causing a chain reaction. ROS can cause permanent damage to cellular lipids, proteins, carbohydrates, and nucleic acids. Damaged DNA can lead to genetic mutations and even cancer. A mutation is a change in the nucleotide sequence in a gene within a cell's DNA, potentially altering the protein coded by that gene. Other diseases believed to be triggered or exacerbated by ROS include Alzheimer's disease, cardiovascular diseases, diabetes, Parkinson's disease, arthritis, Huntington's disease, and schizophrenia, among many others. It is noteworthy that these diseases are largely age-related. Many scientists believe that oxidative stress is a major contributor to the aging process.

Aging and the...

Cell: The Free Radical Theory

The free radical theory on aging was originally proposed in the 1950s, and still remains under debate. Generally speaking, the free radical theory of aging suggests that accumulated cellular damage from oxidative stress contributes to the physiological and anatomical effects of aging. There are two significantly different versions of this theory: one states that the aging process itself is a result of oxidative damage, and the other states that oxidative damage causes age-related disease and disorders. The latter version of the theory is more widely accepted than the former. However, many lines of evidence suggest that oxidative damage does contribute to the aging process. Research has shown that reducing oxidative damage can result in a longer lifespan in certain organisms such as yeast, worms, and fruit flies. Conversely, increasing oxidative damage can shorten the lifespan of mice and worms. Interestingly, a manipulation called calorie-restriction (moderately restricting the caloric intake) has been shown to increase life span in some laboratory animals. It is believed that this increase is at least in part due to a reduction of oxidative stress. However, a long-term study of primates with calorie-restriction showed no increase in their lifespan. A great deal of additional research will be required to better understand the link between reactive oxygen species and aging.

The Cytoskeleton

Much like the bony skeleton structurally supports the human body, the cytoskeleton helps the cells to maintain their structural integrity. The cytoskeleton is a group of fibrous proteins that provide structural support for cells, but this is only one of the functions of the cytoskeleton. Cytoskeletal components are also critical for cell motility, cell reproduction, and transportation of substances within the cell.

The cytoskeleton forms a complex thread-like network throughout the cell consisting of three different kinds of protein-based filaments: microfilaments, intermediate filaments, and microtubules (Figure 3.2.6). The thickest of the three is the microtubule, a structural filament composed of subunits of a protein called tubulin. Microtubules maintain cell shape and structure, help resist compression of the cell, and play a role in positioning the organelles within the cell. Microtubules also make up two types of cellular appendages important for motion: cilia and flagella. Cilia are found on many cells of the body, including the epithelial cells that line the airways of the respiratory system. Cilia move rhythmically; they beat constantly, moving waste materials such as dust, mucus, and bacteria upward through the airways, away from the lungs and toward the mouth. Beating cilia on cells in the female fallopian tubes move egg cells from the ovary towards the uterus. A flagellum (plural = flagella) is an appendage larger than a

cilium and specialized for cell locomotion. The only flagellated cell in humans is the sperm cell that must propel itself towards female egg cells.

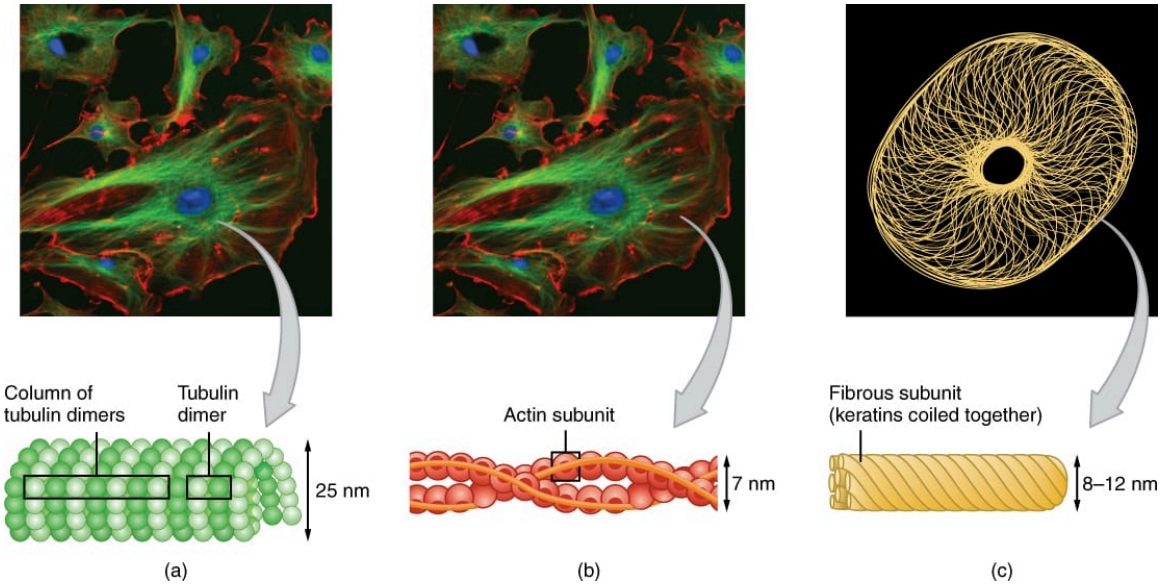


Figure 3.2.6: Florescent images and diagrams showing microtubules, microfilaments, and intermediate filaments with their subunits and relative sizes. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.2.6.

A very important function of microtubules is to set the paths (somewhat like railroad tracks) along which the genetic material can be pulled (a process requiring ATP) during cell division, so that each new daughter cell receives the appropriate set of chromosomes. Two short, identical microtubule structures called centrioles are found near the nucleus of cells. A centriole can serve as the cellular origin point for microtubules extending outward as cilia or flagella or can assist with the separation of DNA during cell division. Microtubules grow out from the centrioles by adding more tubulin subunits, like adding additional links to a chain.

In contrast with microtubules, the microfilament is a thinner type of cytoskeletal filament. Actin, a protein that forms chains, is the primary component of these microfilaments. Actin fibers, twisted chains of actin filaments, constitute a large component of muscle tissue and, along with the protein myosin, are responsible for muscle contraction. Like microtubules, actin filaments are long chains of single subunits (called actin subunits). In muscle cells, these long actin strands, called thin filaments, are “pulled” by thick filaments of the myosin protein to contract the cell.

Actin also has an important role during cell division. When a cell is about to split in half during cell division, actin filaments work with myosin to create a cleavage furrow that eventually splits the cell down the middle, forming two new cells from the original cell.

The final cytoskeletal filament is the intermediate filament. As its name would suggest, an intermediate filament is a filament intermediate in thickness between the microtubules and microfilaments. Intermediate filaments are made up of long fibrous subunits of a protein called keratin that are wound together like the threads that compose a rope. Intermediate filaments, in concert with the microtubules, are important for maintaining cell shape and structure. Unlike the microtubules, which resist compression, intermediate filaments resist tension—the forces that pull apart cells. There are many cases in which cells are prone to tension, such as when epithelial cells of the skin are compressed, tugging them in different directions. Intermediate filaments help anchor organelles together within a cell and also link cells to other cells by forming special cell-to-cell junctions.

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3.3: The Nucleus and DNA Replication

Structure and Function of the Nucleus

The nucleus is the largest and most prominent of a cell's organelles (Figure 3.3.1). The nucleus is generally considered the control center of the cell because it stores all of the genetic instructions for manufacturing proteins. Interestingly, some cells in the body, such as muscle cells, contain more than one nucleus (Figure 3.3.2), which is known as multinucleated. Other cells, such as mammalian red blood cells (RBCs), do not contain nuclei at all. RBCs eject their nuclei as they mature, making space for the large numbers of hemoglobin molecules that carry oxygen throughout the body (Figure 3.3.3). Without nuclei, the life span of RBCs is short, and so the body must produce new ones constantly.

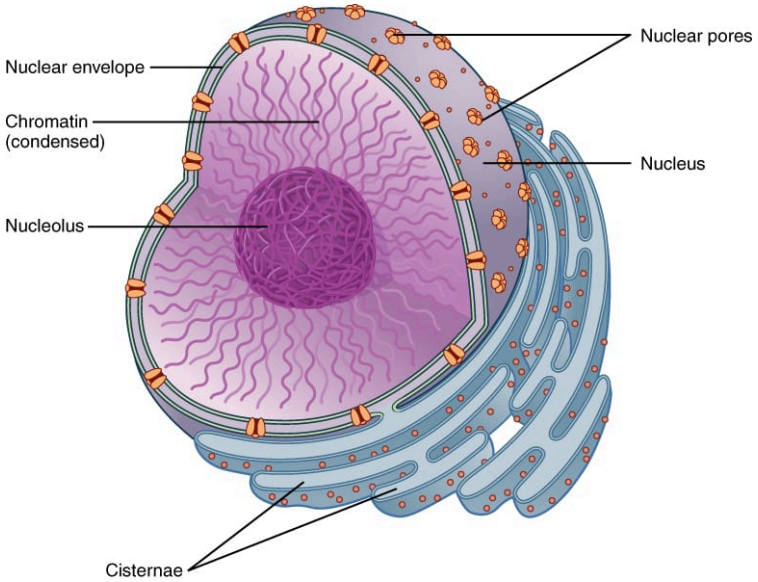


Figure 3.3.1: The nucleus is the control center of the cell. The nucleus of living cells contains the genetic material that determines the entire structure and function of that cell. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.3.1.

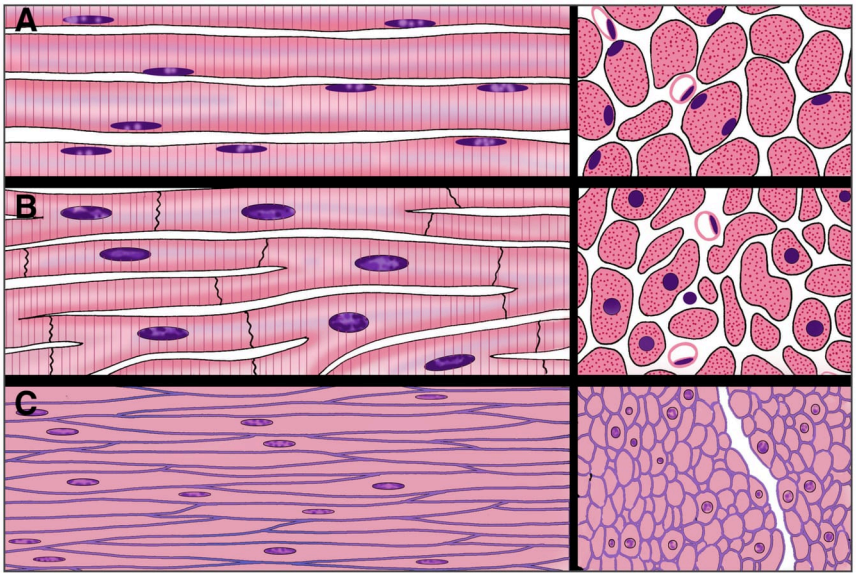


Figure 3.3.2: Unlike cardiac muscle cells (B) and smooth muscle cells (C), which have a single nucleus, a skeletal muscle cell (A) contains many nuclei, and is referred to as "multinucleated." These muscle cells are long and fibrous (often referred to as muscle fibers). During development, many smaller cells fuse to form a mature muscle fiber. The nuclei of the fused cells are conserved in the mature cell, thus imparting a multinucleate characteristic to mature muscle cells. (CC BY-NC-SA 4.0 ; via Muscle Tissue). Alternative text description of Figure 3.3.2.

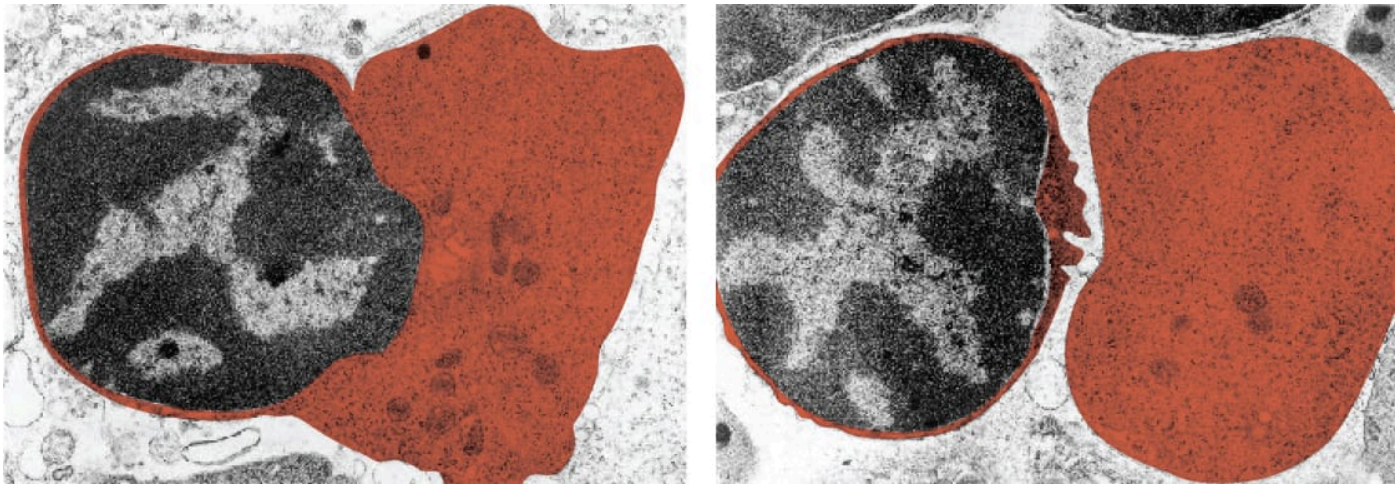


Figure 3.3.3: Mature red blood cells lack a nucleus. As they mature, erythroblasts extrude their nucleus, making room for more hemoglobin. The two panels here show an erythroblast before and after ejecting its nucleus, respectively. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.3.3.

Inside the nucleus lies the blueprint that dictates everything a cell will do and all of the products it will make. This information is stored within DNA. The nucleus sends "commands" to the cell via molecular messengers that translate the information from DNA. Each cell in your body (with the exception of germ cells) contains the complete set of your DNA. When a cell divides, the DNA must be duplicated so that the each new cell receives a full complement of DNA. The following section will explore the structure of the nucleus and its contents, as well as the process of DNA replication.

Organization of the Nucleus and Its DNA

Like most other cellular organelles, the nucleus is surrounded by a membrane called the nuclear envelope. This membranous covering consists of two adjacent lipid bilayers with a thin fluid space in between them. Spanning these two bilayers are nuclear pores. A nuclear pore is a tiny passageway for the passage of proteins, RNA, and solutes between the nucleus and the cytoplasm. Proteins called pore complexes lining the nuclear pores regulate the passage of materials into and out of the nucleus.

Inside the nuclear envelope is a gel-like nucleoplasm with solutes that include the building blocks of nucleic acids. There also can be a dark-staining mass often visible under a simple light microscope, called a nucleolus (plural = nucleoli). The nucleolus is a region of the nucleus that is responsible for manufacturing the RNA necessary for construction of ribosomes. Once synthesized, newly made ribosomal subunits exit the cell's nucleus through the nuclear pores.

The genetic instructions that are used to build and maintain an organism are arranged in an orderly manner in strands of DNA. Within the nucleus are threads of chromatin composed of DNA and associated proteins (Figure 3.3.4). Along the chromatin threads, the DNA is wrapped around a set of histone proteins. A nucleosome is a single, wrapped DNA-histone complex. Multiple nucleosomes along the entire molecule of DNA appear like a beaded necklace, in which the string is the DNA and the beads are the associated histones. When a cell is in the process of division, the chromatin condenses into chromosomes, so that the DNA can be safely transported to the "daughter cells." The chromosome is composed of DNA and proteins; it is the condensed form of chromatin. It is estimated that humans have almost 22,000 genes distributed on 46 chromosomes.

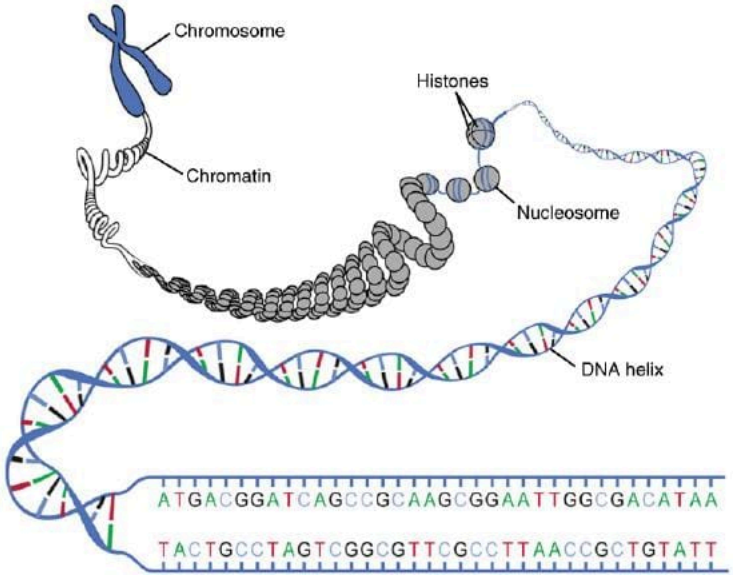


Figure 3.3.4: Strands of DNA are wrapped around supporting histones. These proteins are increasingly bundled and condensed into chromatin, which is packed tightly into chromosomes when the cell is ready to divide. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.3.4.

DNA Replication

In order for an organism to grow, develop, and maintain its health, cells must reproduce themselves by dividing to produce two new daughter cells, each with the full complement of DNA as found in the original cell. Billions of new cells are produced in an adult human every day. Only very few cell types in the body do not divide, including nerve cells, skeletal muscle fibers, and cardiac muscle cells. The division time of different cell types varies. Epithelial cells of the skin and gastrointestinal lining, for instance, divide very frequently to replace those that are constantly being rubbed off of the surface by friction.

A DNA molecule is made of two strands that “complement” each other in the sense that the molecules that compose the strands fit together and bind to each other, creating a double-stranded molecule that looks much like a long, twisted ladder. This double helix can be constructed easily because the two strands are antiparallel, meaning the two strands run in opposite directions. Each side rail of the DNA ladder is composed of alternating sugar and phosphate groups (Figure 3.3.5). The two sides of the ladder are not identical, but are complementary. These two backbones are bonded to each other across pairs of protruding bases, each bonded pair forming one “rung,” or cross member. The four DNA bases are adenine (A), thymine (T), cytosine (C), and guanine (G). Because of their shape and charge, the two bases that compose a pair always bond together. Adenine always binds with thymine, and cytosine always binds with guanine. The particular sequence of bases along the DNA molecule determines the genetic code. Therefore, if the two complementary strands of DNA were pulled apart, you could infer the order of the bases in one strand from the bases in the other, complementary strand. For example, if one strand has a region with the sequence AGTGCCT, then the sequence of the complementary strand would be TCACGGA.

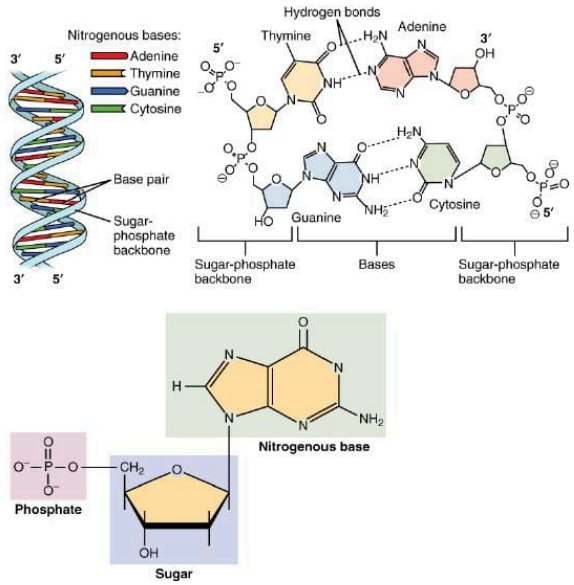


Figure 3.3.5: The DNA double helix is composed of two complementary strands. The strands are bonded together via their nitrogenous base pairs using hydrogen bonds. (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.3.5.

DNA replication is the copying of DNA that occurs before cell division can take place. After a great deal of debate and experimentation, the general method of DNA replication was deduced in 1958 by two scientists in California, Matthew Meselson and Franklin Stahl. This method is illustrated in Figure 3.3.6.

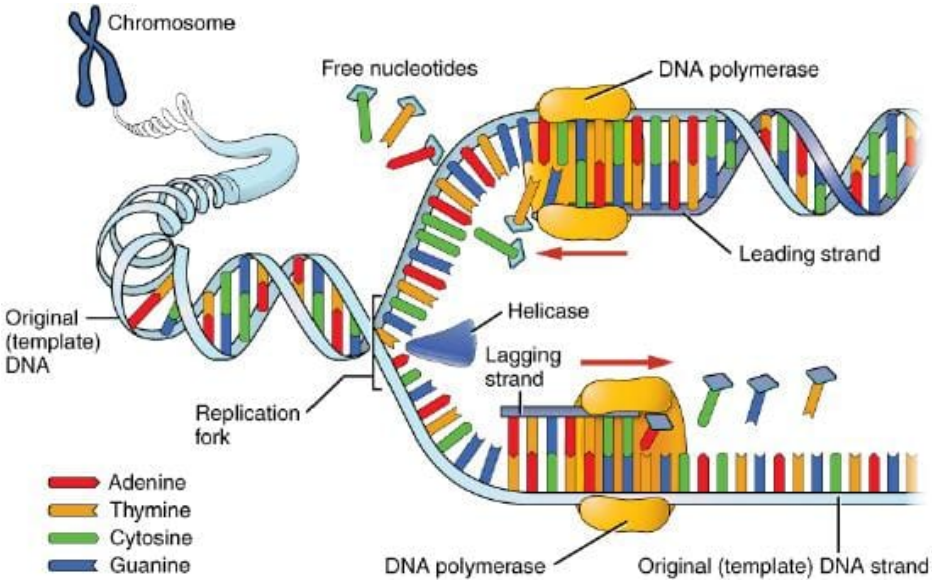


Figure 3.3.6: Replication faithfully duplicates the entire genome of the cell. During DNA replication, a number of different enzymes work together to pull apart the two strands so each strand can be used as a template to synthesize new complementary strands. The two new daughter DNA molecules each contain one pre-existing strand and one newly synthesized strand. Thus, DNA replication is said to be "semiconservative." (CC BY 4.0; via Wikimedia Commons). Alternative text description of Figure 3.3.6.

Stage 1: Initiation. The two complementary strands are separated, much like unzipping a zipper. Special enzymes, including helicase, untwist and separate the two strands of DNA.

Stage 2: Elongation. Each strand becomes a template along which a new complementary strand is built. DNA polymerase brings in the correct bases to complement the template strand, synthesizing a new strand base by base. A DNA polymerase is an enzyme that adds free nucleotides to the end of a chain of DNA, making a new double strand. This growing strand continues to be built until it has fully complemented the template strand.

Stage 3: Termination. Once the two original strands are bound to their own, finished, complementary strands, DNA replication is stopped and the two new identical DNA molecules are complete.

Each new DNA molecule contains one strand from the original molecule and one newly synthesized strand. The term for this mode of replication is “semiconservative,” because half of the original DNA molecule is conserved in each new DNA molecule. This process continues until the cell’s entire, the entire complement of an organism’s DNA, is replicated. As you might imagine, it is very important that DNA replication take place precisely so that new cells in the body contain the exact same genetic material as their parent cells. Mistakes made during DNA replication, such as the accidental addition of an inappropriate nucleotide, have the potential to render a gene dysfunctional or useless. Fortunately, there are mechanisms in place to minimize such mistakes. A DNA proofreading process enlists the help of special enzymes that scan the newly synthesized molecule for mistakes and corrects them. Once the process of DNA replication is complete, the cell is ready to divide. You will explore the process of cell division later in the chapter.

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3.4: Protein Synthesis

DNA as Blueprint for Protein Synthesis

It was mentioned earlier that DNA provides a "blueprint" for the cell structure and physiology. This refers to the fact that DNA contains the information necessary for the cell to build one very important type of molecule: the protein. Most structural components of the cell are made up, at least in part, by proteins and virtually all the functions that a cell carries out are completed with the help of proteins. One of the most important classes of proteins is enzymes, which help speed up necessary biochemical reactions that take place inside the cell. Some of these critical biochemical reactions include building larger molecules from smaller components (such as occurs during DNA replication or synthesis of microtubules) and breaking down larger molecules into smaller components (such as when harvesting chemical energy from nutrient molecules). Whatever the cellular process may be, it is almost sure to involve proteins. Just as the cell's genome describes its full complement of DNA, a cell's proteome is its full complement of proteins. Protein synthesis begins with genes. A gene is a functional segment of DNA that provides the genetic information necessary to build a protein. Each particular gene provides the code necessary to construct a particular protein. Gene expression, which transforms the information coded in a gene to a final gene product, ultimately dictates the structure and function of a cell by determining which proteins are made.

The interpretation of genes works in the following way. Recall that proteins are polymers, or chains, of many amino acid building blocks. The sequence of bases in a gene (that is, its sequence of A, T, C, G nucleotides) translates to an amino acid sequence. A triplet is a section of three DNA bases in a row that codes for a specific amino acid. Similar to the way in which the three-letter code *d-o-g* signals the image of a dog, the three-letter DNA base code signals the use of a particular amino acid. For example, the DNA triplet CAC (cytosine, adenine, and cytosine) specifies the amino acid valine. Therefore, a gene, which is composed of multiple triplets in a unique sequence, provides the code to build an entire protein, with multiple amino acids in the proper sequence (Figure 3.4.1). The mechanism by which cells turn the DNA code into a protein product is a two-step process, with an RNA molecule as the intermediate.

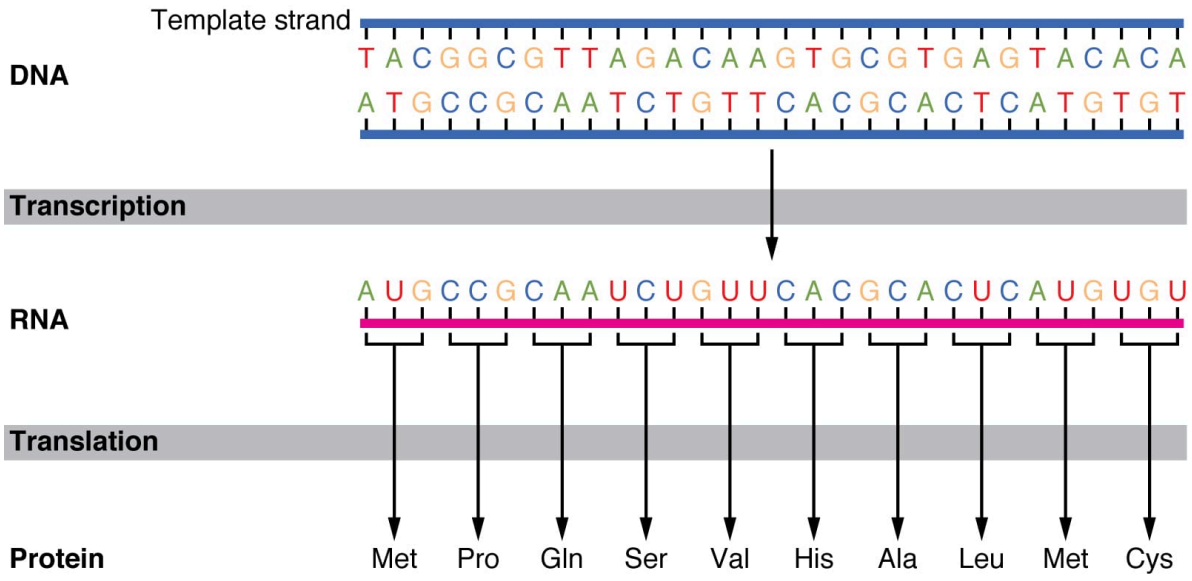


Figure 3.4.1: DNA holds all of the genetic information necessary to build a cell's proteins. The nucleotide sequence of a gene is ultimately translated into an amino acid sequence of the gene's corresponding protein. (CC BY-SA 4.0; via Wikimedia Commons). Alternative text description of Figure 3.4.1.

From DNA to RNA: Transcription

DNA is housed within the nucleus, and protein synthesis takes place in the cytoplasm, thus there must be some sort of intermediate messenger that leaves the nucleus and manages protein synthesis. This intermediate messenger is messenger RNA (mRNA), a single-stranded nucleic acid that carries a copy of the genetic code for a single gene out of the nucleus and into the

cytoplasm where it is used to produce proteins.

There are several different types of RNA, each having different functions in the cell. The structure of RNA is similar to DNA with a few small exceptions. For one thing, unlike DNA, most types of RNA, including mRNA, are single-stranded and contain no complementary strand. Second, the ribose sugar in RNA contains an additional oxygen atom compared with DNA. Finally, instead of the base thymine, RNA contains the base uracil. This means that adenine will always pair up with uracil during the protein synthesis process.

Gene expression begins with the process called transcription, which is the synthesis of a strand of mRNA that is complementary to the gene of interest. This process is called transcription because the mRNA is like a transcript, or copy, of the gene's DNA code. Transcription begins in a fashion somewhat like DNA replication, in that a region of DNA unwinds and the two strands separate, however, only that small portion of the DNA will be split apart. The triplets within the gene on this section of the DNA molecule are used as the template to transcribe the complementary strand of RNA (Figure 3.4.2). A codon is a three-base sequence of mRNA, so-called because they directly encode amino acids. Like DNA replication, there are three stages to transcription: initiation, elongation, and termination.

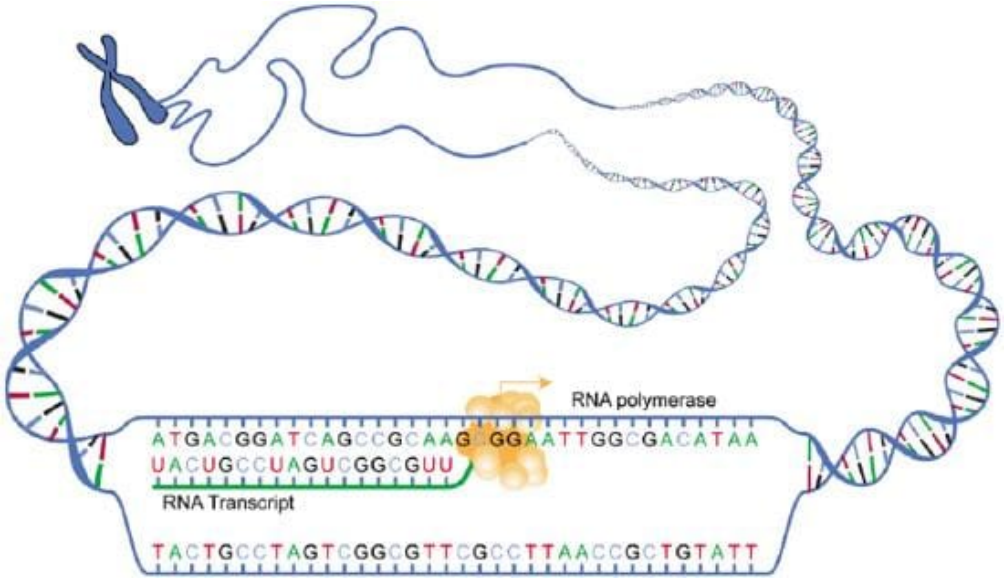


Figure 3.4.2: In the first of the two stages of making protein from DNA, a gene on the DNA molecule is transcribed into a complementary mRNA molecule. (CC BY-SA 4.0; via Wikimedia Commons). Alternative text description of Figure 3.4.2.

Stage 1: Initiation. A region at the beginning of the gene called a promoter a particular sequence of nucleotides—triggers the start of transcription.

Stage 2: Elongation. Transcription starts when RNA polymerase unwinds the DNA segment. One strand, referred to as the coding strand, becomes the template with the genes to be coded. The polymerase then aligns the correct nucleic acid (A, C, G, or U) with its complementary base on the coding strand of DNA. RNA polymerase is an enzyme that adds new nucleotides to a growing strand of RNA. This process builds a strand of mRNA.

Stage 3: Termination. At the end of the gene, a sequence of nucleotides called the terminator sequence causes the new RNA to fold up on itself. This fold causes the RNA to separate from the gene and from RNA polymerase, ending transcription.

Before the mRNA molecule leaves the nucleus and proceeds to protein synthesis, it is modified in a number of ways. For this reason, it is often called a pre-mRNA at this stage. For example, your DNA, and thus complementary mRNA, contains long regions called non-coding regions that do not code for amino acids. Their function is still a mystery, but the process called splicing removes these non-coding regions from the pre-mRNA transcript (Figure 3.4.3). A spliceosome—a structure composed of various proteins and other molecules—attaches to the mRNA and "splices" or cuts out the non-coding regions. The removed segment of the transcript is called an intron. The remaining exons are pasted together. An exon is a segment of RNA that remains after splicing. Interestingly, some introns that are removed from mRNA are not always non-coding. When different coding regions of mRNA are spliced out, different variations of the protein will eventually result, with differences in structure and function. This process results in a much larger variety of possible proteins and protein functions. When the mRNA transcript is ready, it travels

out of the nucleus and into the cytoplasm.

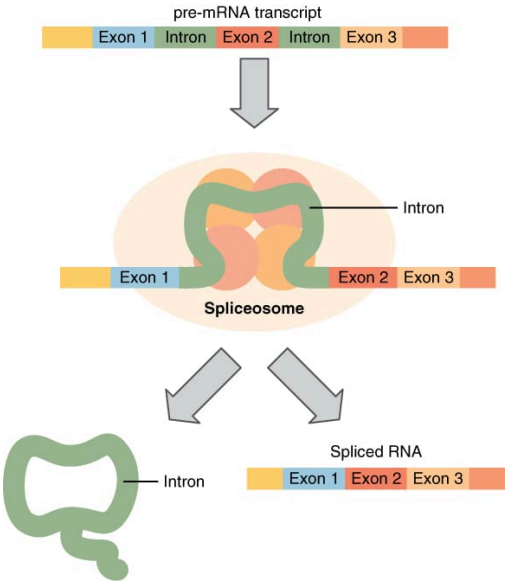


Figure 3.4.3: In the nucleus, a structure called a spliceosome cuts out introns (noncoding regions) within a pre-mRNA transcript and reconnects the exons. (CC BY-SA 4.0; via Wikimedia Commons). Alternative text description of Figure 3.4.3.

From RNA to Protein: Translation

Like translating a book from one language into another, the codons on a strand of mRNA must be translated into the amino acid alphabet of proteins. Translation is the process of synthesizing a chain of amino acids called a polypeptide. Translation requires two major aids: first, a "translator," the molecule that will conduct the translation, and second, a substrate on which the mRNA strand is translated into a new protein, like the translator's "desk." Both of these requirements are fulfilled by other types of RNA. The substrate on which translation takes place is the ribosome.

Remember that many of a cell's ribosomes are found associated with the rough ER, and carry out the synthesis of proteins destined for the Golgi apparatus. Ribosomal RNA (rRNA) is a type of RNA that, together with proteins, composes the structure of the ribosome. Ribosomes exist in the cytoplasm as two distinct components, a small and a large subunit. When an mRNA molecule is ready to be translated, the two subunits come together and attach to the mRNA. The ribosome provides a substrate for translation, bringing together and aligning the mRNA molecule with the molecular "translators" that must decipher its code.

The other major requirement for protein synthesis is the translator molecules that physically "read" the mRNA codons. Transfer RNA (tRNA) is a type of RNA that ferries the appropriate corresponding amino acids to the ribosome, and attaches each new amino acid to the last, building the polypeptide chain one-by-one. Thus tRNA transfers specific amino acids from the cytoplasm to a growing polypeptide. The tRNA molecules must be able to recognize the codons on mRNA and match them with the correct amino acid. The tRNA is modified for this function. On one end of its structure is a binding site for a specific amino acid. On the other end is a base sequence that matches the codon specifying its particular amino acid. This sequence of three bases on the tRNA molecule is called an anticodon. For example, a tRNA responsible for shuttling the amino acid glycine contains a binding site for glycine on one end. On the other end it contains an anticodon that complements the glycine codon (GGA is a codon for glycine, and so the tRNAs anticodon would read CCU). Equipped with its particular cargo and matching anticodon, a tRNA molecule can read its recognized mRNA codon and bring the corresponding amino acid to the growing chain (Figure 3.4.4).

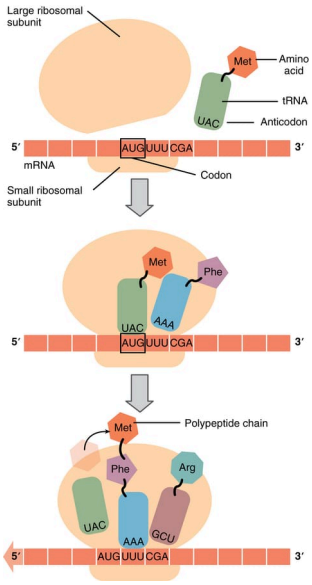


Figure 3.4.4: During translation, the mRNA transcript is "read" by a functional complex consisting of the ribosome and tRNA molecules. tRNAs bring the appropriate amino acids in sequence to the growing polypeptide chain by matching their anti-codons with codons on the mRNA strand. (CC BY-SA 4.0; via Wikimedia Commons). Alternative text description of Figure 3.4.4.

Much like the processes of DNA replication and transcription, translation consists of three main stages: initiation, elongation, and termination. Initiation takes place with the binding of a ribosome to an mRNA transcript. The elongation stage involves the recognition of a tRNA anticodon with the next mRNA codon in the sequence. Once the anticodon and codon sequences are bound (remember, they are complementary base pairs), the tRNA presents its amino acid cargo and the growing polypeptide strand is attached to this next amino acid. This attachment takes place with the assistance of various enzymes and requires energy. The tRNA molecule then releases the mRNA strand, the mRNA strand shifts one codon over in the ribosome, and the next appropriate tRNA arrives with its matching anticodon. This process continues until the final codon on the mRNA is reached which provides a "stop" message that signals termination of translation and triggers the release of the complete, newly synthesized protein. Thus, a gene within the DNA molecule is transcribed into mRNA, which is then translated into a protein product (Figure 3.4.5).

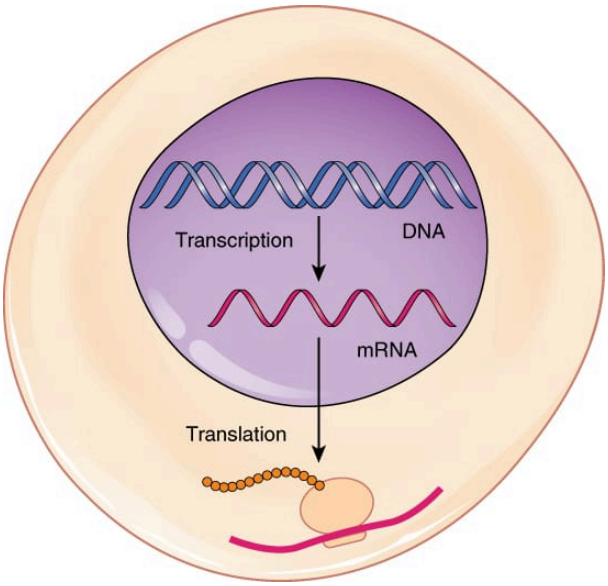


Figure 3.4.5: Transcription within the cell nucleus produces an mRNA molecule, which is modified and then sent into the cytoplasm for translation. The transcript is decoded into a protein with the help of a ribosome and tRNA molecules. (CC BY-SA 4.0; via Wikimedia Commons). Alternative text description of Figure 3.4.5.

Commonly, an mRNA transcription will be translated simultaneously by several adjacent ribosomes. This increases the efficiency of protein synthesis. A single ribosome might translate an mRNA molecule in approximately one minute; so multiple ribosomes aboard a single transcript could produce multiple times the number of the same protein in the same minute. A polyribosome is a

string of ribosomes translating a single mRNA strand.

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3.5: Cell Growth and Division

The Cell Cycle

So far in this chapter, you have read numerous times of the importance and prevalence of cell division. While there are a few cells in the body that do not undergo cell division (such as gametes, red blood cells, most neurons, and some muscle cells), most somatic cells divide regularly. A somatic cell is a general term for a body cell, and all human cells, except for the cells that produce eggs and sperm (which are referred to as germ cells), are somatic cells. Somatic cells contain *two* copies of each of their chromosomes (one copy received from each parent). A homologous pair of chromosomes is the two copies of a single chromosome found in each somatic cell. The human is a diploid organism, having 23 homologous pairs of chromosomes in each of the somatic cells. The condition of having pairs of chromosomes is known as diploidy.

Cells in the body replace themselves over the lifetime of a person. For example, the cells lining the gastrointestinal tract must be frequently replaced when constantly "worn off" by the movement of food through the gut. But what triggers a cell to divide, and how does it prepare for and complete cell division? The cell cycle is the sequence of events in the life of the cell from the moment it is created at the end of a previous cycle of cell division until it then divides itself, generating two new cells.

One "turn" or cycle of the cell cycle consists of two general phases: interphase, followed by mitosis and cytokinesis. Interphase is the period of the cell cycle during which the cell is not dividing. The majority of cells are in interphase most of the time. Mitosis is the division of genetic material, during which the cell nucleus breaks down and two new, fully functional, nuclei are formed. Cytokinesis divides the cytoplasm into two distinctive cells.

Interphase

A cell grows and carries out all normal metabolic functions and processes in a period called G_1 (Figure 3.5.1). G_1 phase (gap 1 phase) is the first gap, or growth phase in the cell cycle. For cells that will divide again, G_1 is followed by replication of the DNA, during the S phase. The S phase (synthesis phase) is period during which a cell replicates its DNA.

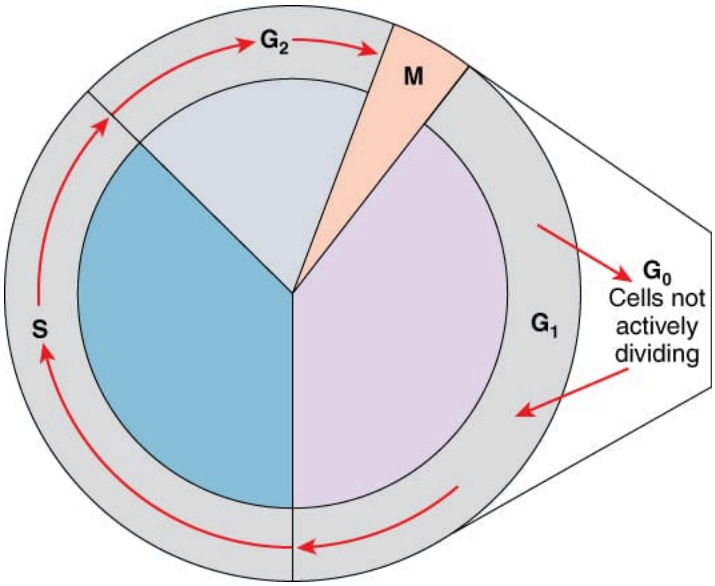


Figure 3.5.1: The two major phases of the cell cycle include mitosis (designated M), when the cell divides, and interphase, when the cell grows and performs all of its normal functions. Interphase is further subdivided into G_1, S, and G_2 phases. (CC BY-SA 4.0; via Wikimedia Commons).
Alternate text description of Figure 3.5.1.

After the synthesis phase, the cell proceeds through the G_2 phase. The G_2 phase is a second gap phase, during which the cell continues to grow and makes the necessary preparations for mitosis. Between G_1, S, and G_2 phases, cells will vary the most in their duration of the G_1 phase. It is here that a cell might spend a couple of hours, or many days. The S phase typically lasts

between 8-10 hours and the G_2 phase approximately 5 hours. In contrast to these phases, the G_0 phase is a resting phase of the cell cycle. Cells that have temporarily stopped dividing and are resting (a common condition) and cells that have permanently ceased dividing (like nerve cells) are said to be in G_0.

The Structure of Chromosomes

Billions of cells in the human body divide every day. During the synthesis phase (S, for DNA synthesis) of interphase, the amount of DNA within the cell precisely doubles. Therefore, after DNA replication but before cell division, each cell actually contains *two* copies of each chromosome. Each copy of the chromosome is referred to as a sister chromatid and is physically bound to the other copy.(Note that the term "sister chromatid" is used regardless of the sex of the person.) The centromere is the structure that attaches one sister chromatid to another. Because a human cell has 46 chromosomes, during this phase, there are 92 chromatids (46 × 2) in the cell. Make sure not to confuse the concept of a pair of chromatids (one chromosome and its exact copy attached during mitosis) and a homologous pair of chromosomes (two paired chromosomes which were inherited separately, one from each parent) (Figure 3.5.2).

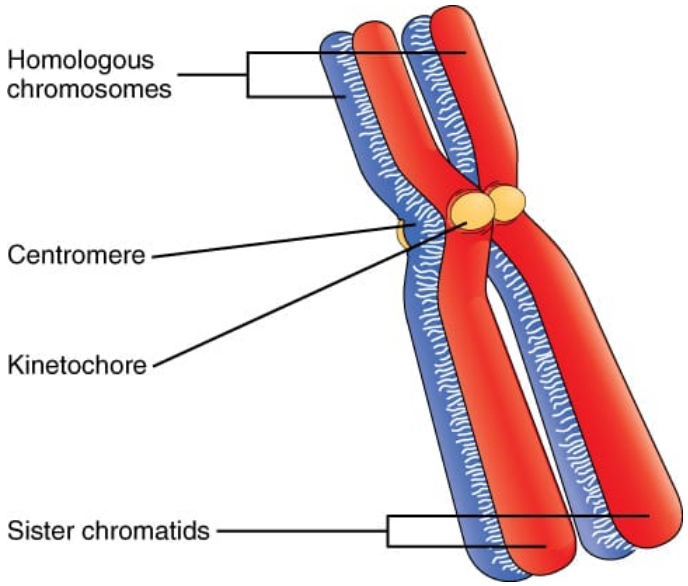


Figure 3.5.2 :A Homologous Pair of Chromosomes with their Attached Sister Chromatids. Each member of the pair was separately inherited from one parent. Each chromosome in the homologous pair is also bound to an identical sister chromatid, which is produced by DNA replication, and results in the familiar “X” shape. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 3.5.2.

Mitosis and Cytokinesis

The mitotic phase of the cell typically takes between 1 and 2 hours. During this phase, a cell undergoes two major processes. First, it completes mitosis, during which the contents of the nucleus are equitably pulled apart and distributed between its two halves. Cytokinesis then occurs, dividing the cytoplasm and cell body into two new cells. Mitosis is divided into four major stages that take place after interphase (Figure 3.5.3) and in the following order: prophase, metaphase, anaphase, and telophase. The process is then followed by cytokinesis.

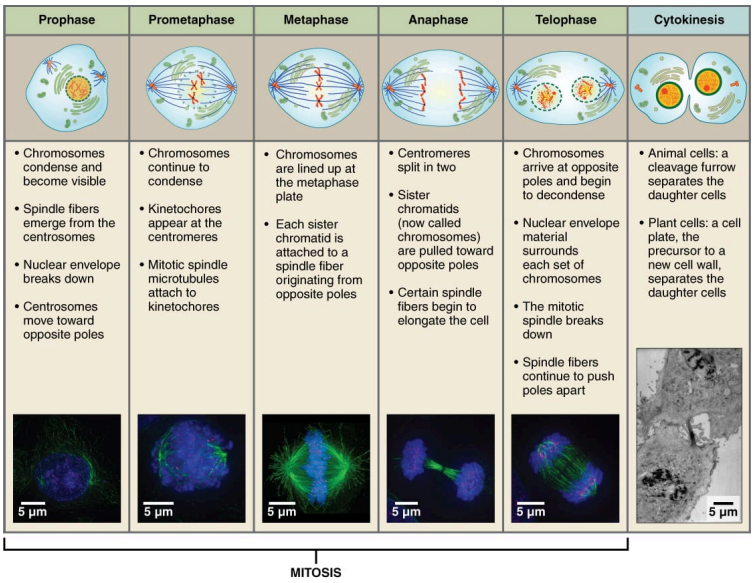


Figure 3.5.3: The stages of cell division oversee the separation of identical genetic material into two new nuclei, followed by the division of the cytoplasm. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 3.5.3.

Phases of Mitosis and Cytokinesis

Microscope images beneath each stage show real cells at each phase of division.

Prophase is the first phase of mitosis, during which the loosely packed chromatin coils and condenses into visible chromosomes. During prophase, each chromosome becomes visible with its identical partner attached, forming the familiar X-shape of sister chromatids. The nucleolus disappears early during this phase, and the nuclear envelope also disintegrates.

A major occurrence during prophase concerns a very important structure that contains the origin site for microtubule growth. Recall the cellular structures called centrioles that serve as origin points from which microtubules extend. These tiny structures also play a very important role during mitosis. A centrosome is a pair of centrioles together. The cell contains two centrosomes side-by-side, which begin to move apart during prophase. As the centrosomes migrate to two different sides of the cell, microtubules begin to extend from each like long fingers from two hands extending toward each other. The mitotic spindle is the structure composed of the centrosomes and their emerging microtubules.

Near the end of prophase there is an invasion of the nuclear area by microtubules from the mitotic spindle. The nuclear membrane has disintegrated, and the microtubules attach themselves to the centromeres that adjoin pairs of sister chromatids. The kinetochore is a protein structure on the centromere that is the point of attachment between the mitotic spindle and the sister chromatids. This stage is referred to as late prophase or “prometaphase” to indicate the transition between prophase and metaphase.

Metaphase is the second stage of mitosis. During this stage, the sister chromatids, with their attached microtubules, line up along a linear plane in the middle of the cell. A metaphase plate forms between the centrosomes that are now located at either end of the cell. The metaphase plate is the name for the plane through the center of the spindle on which the sister chromatids are positioned. The microtubules are now poised to pull apart the sister chromatids and bring one from each pair to each side of the cell.

Anaphase is the third stage of mitosis. Anaphase takes place over a few minutes, when the pairs of sister chromatids are separated from one another, forming individual chromosomes once again. These chromosomes are pulled to opposite ends of the cell by their kinetochores, as the microtubules shorten. Each end of the cell receives one partner from each pair of sister chromatids, ensuring that the two new daughter cells will contain identical genetic material.

Telophase is the final stage of mitosis. Telophase is characterized by the formation of two new daughter nuclei at either end of the dividing cell. These newly formed nuclei surround the genetic material, which uncoils such that the chromosomes return to loosely packed chromatin. Nucleoli also reappear within the new nuclei, and the mitotic spindle breaks apart, each new cell receiving its own complement of DNA, organelles, membranes, and centrioles. At this point, the cell is already beginning to split

in half as cytokinesis begins.

The cleavage furrow is a contractile band made up of microfilaments that forms around the midline of the cell during cytokinesis. (Recall that microfilaments consist of actin.) This contractile band squeezes the two cells apart until they finally separate. Two new cells are now formed. One of these cells (the “stem cell”) enters its own cell cycle; able to grow and divide again at some future time. The other cell transforms into the functional cell of the tissue, typically replacing an “old” cell there.

Imagine a cell that completed mitosis but never underwent cytokinesis. In some cases, a cell may divide its genetic material and grow in size, but fail to undergo cytokinesis. This results in larger cells with more than one nucleus. Usually this is an unwanted aberration and can be a sign of cancerous cells.

Cell Cycle Control

A very elaborate and precise system of regulation controls direct the way cells proceed from one phase to the next in the cell cycle and begin mitosis. The control system involves molecules within the cell as well as external triggers. These internal and external control triggers provide “stop” and “advance” signals for the cell. Precise regulation of the cell cycle is critical for maintaining the health of an organism, and loss of cell cycle control can lead to cancer.

Mechanisms of Cell Cycle Control

As the cell proceeds through its cycle, each phase involves certain processes that must be completed before the cell should advance to the next phase. A checkpoint is a point in the cell cycle at which the cycle can be signaled to move forward or stopped. At each of these checkpoints, different varieties of molecules provide the stop or go signals, depending on certain conditions within the cell. A cyclin is one of the primary classes of cell cycle control molecules (Figure 3.5.4). A cyclin-dependent kinase (CDK) is one of a group of molecules that work together with cyclins to determine progression past cell checkpoints. By interacting with many additional molecules, these triggers push the cell cycle forward unless prevented from doing so by “stop” signals, if for some reason the cell is not ready. At the G_1 checkpoint, the cell must be ready for DNA synthesis to occur. At the G_2 checkpoint the cell must be fully prepared for mitosis. Even during mitosis, a crucial stop and go checkpoint in metaphase ensures that the cell is fully prepared to complete cell division. The metaphase checkpoint ensures that all sister chromatids are properly attached to their respective microtubules and lined up at the metaphase plate before the signal is given to separate them during anaphase.

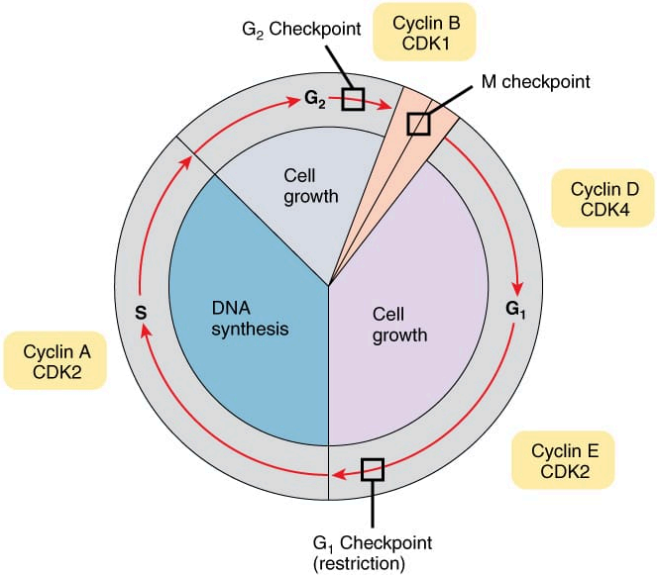


Figure 3.5.4: Cells proceed through the cell cycle under the control of a variety of molecules, such as cyclins and cyclin-dependent kinases. These control molecules determine whether or not the cell is prepared to move into the following stage. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 3.5.4.

The Cell Cycle Out of Control: Implications

Most people understand that cancer or tumors are caused by abnormal cells that multiply continuously. If the abnormal cells

continue to divide unstopped, they can damage the tissues around them, spread to other parts of the body, and eventually result in death. In healthy cells, the tight regulation mechanisms of the cell cycle prevent this from happening, while failures of cell cycle control can cause unwanted and excessive cell division. Failures of control may be caused by inherited genetic abnormalities that compromise the function of certain “stop” and “go” signals. Environmental insult that damages DNA can also cause dysfunction in those signals. Often, a combination of both genetic predisposition and environmental factors lead to cancer.

The process of a cell escaping its normal control system and becoming cancerous may actually happen throughout the body quite frequently. Fortunately, certain cells of the immune system are capable of recognizing cells that have become cancerous and destroying them. However, in certain cases the cancerous cells remain undetected and continue to proliferate. If the resulting tumor does not pose a threat to surrounding tissues, it is said to be benign and can usually be easily removed. If capable of damage, the tumor is considered malignant and the patient is diagnosed with cancer.

Homeostatic Imbalances

Cancer Arises from Homeostatic Imbalances

Cancer is an extremely complex condition, capable of arising from a wide variety of genetic and environmental causes. Typically, mutations or aberrations in a cell’s DNA that compromise normal cell cycle control systems lead to cancerous tumors. Cell cycle control is an example of a homeostatic mechanism that maintains proper cell function and health. While progressing through the phases of the cell cycle, a large variety of intracellular molecules provide stop and go signals to regulate movement forward to the next phase. These signals are maintained in an intricate balance so that the cell only proceeds to the next phase when it is ready. This homeostatic control of the cell cycle can be thought of like a car’s cruise control. Cruise control will continually apply just the right amount of acceleration to maintain a desired speed, unless the driver hits the brakes, in which case the car will slow down. Similarly, the cell includes molecular messengers, such as cyclins, that push the cell forward in its cycle.

In addition to cyclins, a class of proteins that are encoded by genes called proto-oncogenes provide important signals that regulate the cell cycle and move it forward. Examples of proto-oncogene products include cell-surface receptors for growth factors, or cell-signaling molecules, two classes of molecules that can promote DNA replication and cell division. In contrast, a second class of genes known as tumor suppressor genes sends stop signals during a cell cycle. For example, certain protein products of tumor suppressor genes signal potential problems with the DNA and thus stop the cell from dividing, while other proteins signal the cell to die if it is damaged beyond repair. Some tumor suppressor proteins also signal a sufficient surrounding cellular density, which indicates that the cell need not presently divide. The latter function is uniquely important in preventing tumor growth: normal cells exhibit a phenomenon called “contact inhibition;” thus, extensive cellular contact with neighboring cells causes a signal that stops further cell division.

These two contrasting classes of genes, proto-oncogenes and tumor suppressor genes, are like the accelerator and brake pedal of the cell’s own “cruise control system,” respectively. Under normal conditions, these stop and go signals are maintained in a homeostatic balance. Generally speaking, there are two ways that the cell’s cruise control can lose control: a malfunctioning (overactive) accelerator, or a malfunctioning (underactive) brake. When compromised through a mutation, or otherwise altered, proto-oncogenes can be converted to oncogenes, which produce Oncoproteins that push a cell forward in its cycle and stimulate cell division even when it is undesirable to do so. For example, a cell that should be programmed to self-destruct (a process called apoptosis) due to extensive DNA damage might instead be triggered to proliferate by an oncoprotein. On the other hand, a dysfunctional tumor suppressor gene may fail to provide the cell with a necessary stop signal, also resulting in unwanted cell division and proliferation.

A delicate homeostatic balance between the many proto-oncogenes and tumor suppressor genes delicately controls the cell cycle and ensures that only healthy cells replicate. Therefore, a disruption of this homeostatic balance can cause aberrant cell division and cancerous growths.

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3.6: Cellular Differentiation

Overview

How does a complex organism such as a human develop from a single cell—a fertilized egg—into the vast array of cell types such as nerve cells, muscle cells, and epithelial cells that characterize the adult? Throughout development and adulthood, the process of cellular differentiation leads cells to assume their final morphology and physiology. Differentiation is the process by which unspecialized cells become specialized to carry out distinct functions.

Stem Cells

A stem cell is an unspecialized cell that can divide without limit as needed and can, under specific conditions, differentiate into specialized cells. Stem cells are divided into several categories according to their potential to differentiate.

The first embryonic cells that arise from the division of the zygote are the ultimate stem cells; these stems cells are described as totipotent because they have the potential to differentiate into any of the cells needed to enable an organism to grow and develop.

The embryonic cells that develop from totipotent stem cells and are precursors to the fundamental tissue layers of the embryo are classified as pluripotent. A pluripotent stem cell is one that has the potential to differentiate into any type of human tissue but cannot support the full development of an organism. These cells then become slightly more specialized, and are referred to as multipotent cells.

A multipotent stem cell has the potential to differentiate into different types of cells within a given cell lineage or small number of lineages, such as a red blood cell or white blood cell.

Finally, multipotent cells can become further specialized oligopotent cells. An oligopotent stem cell is limited to becoming one of a few different cell types. In contrast, a unipotent cell is fully specialized and can only reproduce to generate more of its own specific cell type.

Stem cells are unique in that they can also continually divide and regenerate new stem cells instead of further specializing. There are different stem cells present at different stages of a human's life. They include the embryonic stem cells of the embryo, fetal stem cells of the fetus, and adult stem cells in the adult. One type of adult stem cell is the epithelial stem cell, which gives rise to the keratinocytes in the multiple layers of epithelial cells in the epidermis of skin. Adult bone marrow has three distinct types of stem cells: hematopoietic stem cells, which give rise to red blood cells, white blood cells, and platelets (Figure $3.6.1$); endothelial stem cells, which give rise to the endothelial cell types that line blood and lymph vessels; and mesenchymal stem cells, which give rise to the different types of muscle cells.

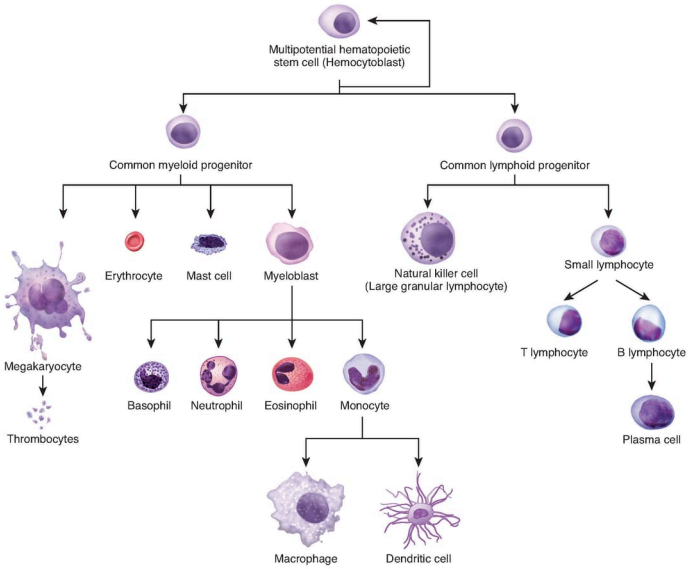


Figure 3.6.1: The process of hematopoiesis involves the differentiation of multipotent cells into blood and immune cells. The multipotent hematopoietic stem cells give rise to many different cell types, including the cells of the immune system and red blood cells. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 3.6.1.

Differentiation

When a cell differentiates (becomes more specialized), it may undertake major changes in its size, shape, metabolic activity, and overall function. Because all cells in the body, beginning with the fertilized egg, contain the same DNA, how do the different cell types come to be so different? The answer is analogous to a movie script. The different actors in a movie all read from the same script, however, they are each only reading their own part of the script. Similarly, all cells contain the same full complement of DNA, but each type of cell only "reads" the portions of DNA that are relevant to its own function. In biology, this is referred to as the unique genetic expression of each cell.

In order for a cell to differentiate into its specialized form and function, it need only manipulate those genes (and thus those proteins) that will be expressed, and not those that will remain silent. The primary mechanism by which genes are turned "on" or "off" is through transcription factors. A transcription factor is one of a class of proteins that bind to specific genes on the DNA molecule and either promote or inhibit their transcription (Figure 3.6.2.

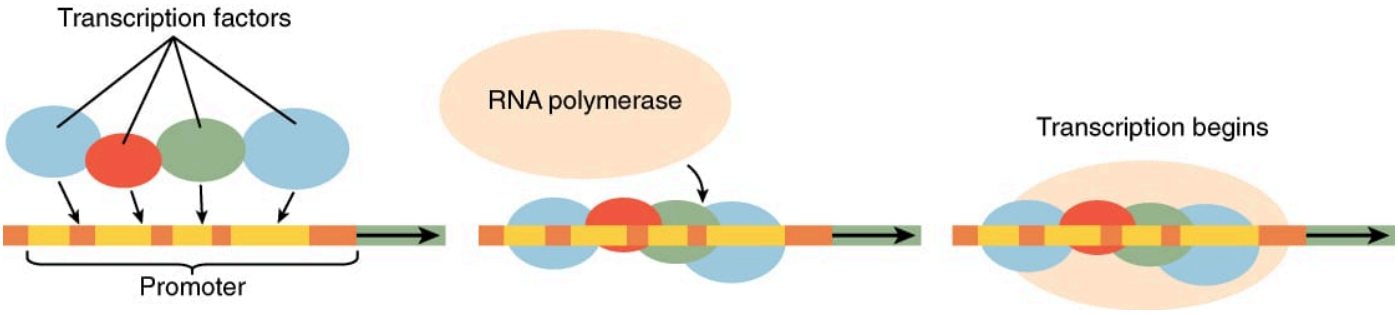


Figure 3.6.2: Transcription initiation diagram showing transcription factors, promoter binding, and RNA polymerase. (CC BY-SA 4.0; via Cellular Differentiation). Alternate text description of Figure 3.6.2.

Stem Cell Research

Stem cell research aims to find ways to use stem cells to regenerate and repair cellular damage. Over time, most adult cells undergo the wear and tear of aging and lose their ability to divide and repair themselves. Stem cells do not display a particular morphology or function. Adult stem cells, which exist as a small subset of cells in most tissues, keep dividing and can differentiate into a number of specialized cells generally formed by that tissue. These cells enable the body to renew and repair body tissues.

The mechanisms that induce a non-differentiated cell to become a specialized cell are poorly understood. In a laboratory setting, it is possible to induce stem cells to differentiate into specialized cells by changing the physical and chemical conditions of growth. Several sources of stem cells are used experimentally and are classified according to their origin and potential for differentiation. Human embryonic stem cells (hESCs) are extracted from embryos and are pluripotent. The adult stem cells that are present in many organs and differentiated tissues, such as bone marrow and skin, are multipotent, being limited in differentiation to the types of cells found in those tissues. The stem cells isolated from umbilical cord blood are also multipotent, as are cells from deciduous teeth (baby teeth). Researchers have recently developed induced pluripotent stem cells (iPSCs) from mouse and human adult stem cells. These cells are genetically reprogrammed multipotent adult cells that function like embryonic stem cells; they are capable of generating cells characteristic of all three germ layers.

Because of their capacity to divide and differentiate into specialized cells, stem cells offer a potential treatment for diseases such as diabetes and heart disease (Figure 3.6.3). Cell-based therapy refers to treatment in which stem cells induced to differentiate in a growth dish are injected into a patient to repair damaged or destroyed cells or tissues. Many obstacles must be overcome for the application of cell-based therapy. Although embryonic stem cells have a nearly unlimited range of differentiation potential, they are seen as foreign by the patient's immune system and may trigger rejection. Also, the destruction of embryos to isolate embryonic stem cells raises considerable ethical and legal questions.

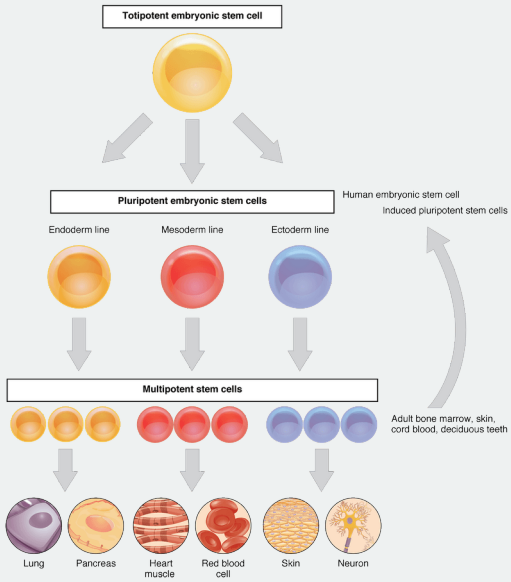


Figure 3.6.3: The capacity of stem cells to differentiate into specialized cells make them potentially valuable in therapeutic applications designed to replace damaged cells of different body tissues. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 3.6.3.

In contrast, adult stem cells isolated from a patient are not seen as foreign by the body, but they have a limited range of differentiation. Some individuals bank the cord blood or deciduous teeth of their child, storing away those sources of stem cells for future use, should their child need it. Induced pluripotent stem cells are considered a promising advance in the field because using them avoids the legal, ethical, and immunological pitfalls of embryonic stem cells.

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3.7: Terms and Definitions

Key Terms

Select to view definitions

Active transport
: form of transport across the cell membrane that requires input of cellular energy

Amphipathic
: describes a molecule that exhibits a difference in polarity between its two ends, resulting in a difference in water solubility

Anaphase
: third stage of mitosis (and meiosis), during which sister chromatids separate into two new nuclear regions of a dividing cell

Anticodon
: consecutive sequence of three nucleotides on a tRNA molecule that is complementary to a specific codon on an mRNA molecule

Autolysis
: breakdown of cells by their own enzymatic action

Autophagy
: lysosomal breakdown of a cell's own components

Cell cycle
: life cycle of a single cell, from its birth until its division into two new daughter cells

Cell membrane
: membrane surrounding all animal cells, composed of a lipid bilayer interspersed with various molecules; also known as plasma membrane

Centriole
: small, self-replicating organelle that provides the origin for microtubule growth and moves DNA during cell division

Centromere
: region of attachment for two sister chromatids

Centrosome
: cellular structure that organizes microtubules during cell division

Channel protein
: membrane-spanning protein that has an inner pore which allows the passage of one or more substances

Checkpoint
: progress point in the cell cycle during which certain conditions must be met in order for the cell to proceed to a subsequence phase

Chromatin
: substance consisting of DNA and associated proteins

Chromosome
: condensed version of chromatin

Cilia
: small appendage on certain cells formed by microtubules and modified for movement of materials across the

cellular surface

Cleavage furrow
contractile ring that forms around a cell during cytokinesis that pinches the cell into two halves

Codon
consecutive sequence of three nucleotides on an mRNA molecule that corresponds to a specific amino acid

Concentration gradient
difference in the concentration of a substance between two regions

Cyclin
one of a group of proteins that function in the progression of the cell cycle

Cyclin-dependent kinase (CDK)
one of a group of enzymes associated with cyclins that help them perform their functions

Cytokinesis
final stage in cell division, where the cytoplasm divides to form two separate daughter cells

Cytoplasm
internal material between the cell membrane and nucleus of a cell, mainly consisting of a water-based fluid called cytosol, within which are all the other organelles and cellular solute and suspended materials

Cytoskeleton
“skeleton” of a cell; formed by rod-like proteins that support the cell’s shape and provide, among other functions, locomotive abilities

Cytosol
clear, semi-fluid medium of the cytoplasm, made up mostly of water

Diffusion
movement of a substance from an area of higher concentration to one of lower concentration

Diploid
condition marked by the presence of a double complement of genetic material (two sets of chromosomes, one set inherited from each of two parents)

DNA polymerase
enzyme that functions in adding new nucleotides to a growing strand of DNA during DNA replication

DNA replication
process of duplicating a molecule of DNA

Electrical gradient
difference in the electrical charge (potential) between two regions

Endocytosis
import of material into the cell by formation of a membrane-bound vesicle

Endoplasmic reticulum (ER)
cellular organelle that consists of interconnected membrane-bound tubules, which may or may not be associated with ribosomes (rough type or smooth type, respectively)

Exocytosis
export of a substance out of a cell by formation of a membrane-bound vesicle

Exon
one of the coding regions of an mRNA molecule that remain after splicing

Extracellular fluid (ECF)
fluid exterior to cells; includes the interstitial fluid, blood plasma, and fluid found in other reservoirs in the body

Facilitated diffusion
diffusion of a substance with the aid of a membrane protein

Flagellum
appendage on certain cells formed by microtubules and modified for movement

G_0 phase
phase of the cell cycle, usually entered from the G_1 phase; characterized by long or permanent periods where the cell does not move forward into the DNA synthesis phase

G_1 phase
first phase of the cell cycle, after a new cell is born

G_2 phase
third phase of the cell cycle, after the DNA synthesis phase

Gene
functional length of DNA that provides the genetic information necessary to build a protein

Gene expression
active interpretation of the information coded in a gene to produce a functional gene product

Genome
entire complement of an organism's DNA; found within virtually every cell

Glycocalyx
coating of sugar molecules that surrounds the cell membrane

Glycoprotein
protein that has one or more carbohydrates attached

Golgi apparatus
cellular organelle formed by a series of flattened, membrane-bound sacs that functions in protein modification, tagging, packaging, and transport

Helicase
enzyme that functions to separate the two DNA strands of a double helix during DNA replication

Histone
family of proteins that associate with DNA in the nucleus to form chromatin

Homologous
describes two copies of the same chromosome (not identical), one inherited from each parent

Hydrophilic
describes a substance or structure attracted to water

Hydrophobic
describes a substance or structure repelled by water

Hypertonic
describes a solution concentration that is higher than a reference concentration

Hypotonic
describes a solution concentration that is lower than a reference concentration

Integral protein
membrane-associated protein that spans the entire width of the lipid bilayer

Intermediate filament
type of cytoskeletal filament made of keratin, characterized by an intermediate thickness, and playing a role in resisting cellular tension

Interphase
entire life cycle of a cell, excluding mitosis

Interstitial fluid (IF)
fluid in the small spaces between cells not contained within blood vessels

Intracellular fluid (ICF)
fluid in the cytosol of cells

Intron
non-coding regions of a pre-mRNA transcript that may be removed during splicing

Iisotonic
describes a solution concentration that is the same as a reference concentration

Kinetochore
region of a centromere where microtubules attach to a pair of sister chromatids

Lligand
molecule that binds with specificity to a specific receptor molecule

Lysosome
membrane-bound cellular organelle originating from the Golgi apparatus and containing digestive enzymes

Messenger RNA (mRNA)
nucleotide molecule that serves as an intermediate in the genetic code between DNA and protein

Metaphase
second stage of mitosis (and meiosis), characterized by the linear alignment of sister chromatids in the center of the cell

Metaphase plate
linear alignment of sister chromatids in the center of the cell, which takes place during metaphase

Microfilament
the thinnest of the cytoskeletal filaments; composed of actin subunits that function in muscle contraction and cellular structural support

Microtubule
the thickest of the cytoskeletal filaments, composed of tubulin subunits that function in cellular movement and structural support

Mitochondrion
one of the cellular organelles bound by a double lipid bilayer that function primarily in the production of cellular energy (ATP)

Mitosis
division of genetic material, during which the cell nucleus breaks down and two new, fully functional, nuclei are formed

Mitotic phase
phase of the cell cycle in which a cell undergoes mitosis

Mitotic spindle
network of microtubules, originating from centrioles, that arranges and pulls apart chromosomes during mitosis

Multipotent
describes the condition of being able to differentiate into different types of cells within a given cell lineage or small number of lineages, such as a red blood cell or white blood cell

Mutation
change in the nucleotide sequence in a gene within a cell's DNA

Nuclear envelope
membrane that surrounds the nucleus; consisting of a double lipid-bilayer

Nuclear pore
one of the small, protein-lined openings found scattered throughout the nuclear envelope

Nucleolus
small region of the nucleus that functions in ribosome synthesis

Nucleosome
unit of chromatin consisting of a DNA strand wrapped around histone proteins

Nucleus
cell's central organelle; contains the cell's DNA

Oligopotent
describes the condition of being more specialized than multipotency; the condition of being able to differentiate into one of a few possible cell types

Organelle
any of several different types of membrane-enclosed specialized structures in the cell that perform specific functions for the cell

Osmosis
diffusion of water molecules down their concentration gradient across a selectively permeable membrane

Passive transport
form of transport across the cell membrane that does not require input of cellular energy

Peripheral protein
membrane-associated protein that does not span the width of the lipid bilayer, but is attached peripherally to integral proteins, membrane lipids, or other components of the membrane

Peroxisome
membrane-bound organelle that contains enzymes primarily responsible for detoxifying harmful substances

Phagocytosis
endocytosis of large particles

Pinocytosis
endocytosis of fluid

Pluripotent
describes the condition of being able to differentiate into a large variety of cell types

Polypeptide
chain of amino acids linked by peptide bonds

Polyribosome
simultaneous translation of a single mRNA transcript by multiple ribosomes

Promoter
region of DNA that signals transcription to begin at that site within the gene

Prophase
first stage of mitosis (and meiosis), characterized by breakdown of the nuclear envelope and condensing of the chromatin to form chromosomes

Proteome
full complement of proteins produced by a cell (determined by the cell's specific gene expression)

Reactive oxygen species (ROS)
a group of extremely reactive peroxides and oxygen-containing radicals that may contribute to cellular damage

Receptor
protein molecule that contains a binding site for another specific molecule (called a ligand)

Receptor-mediated endocytosis
endocytosis of ligands attached to membrane-bound receptors

Ribosomal RNA (rRNA)
RNA that makes up the subunits of a ribosome

Ribosome
cellular organelle that functions in protein synthesis

RNA polymerase
enzyme that unwinds DNA and then adds new nucleotides to a growing strand of RNA for the transcription phase of protein synthesis

S phase
stage of the cell cycle during which DNA replication occurs

Selective permeability
feature of any barrier that allows certain substances to cross but excludes others

Sister chromatid
one of a pair of identical chromosomes, formed during DNA replication

Sodium-potassium pump
(also, Na^+/K^+ ATP-ase) membrane-embedded protein pump that uses ATP to move Na^+ out of a cell and K^+ into the cell

Somatic cell
all cells of the body excluding gamete cells

Spliceosome
complex of enzymes that serves to splice out the introns of a pre-mRNA transcript

Splicing
the process of modifying a pre-mRNA transcript by removing certain, typically non-coding, regions

Stem cell
cell that is oligo-, multi-, or pleuripotent that has the ability to produce additional stem cells rather than becoming further specialized

Telophase
final stage of mitosis (and meiosis), preceding cytokinesis, characterized by the formation of two new daughter nuclei

Totipotent
embryonic cells that have the ability to differentiate into any type of cell and organ in the body

Transcription
process of producing an mRNA molecule that is complementary to a particular gene of DNA

Transcription factor
one of the proteins that regulate the transcription of genes

Transfer RNA (tRNA)
molecules of RNA that serve to bring amino acids to a growing polypeptide strand and properly place them into the sequence

Translation
process of producing a protein from the nucleotide sequence code of an mRNA transcript

Triplet
consecutive sequence of three nucleotides on a DNA molecule that, when transcribed into an mRNA codon, corresponds to a particular amino acid

Unipotent
describes the condition of being committed to a single specialized cell type

Vesicle
membrane-bound structure that contains materials within or outside of the cell

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3.8: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. A sodium ion channel spans all the way through the cell's plasma membrane and provides a tunnel for Na^+ to move in or out of the cell. Because it is embedded in (and passes through) the membrane, this ion channel is best classified as which type of membrane protein?
   A. Receptor protein
   B. Integral protein
   C. Peripheral protein
   D. Glycoprotein
2. A drop of dye is placed into a beaker of water and, over time, becomes evenly distributed without stirring. The dye molecules are moving:
   A. Up their electrical gradient
   B. Up their electrochemical gradient
   C. Down their pressure gradient
   D. Down their concentration gradient
3. A cell uses energy from ATP to pump ions against their concentration gradient and also uses ATP to engulf large particles such as bacteria. Both of these processes are examples of:
   A. Endocytosis
   B. Passive transport
   C. Active transport
   D. Facilitated diffusion
4. Under the microscope, you notice that part of the endoplasmic reticulum (ER) has many tiny dark dots attached to its surface. This region therefore appears "rough." These dots are:
   A. Peroxisomes
   B. Ribosomes
   C. Lysosomes
   D. Proteins
5. A cell is actively producing secreted and membrane proteins. Which of the following functions is specifically associated with the rough endoplasmic reticulum during this process?
   A. Production of proteins
   B. Detoxification of certain substances
   C. Synthesis of steroid hormones
   D. Regulation of intracellular calcium concentration
6. A muscle cell is using large amounts of glucose and oxygen and needs a great deal of ATP to keep contracting. Which organelles are primarily responsible for producing large quantities of ATP under these conditions?
   A. Mitochondria
   B. Peroxisomes
   C. Lysosomes
   D. Endoplasmic reticulum
7. A neuron maintains a high concentration of Na^+ outside the cell and a high concentration of K^+ inside the cell. To do this,

it continuously uses ATP to run the Na⁺/K⁺ pump in its membrane. This pump moves ions:

A. Down their concentration gradients without ATP
B. Against their concentration gradients using ATP
C. Only down their electrical gradients
D. By simple diffusion through the lipid bilayer

8. A white blood cell encounters bacteria in the tissue fluid. It extends parts of its membrane around the bacteria and engulfs them into vesicles, which then fuse with lysosomes. This specific process of “cell eating” is best described as:
   A. Pinocytosis
   B. Phagocytosis
   C. Receptor-mediated exocytosis
   D. Simple diffusion
9. A researcher observes that a certain hormone binds to a protein on the cell surface, but the protein itself does not form a pore or channel. Instead, upon binding, it activates an internal signaling cascade. This membrane protein is functioning primarily as a:
   A. Ion channel (integral protein)
   B. Receptor protein
   C. Peripheral cytoskeletal protein
   D. Carrier protein for facilitated diffusion
10. Microfilaments, intermediate filaments, and microtubules are three major components of the cytoskeleton. Which feature is common to all three?
   A. They all serve to scaffold the organelles within the cell.
   B. They are all characterized by roughly the same diameter.
   C. They are all polymers of protein subunits.
   D. They all help the cell resist compression and tension to the same extent.
11. A certain genetic disease causes defects in the microtubules of epithelial cells lining the respiratory tract. The cilia in these cells do not beat properly. Which cytoskeletal component is directly affected?
   A. Microfilaments (actin filaments)
   B. Intermediate filaments
   C. Microtubules
   D. Keratin fibers only
12. Both the nucleus and the mitochondria are important organelles in eukaryotic cells. Which feature do they share?
   A. Protein-lined membrane pores in a single membrane
   B. A double membrane surrounding the organelle
   C. The synthesis of ribosomes in their interior
   D. The direct production of all cellular ATP
13. A student examines a nucleus under the electron microscope and focuses on a darker region called the nucleolus. Which structure would most likely be found there?
   A. Chromatin (DNA + histone complex) spread throughout the nucleus
   B. Histones alone
   C. Ribosomes (or ribosomal subunits) being assembled
   D. Nucleosomes arranged into condensed chromosomes
14. A segment of DNA has the base sequence G C T T A T A T on one strand. What is the complementary DNA sequence on the opposite strand?
   A. T A G G C G C G
   B. A T C C G C G C
   C. C G A A T A T A
   D. T G C C T C T C
15. Think about how DNA is packaged in the nucleus. DNA wraps around proteins to form nucleosomes, nucleosomes coil to form chromatin, and chromatin further condenses into chromosomes. Which option correctly orders these structures from least to most complex?
   A. DNA, nucleosome, chromatin, chromosome
   B. Nucleosome, DNA, chromosome, chromatin
   C. DNA, chromatin, nucleosome, chromosome
   D. Nucleosome, chromatin, DNA, chromosome
16. A student looks at a dividing cell under the microscope and sees chromosomes condensed and clearly visible, but not yet lined up in the middle of the cell. Which phase is this?
   A. Interphase

B. Prophase
C. Metaphase
D. Anaphase

17. A cell has chromosomes at opposite poles, and a new nuclear envelope is beginning to form around each set. The chromosomes are starting to decondense. Which phase is this?
A. Prophase
B. Metaphase
C. Anaphase
D. Telophase

18. In a growing embryo, certain cells divide very rapidly. Which combination promotes faster progression through the cell cycle?
A. Low cyclin levels and low CDK activity
B. High cyclin levels and active cyclin-dependent kinases (CDKs)
C. No cyclins and no CDKs
D. Only tumor suppressor genes active

19. A gene encoding a membrane protein is being expressed in a liver cell. The first step in using this gene to make a protein is:
A. Translation of mRNA on a ribosome
B. Transcription of DNA into pre-mRNA in the nucleus
C. Replication of the gene during S phase
D. Export of the protein through the Golgi apparatus

20. A ribosome is bound to an mRNA molecule in the cytoplasm. As it moves along the mRNA, it reads three-nucleotide “words” that specify amino acids. Each “word” is called a:
A. Anticodon
B. Codon
C. Intron
D. Promoter

21. An mRNA codon reads 5′–AUG–3′. Which amino acid does this codon typically specify, and what is its special role?
A. Glycine; signals the end of translation
B. Methionine; usually serves as the start codon
C. Proline; involved only in collagen synthesis
D. Tryptophan; only found in bacteria

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3.9: Applied Thinking - Self Assessment

Challenge Yourself

a. Critical thinking is essential in a time of endless information and AI, helping you move from passive memorizing to actively making sense of what you learn.

b. Use these critical thinking prompts for self-assessment after studying the Cell chapter. As you respond:

- Write your answers in your own words, using complete sentences. Organize your ideas into short paragraphs rather than lists or bullet points.
- Emphasize your reasoning process. Do not just state a brief "right answer"; explain why it is correct, how you know, and what evidence or examples support it.
- Use appropriate scientific vocabulary for this chapter (e.g., simple diffusion, facilitated diffusion, active transport, transcription, transcription factors, translation, phases of mitosis, cyclins) and define terms briefly if you are unsure.
- When a question asks you to compare, contrast, or explain why/how:
  - Clearly state the similarities and/or differences between the items.
  - Include at least one reason, mechanism, or concrete example to support each point you make.
- Treat these questions as a self-assessment tool:
  - First, try to answer from memory, without looking at your notes or textbook.
  - Then consult your notes, textbook, or other reliable resources and revise your answer to correct or deepen it.
  - Mark any questions where you felt uncertain, changed your answer a lot, or needed to look up many details. Use those marks to identify topics you should review again.

c. By following these steps, you will use the critical thinking questions not just to check what you remember, but to build deeper, more flexible understanding of human tissues and how structure supports function.

1. Many small, nonpolar substances (such as oxygen, carbon dioxide, and some lipids) can diffuse directly through the phospholipid bilayer, but ions and large polar molecules cannot. In 1 short paragraph, explain which chemical properties of these "easily diffusing" molecules allow them to cross the lipid bilayer without assistance. Then give one specific example of a substance that cannot diffuse easily through the bilayer and explain why its properties prevent this.
2. Receptor-mediated endocytosis is often called more "selective" or "specific" than phagocytosis or pinocytosis. In 1–2 paragraphs, explain what makes receptor-mediated endocytosis more selective. In your answer, clearly describe the roles of receptors, ligands, and coated pits. Then briefly compare this process with phagocytosis and pinocytosis, focusing on how materials are taken into the cell in each case.
3. Osmosis, diffusion, filtration, and the movement of ions away from like charges are all examples of passive transport processes. In a short essay, first identify and explain the common underlying principle that all passive processes share. Then choose at least two of these processes and contrast them in terms of:
   a. What is moving (water, solutes, ions, fluid as a whole)
   b. What drives the movement (concentration gradient, pressure gradient, electrical gradient).
4. The endoplasmic reticulum (ER), mitochondria, and Golgi apparatus all have complex internal membranes and folded structures. Choose any two of these organelles. In a well-organized paragraph, explain how specific structural features of each one (such as membrane folds, internal spaces, or location in the cell) help it carry out its main function(s), such as protein synthesis, energy production, or packaging and secretion.
5. Lysosomes and peroxisomes are both membrane-bound organelles involved in breaking down substances inside the cell. Write a brief comparison in which you describe at least two similarities in their structure and primary function, in the cell; identify at least one important difference in the types of molecules they break down or the enzymes they contain, and explain why this difference is important for maintaining cell health.
6. DNA replication is described as "semiconservative." In your own words, explain what this term means at the molecular level. Why might this method of replication be an advantage for maintaining the integrity of the genetic information?
7. Both transcription and DNA replication involve using a DNA template to build a new nucleic acid strand. In 1–2 paragraphs, describe two important similarities between transcription and DNA replication (for example, base-pairing rules, template use, involvement of polymerase enzymes) and two important differences (for example, the type of nucleic acid produced, where

and when each process occurs, or which strands are copied). For each similarity and difference you choose, briefly explain why it is functionally important to the cell.

8. Anaphase should begin only after all sister chromatids are correctly attached to spindle microtubules and aligned at the metaphase plate. Imagine this checkpoint fails and anaphase starts too early. In a short essay, predict what kinds of errors might occur in chromosome distribution. Then explain how these errors could affect the resulting daughter cells (for example, chromosome number, function, or viability) and how they might impact the organism as a whole.
9. Cyclins and cyclin-dependent kinases (CDKs) work together to regulate the timing of the cell cycle. In a well-structured paragraph, explain:
    a. What cyclins are
    b. What CDKs are
    c. How interactions between specific cyclins and CDKs act as a timing and control system for progression through different phases of the cell cycle
10. Stem cells have potential applications in anti-aging therapies and limb or organ regeneration. In a short essay, discuss the possible future role of stem cells in anti-aging or in regenerating limbs or complex organs. Evaluate both:
    a. The scientific feasibility (what makes these applications possible or challenging at the cellular and tissue levels)
    b. The ethical implications of creating complex tissues or organs from stem cells (for example, access, consent, and potential risks or misuse)

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3.10: Alternative Text Descriptions

Figure 3.1.1: Structure of a Phospholipid

This figure shows the structure of a phospholipid molecule. The molecule has two main parts: a hydrophilic head, which is attracted to water, and two hydrophobic fatty acid tails, which repel water and extend downward from the head.

Hydrophilic Head

The hydrophilic head is shown as a large circular region at the top of the diagram. It contains:

- A phosphate group
- A glycerol backbone

The phosphate group, labeled on the right, contains a phosphorus atom bonded to oxygen atoms. A label R appears above the phosphate group, indicating a variable chemical group attached to the phosphate.

The glycerol backbone is located below the phosphate group and connects the head to the two fatty acid tails.

Hydrophobic Tails

Two fatty acid tails extend downward from the glycerol backbone.

- The left tail is labeled Saturated fatty acid. It is straight and contains only single carbon-carbon bonds.
- The right tail is labeled Unsaturated fatty acid. It contains a carbon-carbon double bond, which creates a bend or kink in the chain.

Labeled Regions

Labels along the left side identify:

- The upper portion as the hydrophilic head
- The lower portion as the hydrophobic tails

Summary

The figure illustrates the amphipathic structure of a phospholipid. It has:

- A polar head that interacts with water
- Two nonpolar tails that repel water

Figure 3.1.2: Phospholipid Bilayer

This image illustrates the structure of a phospholipid bilayer, which forms the basic structure of cell membranes. The diagram shows two layers of phospholipids arranged horizontally. The top region is labeled “Extracellular” (outside the cell). The bottom region is labeled “Intracellular” (inside the cell). A bracket label on the right identifies the entire structure as the “Phospholipid bilayer.”

1. Phospholipid Arrangement - Each phospholipid molecule consists of:
    - A round head (colored red or orange) labeled “Hydrophilic head”
    - Two elongated tails (yellow, wavy lines) labeled “Hydrophobic tail”
2. Top Layer (Outer Leaflet)

- The hydrophilic heads are positioned facing upward toward the extracellular space.
- The hydrophobic tails extend downward toward the center of the bilayer.

3. Bottom Layer (Inner Leaflet)
   - The hydrophilic heads are positioned facing downward toward the intracellular space.
   - The hydrophobic tails extend upward toward the center.
4. Center of the Bilayer
   - The hydrophobic tails from both layers meet in the middle, forming a nonpolar interior.
   - This central region prevents water and many polar molecules from easily passing through.

Figure 3.1.3: Lipid Bilayer With Various Components

This image illustrates the fluid mosaic model of the cell membrane, showing the arrangement of lipids, proteins, and carbohydrates within a phospholipid bilayer. The diagram shows a horizontal cross-section of a cell membrane. The membrane separates two regions (top and bottom), representing the outside and inside of the cell. A bracket on the right labels the entire structure as the “Phospholipid bilayer.”

1. Phospholipid Bilayer Structure
   - The membrane consists of two layers of phospholipids:
     - Round red/orange spheres form the outer surfaces (hydrophilic heads)
     - Long, thin yellow tails extend inward from both sides (hydrophobic tails)
   - The hydrophobic tails face each other in the center, creating a nonpolar interior layer.
2. Membrane Proteins - Several types of proteins are embedded in or associated with the bilayer:
   - Integral Membrane Proteins
   - Large blue structures that span the entire membrane from top to bottom, labeled as “Integral membrane protein.”
   - These proteins are embedded within the lipid bilayer.
3. Channel Proteins
   - A specific type of integral protein labeled “Channel protein.”
   - Appears as a tube-like structure forming a passage through the membrane.
   - Allows certain substances to move across the membrane.
4. Peripheral Membrane Proteins - Smaller blue structures attached to the surface of the membrane, not spanning it, labeled as “Peripheral membrane protein.”
5. Cholesterol
   - Small yellowish or tan molecules located between the phospholipid tails, labeled “Cholesterol.”
   - Positioned within the hydrophobic interior of the membrane.
6. Glycoproteins - Proteins with attached carbohydrate chains extending outward from the membrane surface, labeled as “Glycoprotein: protein with carbohydrate attached.”
7. Glycolipids
   - Lipids with attached carbohydrate chains extending outward, labeled as “Glycolipid: lipid with carbohydrate attached.”
   - The carbohydrate chains appear as branching structures projecting outward, likely on the extracellular side.

Figure 3.1.4: Diffusion Through Lipid Layer

This image illustrates the process of simple diffusion across a lipid bilayer (plasma membrane), showing how small uncharged molecules move from an area of high concentration to an area of lower concentration over time. The diagram is arranged horizontally and divided into three sections representing progression over time. At the top center is the label “Extracellular fluid.” At the bottom center is the label “Cytoplasm.” A horizontal bar at the bottom labeled “Time” includes an arrow pointing to the right, indicating the direction of time progression from left to right.

1. Lipid Bilayer (Plasma Membrane)
   - A horizontal structure across the center of the image represents the lipid bilayer (plasma membrane).
   - It is made of two layers:
     - Round red or orange heads (hydrophilic) facing outward
     - Thin, yellow tails (hydrophobic) facing inward toward each other
2. Small Uncharged Molecules
   - Numerous small blue shapes, labeled “Small uncharged molecules,” are shown above and below the membrane.
   - These represent molecules such as oxygen or carbon dioxide that can diffuse directly through the membrane.
3. Left Section – Initial State

    - Many blue molecules are clustered in the extracellular fluid above the membrane.
    - Few or no molecules are present in the cytoplasm below.
    - This represents a high concentration outside the cell and a low concentration inside.
4. Middle Section – Diffusion in Progress
    - Some molecules have crossed the membrane and now appear in the cytoplasm.
    - The distribution begins to even out between the outside and inside.
    - This shows molecules moving down their concentration gradient.
5. Right Section – Equilibrium State
    - Molecules are more evenly distributed on both sides of the membrane.
    - The number of molecules outside and inside is similar.
    - Although molecules may still move, there is no net change in concentration.

Figure 3.1.5: Facilitated Diffusion

This image illustrates facilitated diffusion across a plasma membrane, showing two mechanisms: channel proteins and carrier proteins. The diagram is divided into two labeled sections: (a) and (b).

a. Channel Protein Transport - The top region is labeled “Extracellular fluid.” The bottom region is labeled “Cytoplasm.” A horizontal structure labeled “Plasma membrane” separates the two regions.
    - The membrane is shown as a phospholipid bilayer with round heads forming the outer surfaces and tails forming the inner region.
    - Channel Protein is a large structure labeled “Channel” spans the membrane. It forms a continuous opening (pore) from the extracellular fluid to the cytoplasm.
    - Molecules are small shapes represent molecules moving through the membrane. The arrows indicate movement from outside to inside through the channel.
b. Carrier Protein Transport has a similar membrane structure separates extracellular fluid (top) and cytoplasm (bottom). Multiple structures embedded in the membrane are labeled “Carrier proteins.”
    - Carrier Protein Function binds a molecule on one side of the membrane, changes shape to move the molecule across and releases the molecule on the opposite side.
c. Molecules are oval shapes that represent different types of molecules. The Arrows show molecules moving into the cell via carrier proteins.

Figure 3.1.6: Osmosis

This image shows osmosis in two stages. A container is divided by a semipermeable membrane, shown as a vertical dashed line. One side has a lower solute concentration and the other side has a higher solute concentration. The arrow between the two containers indicates the change over time. In the second stage, water has moved across the membrane toward the side with more solute particles, causing the liquid level on that side to rise and the level on the other side to fall. The image emphasizes that osmosis is the movement of water across a selectively permeable membrane from lower solute concentration to higher solute concentration.

Figure 3.1.7: Hypertonic Solution

compares how **red blood cells respond to three different solution types**: hypertonic, isotonic, and hypotonic. The diagram is arranged in three columns from left to right, each labeled at the top.

Overall Layout

- The three sections are labeled:
    - **Hypertonic** (left)
    - **Isotonic** (center)
    - **Hypotonic** (right)
- Each section includes:
    - A circular view showing red blood cells
    - A smaller diagram below showing **water (H_2O) movement** with arrows

Left Section – Hypertonic Solution

Cell Appearance

- Red blood cells appear **shrunken and irregular in shape**.
- The cells have a wrinkled or spiky appearance.

Water Movement

- Arrows labeled **H_2O** point **outward from the cell**.

Key Concept

- Water moves **out of the cells** into the surrounding solution.
- This causes cells to **lose water and shrink** (crenation).

Center Section – Isotonic Solution

Cell Appearance

- Red blood cells appear **normal, round, and smooth**.
- Cells are evenly shaped and maintain their typical form.

Water Movement

- Arrows labeled **H_2O** point **both into and out of the cell** equally.

Key Concept

- Water moves **in and out at equal rates**.
- There is **no net change** in cell size or shape.

Right Section – Hypotonic Solution

Cell Appearance

- Red blood cells appear **swollen and enlarged**.
- One cell is shown **bursting**, releasing contents outward.

Water Movement

- Arrows labeled **H_2O** point **into the cell**.

Key Concept

- Water enters the cells by osmosis.
- Cells **swell and may burst** (lysis).

Figure 3.1.8: Sodium-Potassium Pump

This image illustrates the sodium–potassium pump, a form of active transport across the plasma membrane. It shows how sodium

(Na⊕) and potassium (K⊕) ions move in opposite directions using energy from ATP. The diagram is a horizontal cross-section of a plasma membrane. The top region is labeled “Extracellular space.” The bottom region is labeled “Cytoplasm.” A phospholipid bilayer runs horizontally across the center. Several embedded protein structures represent transport proteins (pumps).

1. Ions and Their Distribution
   - Sodium ions (Na⊕) are illustrated as hexagonal shapes, mostly concentrated in the extracellular space (above the membrane).
   - Potassium ions (K⊕) are illustrated as oval shapes, primarily concentrated in the cytoplasm (below the membrane).
   - A vertical scale on the right labeled “Concentration” shows:
     - Higher sodium concentration outside
     - Higher potassium concentration inside
2. Plasma Membrane Structure
   - The membrane consists of a phospholipid bilayer with circular heads on both sides (hydrophilic) and tails facing inward (hydrophobic)
   - Embedded within the membrane are large brown protein structures, representing the sodium–potassium pump.
3. Step-by-Step Process:
   a. Sodium Binding and Transport Out
      - Three sodium ions bind to the pump on the cytoplasmic side.
      - An arrow indicates that these sodium ions are transported outward across the membrane to the extracellular space.
   b. ATP Energy Input
      - A molecule labeled ATP is shown near the pump.
      - ATP is broken down into ADP (adenosine diphosphate) and a phosphate group.
      - The phosphate attaches to the pump, causing a conformational (shape) change.
   c. Potassium Binding and Transport In
      - Two potassium ions bind to the pump on the extracellular side.
      - After another shape change, arrows show potassium ions being transported into the cytoplasm.
   d. Release and Reset
      - The phosphate group is released.
      - The pump returns to its original shape, ready to repeat the cycle

Figure 3.1.9: Process of Endocytosis

This image illustrates the process of endocytosis, where a cell takes material into the cell by forming vesicles from the plasma membrane. The diagram is divided into three labeled sections from left to right: Phagocytosis, Pinocytosis, and Receptor-mediated endocytosis. The image is arranged horizontally in three panels separated by vertical lines. A boundary represents the plasma membrane, enclosing the cytoplasm below. The region above the membrane represents the extracellular environment. Each panel shows a different mechanism of endocytosis using arrows and structural changes in the membrane.

1. Left Panel – Phagocytosis (“Cell Eating”) involves the engulfing of large particles such as food or debris.
   - A large particle is located outside the cell. The membrane engulfs the particle completely.
   - A vesicle forms inside the cell labeled “vacuole”.
2. Middle Panel – Pinocytosis (“Cell Drinking”) involves the uptake of extracellular fluid and dissolved molecules in small quantities.
   - The extracellular space contains fluid and small dissolved substances.
   - The plasma membrane folds inward to form small pockets.
   - These pockets pinch off to form small vesicles inside the cytoplasm, labeled “Vesicle.”
3. Right Panel – Receptor-Mediated Endocytosis is highly specific, allowing the cell to take in particular substances using receptors.
   - small particles bind to specific receptor proteins embedded in the membrane.
   - The membrane forms an indentation labeled “Coated vesicle”
   - The bound molecules cluster at receptor sites.
   - The membrane folds inward and pinches off to form a coated vesicle containing selected molecules.

Figure 3.1.10: The process of exocytosis

This image illustrates the process of exocytosis, where materials inside a cell are transported to the cell membrane and released into the extracellular space. The diagram shows a cross-section of a cell boundary, with the extracellular fluid labeled at the top,

the cytoplasm labeled at the bottom, a horizontal line represents the plasma membrane, separating the two regions and arrows indicate the direction of movement from inside the cell to outside.

1. Vesicle Inside the Cell
    - A circular structure labeled “Vesicle” is located within the cytoplasm.
    - The vesicle contains several small particles, representing molecules to be transported.
    - An arrow points from the vesicle toward the plasma membrane.
2. Fusion with the Membrane
    - The vesicle moves upward and fuses with the plasma membrane.
    - The membrane bulges outward where the vesicle joins it.
    - This fusion creates an opening between the vesicle interior and the extracellular space.
3. Release of Contents
    - The particles move out of the vesicle and into the extracellular fluid, indicated by arrows.
    - The vesicle membrane becomes part of the plasma membrane after fusion.

Figure 3.1.11: Pancreatic Acinar Cell

This image is an electron micrograph of pancreatic acinar cells, showing numerous dark, round secretory vesicles clustered within the cell. The labeled acinar cell occupies the center of the image, and the labeled secretory vesicles appear as dense dots packed throughout the cytoplasm.

Figure 3.2.1: Prototypical Human Cell

The figure shows a labeled diagram of an animal cell enclosed by a plasma membrane. The cytoplasm fills the interior of the cell and contains numerous organelles and cytoskeletal structures.

Near the center-left of the cell is a large nucleus. Within the nucleus, threadlike chromatin is distributed throughout the interior, and a darker, circular nucleolus is located near the center. Surrounding the nucleus are folded membranes of the rough endoplasmic reticulum, which are covered with many small ribosomes shown as dots attached to the membrane surfaces.

To the right of the nucleus is the smooth endoplasmic reticulum, shown as a network of membrane tubules without attached ribosomes. Adjacent to the smooth endoplasmic reticulum and slightly above it is the centrosome.

In the lower-left region of the cell is the Golgi apparatus, depicted as a stack of flattened membrane sacs. Small Golgi vesicles are located nearby. A secretory vesicle appears in the lower-right portion of the cell near the plasma membrane.

Several mitochondria are distributed throughout the cell, including examples in the upper central region and along the right side. Lysosomes are clustered primarily along the right side of the cell, while peroxisomes are located near the lower center and lower-right regions.

A large vacuole is positioned near the bottom center of the cell.

Components of the cytoskeleton extend throughout the cytoplasm. Microtubules are shown primarily in the upper-right region, microfilaments are concentrated along the right side beneath the plasma membrane, and intermediate filaments are distributed across the upper and left portions of the cell.

The diagram illustrates the major organelles of an animal cell and their relative locations within the cytoplasm.

Figure 3.2.2: Animal Cell Structure

This image has three labeled panels comparing rough endoplasmic reticulum and smooth endoplasmic reticulum.

- In panel (a), a cell illustration shows the endoplasmic reticulum near the nucleus. Rough ER appears as folded membrane sacs covered with small dots representing ribosomes. Smooth ER appears as connected tubular membranes without ribosomes.
- In panel (b), an electron micrograph shows rough ER as stacked, wavy membrane layers with many small dark particles attached to the surface. These particles are labeled ribosomes.

- In panel (c), an electron micrograph shows smooth ER as membrane structures without attached ribosomes. The smooth ER is labeled directly in the image.

Figure 3.2.3: Golgi apparatus

This image has two panels illustrating the structure and function of the Golgi apparatus.

In panel (a), a cell diagram shows the Golgi apparatus positioned near the rough endoplasmic reticulum and the nucleus. Transport vesicles bud from the rough ER and move to the cis face of the Golgi apparatus. The Golgi is shown as a stack of flattened membrane sacs called cisternae. Material moves through the Golgi from the cis face to the trans face. Secretory vesicles then bud from the trans face and move toward the plasma membrane.

The labeled structures in panel (a) include:

- nucleus
- rough ER
- transport vesicle
- cis face
- cisternae
- trans face
- Golgi apparatus
- secretory vesicle
- plasma membrane

In panel (b), an electron micrograph shows the Golgi apparatus as a curved stack of flattened membranes. The cis face and trans face are labeled to show the two sides of the organelle.

Figure 3.2.4: Mitochondrion

This image has two panels showing the structure of a mitochondrion.

In panel (a), a diagram shows an oval-shaped mitochondrion cut open to reveal its internal structure. The outer membrane forms the smooth outer boundary. Inside it is the inner membrane, which folds inward repeatedly to form cristae. The narrow region between the outer membrane and inner membrane is labeled the intermembrane space.

In panel (b), an electron micrograph shows a mitochondrion with the same major structures labeled. The outer membrane outlines the organelle. The inner membrane appears as folded layers inside the mitochondrion. These folds correspond to the cristae seen in the diagram. The space between the two membranes is labeled as the intermembrane space.

Figure 3.2.5: Peroxisome

This image shows a circular cross-section with an outer boundary labeled plasma membrane. The membrane is identified as a lipid bilayer. Inside the membrane is a large central structure labeled crystalline core. The image highlights the relationship between the outer membrane and the internal core.

Figure 3.2.6: Cytoskeletal Filaments

This image compares three types of cytoskeletal structures found in cells: microtubules, microfilaments (actin filaments), and intermediate filaments. Each structure is shown at two levels: a cellular view and a molecular subunit view.

a. Microtubules - Microtubules provide internal support for the cell. They serve as tracks for movement of materials inside the cell. Microtubules help organize cell shape and assist in processes such as cell division.
   - Microtubules are shown as hollow cylindrical structures.
   - They are made from repeating units labeled tubulin dimers.
   - These dimers are arranged in long columns to form a tube-like structure labeled Column of tubulin dimers.
   - The diameter is labeled 25 nanometers (nm).

b. Microfilaments (Actin Filaments) - Microfilaments support the cell's shape and surface structure. These enable cell movement and contraction. Microfilaments are involved in processes such as muscle contraction and cell motility.
   - Microfilaments are shown as thin, flexible strands.
   - They are made of repeating units labeled actin subunits.
   - These subunits form a twisted, chain-like structure.
   - The diameter is labeled 7 nanometers (nm).
c. Intermediate Filaments - Intermediate filaments provide tensile strength, helping cells resist stretching forces. These stabilize cell structure and help maintain mechanical integrity.
   - Intermediate filaments are rope-like fibers made of coiled strands.
   - The subunits are described as fibrous proteins (keratins) twisted together.
   - The diameter is labeled 8 to 12 nanometers (nm).

Figure 3.3.1: The Nucleus

This image shows a eukaryotic cell nucleus. It includes the nuclear envelope, which is a double membrane dotted with nuclear pores. Inside the nucleus is condensed chromatin and a dense, spherical nucleolus. Surrounding the nucleus are membrane folds labeled as cisternae. The image highlights the structure and organization of the nucleus and its components. Labels included:

- Nucleus
- Nuclear pores
- Nuclear envelope
- Chromatin(condensed)
- Nucleolus
- Cisternae

Figure 3.3.2: Comparison of Skeletal, Cardiac, and Smooth Muscle Tissue

This image compares the three types of muscle tissue: skeletal muscle (A), cardiac muscle (B), and smooth muscle (C). Each row includes a longitudinal view on the left and a cross-sectional view on the right.

Panel A: Skeletal Muscle

The longitudinal view shows long, cylindrical muscle fibers arranged parallel to one another. Multiple elongated nuclei are visible near the outer edges of the fibers. The fibers have a striated appearance.

The cross-sectional view shows large muscle fibers cut into rounded or polygonal profiles. Multiple nuclei are located near the outer edge of the cells.

This panel shows that skeletal muscle fibers are multinucleated, meaning each fiber contains many nuclei.

Panel B: Cardiac Muscle

The longitudinal view shows shorter, branching muscle fibers with a striated appearance. Individual cells usually contain a single centrally located nucleus.

The cross-sectional view shows irregularly shaped cell profiles, most with one central nucleus.

This panel shows that cardiac muscle cells are generally uninucleated, meaning each cell contains one nucleus near the center.

Panel C: Smooth Muscle

The longitudinal view shows elongated, spindle-shaped cells arranged in parallel layers. The cells do not show visible striations and contain a single central nucleus.

The cross-sectional view shows small, closely packed cell profiles, each with one centrally located nucleus.

This panel shows that smooth muscle cells are also generally uninucleated and lack the striations seen in skeletal and cardiac muscle.

The figure compares the structure of the three muscle tissue types. Skeletal muscle consists of long multinucleated fibers specialized for voluntary movement. Cardiac muscle consists of branching cells with single nuclei that form the contractile tissue of the heart. Smooth muscle consists of spindle-shaped cells with single nuclei that control involuntary movements within the walls of organs and blood vessels. The figure emphasizes differences in cell shape, arrangement, striations, and number of nuclei among the three muscle types.

Figure 3.3.3: Red Blood Cell Extruding its Nucleus

This image contains two panels. In both panels, there are several microscopic cells visible in gray scale, which are false-colored for clarity. The dominant cells are highlighted in a reddish-orange color, while internal structures, primarily the nuclei, are a darker gray.

- Left Panel: Depicts a developing red blood cell (erythroblast) actively extruding its large, dark, and irregularly shaped nucleus. A small portion of cytoplasm is visible around the edge of the nucleus as it is pushed out of the cell.
- Right Panel: Shows the result of this process. The cell on the right is a mature red blood cell, which is biconcave (disk-shaped with a depression in the center) and lacks a nucleus, appearing as a uniform reddish-orange color. To its left is a discarded nucleus after being expelled, appearing as a dense, dark gray mass.

Figure 3.3.4: DNA Macrostructure

This image shows a diagram illustrating how DNA is packaged inside a cell. A chromosome and its component chromatin are shown to expand into nucleosomes with histones, which further unravel into a DNA helix and finally into a DNA ladder.

- On the left, there is a X-shaped chromosome.
- A thin fiber labeled chromatin extends from the chromosome.
- The chromatin fiber appears coiled, and a zoomed-in section shows groups of small spherical proteins labeled histones.
- DNA wraps around these histone proteins to form bead-like structures called nucleosomes.
- To the right, the nucleosomes unwind into a long, twisted ladder-shaped DNA helix.
- At the bottom of the image, the DNA is shown in even more detail as a sequence of base pairs (A, T, C, and G) connected by colored lines, representing the genetic code.

Figure 3.3.5: Molecular Structure of DNA

This image explains the structure of DNA, including its overall shape, the arrangement of nucleotides, and how individual components connect to form the molecule.

- DNA is shown as a double helix, meaning two strands twist around each other. Each strand has ends labeled 5-prime and 3-prime, and the two strands run in opposite directions. This double-stranded structure helps DNA store and protect genetic information and supports accurate copying during replication.
- Each strand is made of a repeating sugar-phosphate backbone. The backbone is labeled as alternating phosphate groups and five-carbon sugar molecules that form a long chain. This backbone provides structural support and stability and forms the outer framework of the DNA molecule.
- Attached to each sugar is a nitrogenous base. The four bases are labeled adenine, thymine, guanine, and cytosine. These bases extend inward from each strand toward the center of the double helix. The sequence of the bases stores genetic information and provides the instructions used to build proteins.
- Bases from one strand pair with bases on the opposite strand to form base pairs. The base pairing is labeled to show that adenine pairs with thymine and guanine pairs with cytosine. This complementary base pairing supports accurate DNA replication because one strand can serve as a template for building the other.
- The paired bases are connected by hydrogen bonds, which are labeled in the diagram. These bonds help hold the two strands together while still allowing the strands to separate during replication and transcription.

- A single nucleotide is also shown and labeled as the building block of DNA. Each nucleotide consists of a phosphate group, a sugar, and a nitrogenous base. Nucleotides link together to form DNA strands, and their sequence stores biological information.

Figure 3.3.6: DNA Replication

This image illustrates the process of DNA replication, showing how a double-stranded DNA molecule is copied to form two new strands.

- The DNA molecule is shown partially unwound, forming a replication fork, which is a Y-shaped region where replication occurs. One part of the DNA remains in its original double-stranded form, while another region is being actively copied. The replication fork is the site where DNA strands separate and new strands are synthesized.
- Two strands of DNA serve as templates for building new complementary strands. Each template strand contains a sequence of bases. Each original strand provides the pattern for forming a new strand, ensuring accurate duplication of genetic information.
- A protein labeled helicase is positioned at the replication fork. It separates the two strands of the DNA molecule. Helicase breaks the bonds between paired bases, allowing the strands to unwind and be copied.
- Individual units called free nucleotides are shown near the replication area. These nucleotides match with exposed bases on the template strands. Free nucleotides are the building blocks used to assemble new DNA strands.
- Enzymes labeled DNA polymerase are attached to the strands being formed. These enzymes move along the template strands. DNA polymerase adds nucleotides to the growing strand, forming a new complementary DNA strand. It ensures correct base pairing during replication.
- One new strand is labeled the leading strand. This strand is synthesized in a continuous direction along the template. The leading strand is built smoothly and continuously, allowing rapid replication.
- The second new strand is labeled the lagging strand. This strand is formed in short segments, not continuously. Because of strand direction, the lagging strand is assembled in pieces and later joined together.
- Each strand has labeled ends called 5-prime (5′) and 3-prime (3′). The strands run in opposite directions. DNA polymerase can only add nucleotides in one direction, which explains why one strand is continuous and the other is built in segments.
- Specific pairing occurs between bases: adenine pairs with thymine and guanine pairs with cytosine. Complementary pairing ensures accurate copying of genetic information.

Figure 3.4.1: The Genetic Code

This image shows the process of gene expression from DNA to protein. A DNA template strand is transcribed into an RNA strand, and the RNA strand is then translated into a protein.

- At the top is DNA, labeled template strand, shown as a sequence of nucleotide bases.
- An arrow points downward to transcription, where the DNA sequence is copied into RNA.
- The RNA strand contains the bases A, U, C, and G, with uracil replacing thymine.
- Below the RNA strand is translation, where the RNA is read in groups of three bases called codons.
- Each codon corresponds to a specific amino acid.
- At the bottom, the resulting protein is shown as a sequence of amino acids: methionine, proline, glutamine, serine, valine, histidine, alanine, leucine, methionine, and cysteine.

Figure 3.4.2: Transcription from DNA to mRNA

This image shows transcription, the process of making RNA from DNA.

- At the top left is a chromosome, which unwinds into a long DNA double helix.
- A section of the DNA opens, exposing the bases.
- A yellow enzyme labeled RNA polymerase sits on the DNA and moves along it in one direction.
- As RNA polymerase moves, it builds an RNA transcript by matching complementary bases.
- The RNA strand forms below the DNA and contains the bases A, U, C, and G, with uracil replacing thymine.
- The newly made RNA strand separates from the DNA as the DNA helix closes behind the enzyme.

Figure 3.4.3: RNA Splicing

This image is a biological process diagram illustrating RNA splicing, the mechanism by which introns are removed from a pre-messenger RNA (pre-mRNA) transcript and exons are joined together to form a mature RNA molecule.

At the top of the diagram is a horizontal bar labeled “pre-mRNA transcript.” The transcript is divided into alternating colored segments representing exons and introns. From left to right, the segments are labeled Exon 1, Intron, Exon 2, Intron, and Exon 3. Exons are shown in shades of yellow, blue, orange, and tan, while introns are shown in green.

A large downward arrow points from the pre-mRNA transcript to the center of the figure, where a structure labeled “Spliceosome” is depicted. The spliceosome is illustrated as a large oval-shaped complex containing intertwined colored shapes that surround and interact with the RNA transcript. A label identifies one of the green looped RNA regions as an “Intron.”

Within the spliceosome, the RNA transcript is shown looping so that the intron region folds inward while Exon 1, Exon 2, and Exon 3 are positioned along a lower horizontal strand. This arrangement represents the spliceosome bringing exon sequences together while preparing the intron for removal.

Two diagonal arrows extend downward from the spliceosome, indicating the formation of two separate products after splicing.

On the lower left is the excised intron, shown as a green lariat-shaped loop with a tail. A label identifies this structure as “Intron.” This represents the intron sequence that has been removed from the transcript.

On the lower right is a horizontal RNA strand labeled “Spliced RNA.” The strand contains the exon segments joined together in sequence as Exon 1, Exon 2, and Exon 3, with no intron sequences present. The exons are shown as contiguous colored blocks, illustrating that the introns have been removed and the remaining coding sequences have been connected to form the mature RNA product.

Figure 3.4.4: Translation from RNA to Protein

This image shows the process of translation, where a ribosome reads genetic information from messenger RNA (mRNA) to build a protein.

- The image is arranged vertically in three stages, showing progression over time. A strand labeled mRNA runs horizontally and is marked with direction from 5-prime (5′) on one end to 3-prime (3′) on the other. A structure labeled ribosome surrounds part of the mRNA and consists of a large subunit and a small subunit. Transfer RNA, labeled tRNA, interacts with the mRNA inside the ribosome. Each tRNA carries an amino acid and contains an anticodon.
- In the first stage, the ribosome is assembled on the mRNA. A codon labeled AUG is identified on the mRNA, and a tRNA with anticodon UAC binds to this codon. This tRNA carries the amino acid methionine (Met). The AUG codon acts as the start signal for translation, and the binding of the first tRNA establishes the starting point for protein synthesis.
- In the second stage, a second tRNA binds to the next codon on the mRNA. Two tRNA molecules are now held inside the ribosome at the same time. The second tRNA carries another amino acid, such as phenylalanine (Phe). The ribosome positions the two amino acids close together, and a chemical bond forms between the amino acids, beginning the polypeptide chain. The ribosome then moves along the mRNA to read the next codon.
- In the third stage, multiple tRNA molecules interact with the mRNA one after another. Additional amino acids, such as arginine (Arg), are added. A chain labeled polypeptide chain extends from the ribosome. The ribosome continues linking amino acids in sequence, and the growing chain represents a new protein being synthesized. The order of codons determines the sequence of amino acids, which determines protein structure.
- The mRNA contains codons such as AUG, UUU, and CGA, and tRNA molecules have matching anticodons such as UAC, AAA, and GCU. Codon-anticodon pairing ensures that the correct amino acid is added at each step, which maintains accuracy in protein synthesis.
- The ribosome moves along the mRNA from the 5′ end toward the 3′ end. This directional movement ensures that the protein is built in the correct order, following the genetic sequence.

Figure 3.4.5: From DNA to Protein: Transcription through Translation

This image shows the central dogma of molecular biology, explaining how genetic information flows inside a cell. The figure shows a schematic of a cell where transcription from DNA to mRNA takes place inside the nucleus and translation from mRNA to

protein takes place in the cytoplasm.

- The image shows a cell with a nucleus in the center. Inside the nucleus, DNA is shown at the top.
- An arrow labeled transcription points from DNA to mRNA, indicating that DNA is copied into messenger RNA. The mRNA then moves out of the nucleus into the surrounding area of the cell.
- In the cytoplasm, an arrow labeled translation points from mRNA to a protein. Translation occurs at a ribosome, shown as a rounded structure, where the mRNA is used to build a chain of amino acids.

Figure 3.5.1: Cell Cycle

This image shows the cell cycle as a circular process.

- Most of the circle is interphase, divided into three stages:
  - G_1, where the cell grows and carries out normal functions.
  - S, where DNA is copied.
  - G_2, where the cell prepares for division.
- A small wedge labeled M phase represents mitosis, when the cell divides.
- Arrows around the circle show the cycle moving in a continuous direction.
- A side branch labeled G_0 shows cells that exit the cycle and are not actively dividing.

Figure 3.5.2: The Structure of Chromosomes

This image shows two paired chromosomes and labels their major structural parts.

The two chromosomes are identified as homologous chromosomes. Each chromosome is made of two sister chromatids joined near the center. The central joining region is labeled the centromere. A structure at the centromere is labeled the kinetochore. The purpose of the diagram is to identify the relationship between homologous chromosomes, sister chromatids, the centromere, and the kinetochore.

Figure 3.5.3: Cell Division: Mitosis Followed by Cytokinesis

This image is a chart summarizes the stages of mitosis in six columns: prophase, prometaphase, metaphase, anaphase, telophase, and cytokinesis. Each column includes a cell diagram, a bulleted description, and a microscope image.

- Prophase: Chromosomes condense and become visible. Spindle fibers emerge from the centrosomes. The nuclear envelope breaks down, and centrosomes move toward opposite poles.
- Prometaphase: Chromosomes continue to condense. Kinetochores appear at the centromeres. Mitotic spindle microtubules attach to the kinetochores.
- Metaphase: Chromosomes line up at the metaphase plate. Each sister chromatid is attached to a spindle fiber from opposite poles.
- Anaphase: Centromeres split in two. Sister chromatids, now called chromosomes, are pulled toward opposite poles. Some spindle fibers lengthen the cell.
- Telophase: Chromosomes arrive at opposite poles and begin to decondense. Nuclear envelope material surrounds each set of chromosomes. The mitotic spindle breaks down, and spindle fibers continue to push the poles apart.
- Cytokinesis**:** In animal cells, a cleavage furrow separates the daughter cells. In plant cells, a cell plate forms as a precursor to a new cell wall and separates the daughter cells

Figure 3.5.4: Control of the Cell Cycle

This figure shows the cell cycle as a circular process regulated by checkpoints and cyclin-CDK complexes. Red arrows around the circle indicate that the cycle progresses clockwise through four phases: G1, S, G2, and M.

G1 occupies the right half of the circle and is labeled “cell growth.” At the end of G1, before DNA replication begins, the G1 checkpoint (restriction point) determines whether the cell can proceed into S phase. Cyclin D-CDK4 functions during G1, and Cyclin E-CDK2 promotes the transition from G1 into S phase.

S phase occupies the left side of the circle and is labeled “DNA synthesis,” indicating that the cell replicates its DNA. Cyclin A-CDK2 functions during this phase as DNA replication occurs.

G2 is located at the top of the circle and is also labeled “cell growth.” Before the cell enters mitosis, it passes through the G2 checkpoint, which regulates the transition from G2 into M phase. Cyclin B-CDK1 controls entry into mitosis.

M phase is a small wedge-shaped section near the top right of the circle and represents cell division. The M checkpoint occurs during mitosis and helps ensure that cell division proceeds correctly before the cycle returns to G1.

Together, the diagram shows that cells progress sequentially through growth, DNA replication, additional growth, and division, while checkpoints monitor progression at key transitions. Specific cyclin-CDK complexes regulate movement through each stage and help drive the cell from one phase to the next.

Figure 3.6.1: Hematopoiesis

This image shows hematopoiesis, the process by which all blood cells develop from stem cells.

- At the top is a multipotential hematopoietic stem cell.
- This stem cell divides into two main pathways:
  - Common myeloid progenitor
  - Common lymphoid progenitor
- The myeloid lineage produces:
  - Megakaryocytes, which form thrombocytes or platelets
  - Erythrocytes (red blood cells)
  - Mast cells
  - Myeloblasts, which develop into basophils, neutrophils, eosinophils, and monocytes
  - Monocytes further differentiate into macrophages and dendritic cells
- The lymphoid lineage produces:
  - Natural killer cells
  - Small lymphocytes, which become T lymphocytes and B lymphocytes
  - B lymphocytes can further develop into plasma cells

Figure 3.6.2: Transcription Factors

This image illustrates how transcription begins on a DNA strand.

- On the left, several transcription factors bind to a specific DNA region called the promoter.
- In the center, RNA polymerase binds to the transcription factors and the promoter, forming a transcription initiation complex.
- On the right, RNA polymerase is fully positioned on the DNA, and transcription begins, shown by an arrow indicating movement along the DNA.

Figure 3.6.3: Stem Cells

This image shows how stem cell potency becomes more limited as cells differentiate. At the top, a totipotent embryonic stem cell is shown as the most flexible cell type. Arrows point downward to pluripotent embryonic stem cells. Below that, pluripotent cells give rise to multiple cell lineages. These then lead to multipotent stem cells, which are more restricted and produce a narrower range of related cell types. At the bottom, the diagram shows examples of specialized cells produced through differentiation, including muscle cells, red blood cells, epithelial cells, and a neuron. The purpose of the diagram is to compare totipotent, pluripotent, and multipotent stem cells and show that differentiation leads to increasingly specialized cells.

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4: THE TISSUE LEVEL OF ORGANIZATION

Chapter Overview

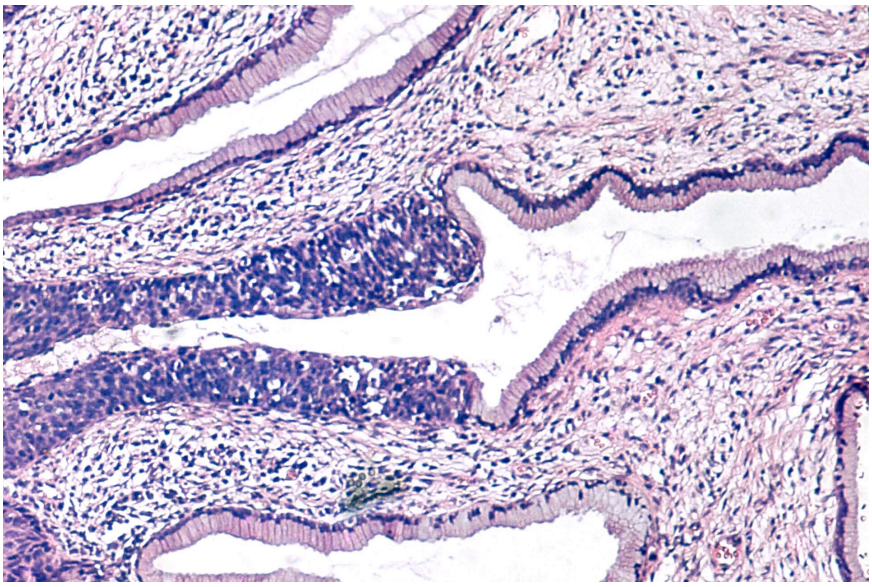


Figure 4.1: This figure is a view of the regular architecture of normal tissue contrasted with the irregular arrangement of cancerous cells. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.1.

Four Basic Tissue Types

The human body contains more than 200 types of cells that can all be classified into four types of tissues: epithelial, connective, muscle, and nervous. Epithelial tissues act as coverings controlling the movement of materials across the surface. Connective tissue integrates the various parts of the body and provides support and protection to organs. Muscle tissue allows the body to move. Nervous tissues propagate information.

Histology and Embryonic Germ Layers

The study of the shape and arrangement of cells in tissue is called histology. All cells and tissues in the body derive from three germ layers in the embryo: the ectoderm, mesoderm, and endoderm.

Body Membranes and Their Functions

Different types of tissues form membranes that enclose organs, provide a friction-free interaction between organs, and keep organs together. Synovial membranes are connective tissue membranes that protect and line the joints. Epithelial membranes are formed from epithelial tissue attached to a layer of connective tissue. There are three types of epithelial membranes: mucous, which contain glands; serous, which secrete fluid; and cutaneous which makes up the skin.

Structure and Functions of Epithelial Tissue

In epithelial tissue, cells are closely packed with little or no extracellular matrix except for the basal lamina that separates the epithelium from underlying tissue. The main functions of epithelia are protection from the environment, coverage, secretion and excretion, absorption, and filtration. Cells are bound together by tight junctions that form an impermeable barrier. They can also be connected by gap junctions, which allow free exchange of soluble molecules between cells, and anchoring junctions, which attach cell to cell or cell to matrix. The different types of epithelial tissues are characterized by their cellular shapes and arrangements: squamous, cuboidal, or columnar epithelia. Single cell layers form simple epithelia, whereas stacked cells form

stratified epithelia. Very few capillaries penetrate these tissues.

Glands and Their Modes of Secretion

Glands are secretory tissues and organs that are derived from epithelial tissues. Exocrine glands release their products through ducts. Endocrine glands secrete hormones directly into the interstitial fluid and blood stream. Glands are classified both according to the type of secretion and by their structure. Merocrine glands secrete products as they are synthesized. Apocrine glands release secretions by pinching off the apical portion of the cell, whereas holocrine gland cells store their secretions until they rupture and release their contents. In this case, the cell becomes part of the secretion.

General Characteristics of Connective Tissue

Connective tissue is a heterogeneous tissue with many cell shapes and tissue architecture. Structurally, all connective tissues contain cells that are embedded in an extracellular matrix stabilized by proteins. The chemical nature and physical layout of the extracellular matrix and proteins vary enormously among tissues, reflecting the variety of functions that connective tissue fulfills in the body. Connective tissues separate and cushion organs, protecting them from shifting or traumatic injury. Connect tissues provide support and assist movement, store and transport energy molecules, protect against infections, and contribute to temperature homeostasis.

Cells and Extracellular Matrix in Connective Tissue

Many different cells contribute to the formation of connective tissues. They originate in the mesodermal germ layer and differentiate from mesenchyme and hematopoietic tissue in the bone marrow. Fibroblasts are the most abundant and secrete many protein fibers, adipocytes specialize in fat storage, hematopoietic cells from the bone marrow give rise to all the blood cells, chondrocytes form cartilage, and osteocytes form bone. The extracellular matrix contains fluid, proteins, polysaccharide derivatives, and, in the case of bone, mineral crystals. Protein fibers fall into three major groups: collagen fibers that are thick, strong, flexible, and resist stretch; reticular fibers that are thin and form a supportive mesh; and elastin fibers that are thin and elastic.

Types of Connective Tissue Proper

The major types of connective tissue are connective tissue proper, supportive tissue, and fluid tissue. Loose connective tissue proper includes adipose tissue, areolar tissue, and reticular tissue. These serve to hold organs and other tissues in place and, in the case of adipose tissue, isolate and store energy reserves. The matrix is the most abundant feature for loose tissue although adipose tissue does not have much extracellular matrix. Dense connective tissue proper is richer in fibers and may be regular, with fibers oriented in parallel as in ligaments and tendons, or irregular, with fibers oriented in several directions. Organ capsules (collagenous type) and walls of arteries (elastic type) contain dense irregular connective tissue.

Supportive and Fluid Connective Tissues: Cartilage, Bone, and Blood

Cartilage and bone are supportive tissue. Cartilage contains chondrocytes and is somewhat flexible. Hyaline cartilage is smooth and clear, covers joints, and is found in the growing portion of bones. Fibrocartilage is tough because of extra collagen fibers and forms, among other things, the intervertebral discs. Elastic cartilage can stretch and recoil to its original shape because of its high content of elastic fibers. The matrix contains very few blood vessels. Bones are made of a rigid, mineralized matrix containing calcium salts, crystals, and osteocytes lodged in lacunae. Bone tissue is highly vascularized. Cancellous bone is spongy and less solid than compact bone. Fluid tissue, for example blood and lymph, is characterized by a liquid matrix and no supporting fibers.

Types and Features of Muscle Tissue

The three types of muscle cells are skeletal, cardiac, and smooth. Their morphologies match their specific functions in the body. Skeletal muscle is voluntary and responds to conscious stimuli. The cells are striated and multinucleated appearing as long, unbranched cylinders. Cardiac muscle is involuntary and found only in the heart. Each cell is striated with a single nucleus and they attach to one another to form long fibers. Cells are attached to one another at intercalated disks. The cells are interconnected physically and electrochemically to act as a syncytium. Cardiac muscle cells contract autonomously and involuntarily. Smooth muscle is involuntary. Each cell is a spindle-shaped fiber and contains a single nucleus. No striations are evident because the

actin and myosin filaments do not align in the cytoplasm.

Neurons and Supporting Cells in Nervous Tissue

The most prominent cell of the nervous tissue, the neuron, is characterized mainly by its ability to receive stimuli and respond by generating an electrical signal, known as an action potential, which can travel rapidly over great distances in the body. A typical neuron displays a distinctive morphology: a large cell body branches out into short extensions called dendrites, which receive chemical signals from other neurons, and a long tail called an axon, which relays signals away from the cell to other neurons, muscles, or glands. Many axons are wrapped by a myelin sheath, a lipid derivative that acts as an insulator and speeds up the transmission of the action potential. Other cells in the nervous tissue, the neuroglia, include the astrocytes, microglia, oligodendrocytes, and Schwann cells.

Inflammation and Tissue Repair Processes

Inflammation is the classic response of the body to injury and follows a common sequence of events. The area is red, feels warm to the touch, swells, and is painful. Injured cells, mast cells, and resident macrophages release chemical signals that cause vasodilation and fluid leakage in the surrounding tissue. The repair phase includes blood clotting, followed by regeneration of tissue as fibroblasts deposit collagen. Some tissues regenerate more readily than others. Epithelial and connective tissues replace damaged or dead cells from a supply of adult stem cells. Muscle and nervous tissues undergo either slow regeneration or do not repair at all.

Effects of Aging on Body Tissues and Organs

Age affects all the tissues and organs of the body. Damaged cells do not regenerate as rapidly as in younger people. Perception of sensation and effectiveness of response are lost in the nervous system. Muscles atrophy, and bones lose mass and become brittle. Collagen decreases in some connective tissue, and joints stiffen.

Chapter Objectives

After studying this chapter, you will be able to:

- Distinguish the four major tissue types—epithelial, connective, muscle, and nervous—and explain how each contributes to the overall structure and function of the human body.
- Identify and describe the four principal tissue membranes (mucous, serous, cutaneous, synovial), and relate their structural characteristics (location, epithelial vs connective components, secretions) to their specific protective and functional roles.
- Classify major epithelial tissue types by cell shape and arrangement (simple vs stratified; squamous, cuboidal, columnar, transitional), and explain how these structural features support their functions in protection, absorption, secretion, filtration, and exchange.
- Classify major connective tissue types (e.g., loose, dense, cartilage, bone, blood, adipose) and correlate their cellular composition, fiber types, and matrix properties with their functions in support, binding, protection, transport, and energy storage.
- Describe the structural and functional characteristics of the three types of muscle tissue (skeletal, cardiac, smooth), including cell shape, striation, nuclei, control (voluntary/involuntary), and specialized junctions, and explain how these features enable different forms of movement and force generation.
- Describe the key features of nervous tissue, including neurons and neuroglia, and explain how neuronal structure (cell body, dendrites, axon, synapses) and glial support enable rapid information processing, communication, and regulation of muscle and gland activity across the body.

4.1: Types of Tissues

4.2: Epithelial Tissue

4.3: Connective Tissue Supports and Protects

4.4: Muscle Tissue and Motion
4.5: Nervous Tissue Mediates Perception and Response
4.6: Terms and Definitions
4.7: Chapter Review Questions
4.8: Applied Thinking Self-Assessment
4.9: Alternate Text Descriptions

Thumbnails: Four major tissue types of the human body. (CC BY-SA 4.0; via Human Anatomy and Physiology1).

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4.1: Types of Tissues

The Four Types of Tissues

The term tissue is used to describe a group of cells found together in the body. The cells within a tissue share a common embryonic origin. Microscopic observation reveals that the cells in a tissue share morphological features and are arranged in an orderly pattern that achieves the tissue's functions. From the evolutionary perspective, tissues appear in more complex organisms. For example, multicellular protists, ancient eukaryotes, do not have cells organized into tissues.

Although there are many types of cells in the human body, they are organized into four broad categories of tissues: epithelial, connective, muscle, and nervous. Each of these categories is characterized by specific functions that contribute to the overall health and maintenance of the body. A disruption of the structure is a sign of injury or disease. Such changes can be detected through histology, the microscopic study of tissue appearance, organization, and function.

Epithelial tissue, also referred to as epithelium, refers to the sheets of cells that cover exterior surfaces of the body, line internal cavities and passageways, and form certain glands. Connective tissue, as its name implies, binds the cells and organs of the body together and functions in the protection, support, and integration of all parts of the body. Muscle tissue is excitable, responding to stimulation and contracting to provide movement, and occurs as three major types: skeletal (voluntary) muscle, smooth muscle, and cardiac muscle in the heart. Nervous tissue is also excitable, allowing the propagation of electrochemical signals in the form of nerve impulses that communicate between different regions of the body (Figure 4.1.1).

The next level of organization is the organ, where several types of tissues come together to form a working unit. Just as knowing the structure and function of cells helps you in your study of tissues, knowledge of tissues will help you understand how organs function. The epithelial and connective tissues are discussed in detail in this chapter. Muscle and nervous tissues will be discussed only briefly in this chapter.

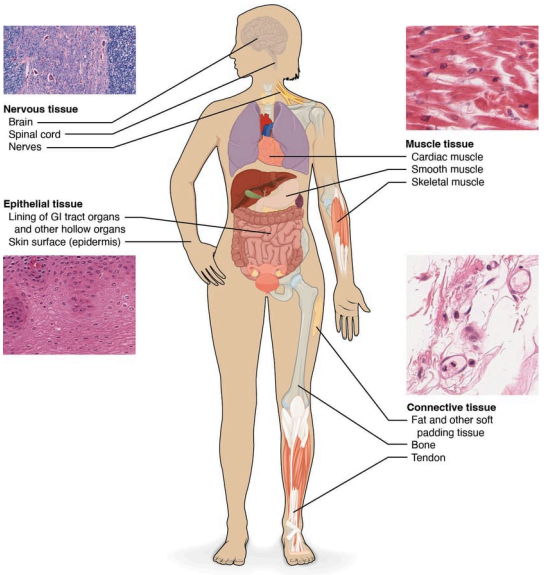


Figure 4.1.1: The four types of tissues are exemplified in nervous tissue, stratified squamous epithelial tissue, cardiac muscle tissue, and connective tissue. (CC BY 4.0; via OpenStax). Alternate text description of Figure 4.1.1.

Embryonic Origin of Tissues

The zygote, or fertilized egg, is a single cell formed by the fusion of an egg and sperm. After fertilization the zygote gives rise to rapid mitotic cycles, generating many cells to form the embryo. The first embryonic cells generated have the ability to differentiate into any type of cell in the body and, as such, are called totipotent, meaning each has the capacity to divide, differentiate, and develop into a new organism. As cell proliferation progresses, three major cell lineages are established within the embryo. As explained in a later chapter, each of these lineages of embryonic cells forms the distinct germ layers from which all the tissues

and organs of the human body eventually form. Each germ layer is identified by its relative position: ectoderm (ecto- = “outer”), mesoderm (meso- = “middle”), and endoderm (endo- = “inner”). Figure 4.1.2 shows the types of tissues and organs associated with the each of the three germ layers. Note that epithelial tissue originates in all three layers, whereas nervous tissue derives primarily from the ectoderm and muscle tissue from mesoderm.

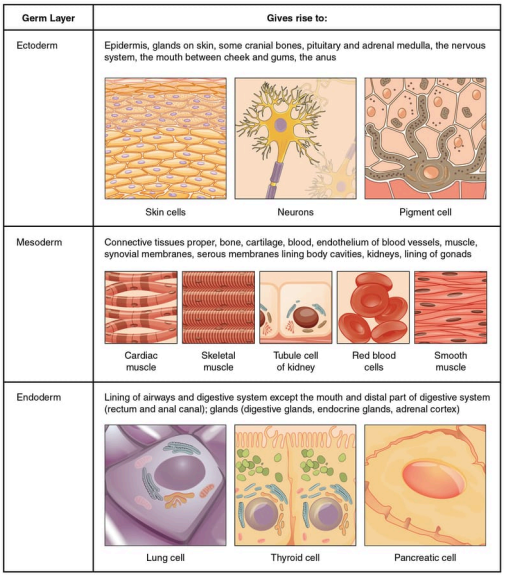


Figure 4.1.2: Embryonic Origin of Tissues and Major Organs. (CC BY 4.0; via OpenStax). Alternate text description of Figure 4.1.2.

Tissue Membranes

A tissue membrane is a thin layer or sheet of cells that covers the outside of the body (for example, skin), the organs (for example, pericardium), internal passageways that lead to the exterior of the body (for example, mucosa of stomach), and the lining of the moveable joint cavities. There are two basic types of tissue membranes: connective tissue and epithelial membranes (Figure 4.1.3).

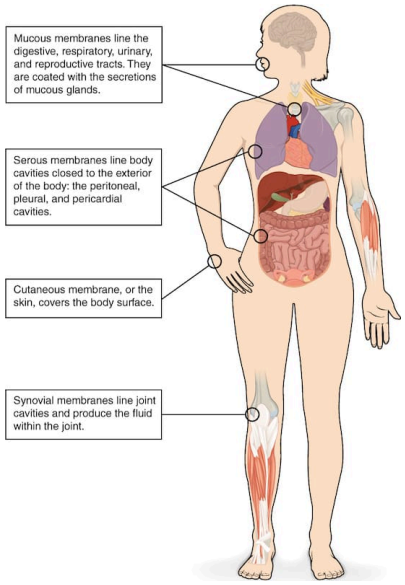


Figure 4.1.3: The two broad categories of tissue membranes in the body are (1) connective tissue membranes, which include synovial membranes, and (2) epithelial membranes, which include mucous membranes, serous membranes, and the cutaneous membrane, in other words, the skin. (CC BY 4.0; via OpenStax). Alternate text description of Figure 4.1.3.

Connective Tissue Membranes

The connective tissue membrane is formed solely from connective tissue. These membranes encapsulate organs, such as the kidneys, and line our movable joints. A synovial membrane is a type of connective tissue membrane that lines the cavity of a freely movable joint. For example, synovial membranes surround the joints of the shoulder, elbow, and knee. Fibroblasts in the inner layer of the synovial membrane release hyaluronan into the joint cavity. The hyaluronan effectively traps available water to form the synovial fluid, a natural lubricant that enables the bones of a joint to move freely against one another without much friction. This synovial fluid readily exchanges water and nutrients with blood, as do all body fluids.

Epithelial Membranes

The epithelial membrane is composed of epithelium attached to a layer of connective tissue, for example, your skin. The mucous membrane is also a composite of connective and epithelial tissues. Sometimes called mucosae, these epithelial membranes line the body cavities and hollow passageways that open to the external environment, and include the digestive, respiratory, excretory, and reproductive tracts. Mucus, produced by the epithelial exocrine glands, covers the epithelial layer. The underlying connective tissue, called the lamina propria (literally “own layer”), help support the fragile epithelial layer.

A serous membrane is an epithelial membrane composed of mesodermally derived epithelium called the mesothelium that is supported by connective tissue. These membranes line the coelomic cavities of the body, that is, those cavities that do not open to the outside, and they cover the organs located within those cavities. They are essentially membranous bags, with mesothelium lining the inside and connective tissue on the outside. Serous fluid secreted by the cells of the thin squamous mesothelium lubricates the membrane and reduces abrasion and friction between organs. Serous membranes are identified according locations. Three serous membranes line the thoracic cavity; the two pleura that cover the lungs and the pericardium that covers the heart. A fourth, the peritoneum, is the serous membrane in the abdominal cavity that covers abdominal organs and forms double sheets of mesenteries that suspend many of the digestive organs.

The skin is an epithelial membrane also called the cutaneous membrane. It is a stratified squamous epithelial membrane resting on top of connective tissue. The apical surface of this membrane is exposed to the external environment and is covered with dead, keratinized cells that help protect the body from desiccation and pathogens.

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4.2: Epithelial Tissue

Generalized Functions of Epithelial Tissue

Most epithelial tissues are essentially large sheets of cells covering all the surfaces of the body exposed to the outside world and lining the outside of organs. Epithelium also forms much of the glandular tissue of the body. Skin is not the only area of the body exposed to the outside. Other areas include the airways, the digestive tract, as well as the urinary and reproductive systems, all of which are lined by an epithelium. Hollow organs and body cavities that do not connect to the exterior of the body, which includes, blood vessels and serous membranes, are lined by endothelium (plural = endothelia), which is a type of epithelium.

Epithelial cells derive from all three major embryonic layers. The epithelia lining the skin, parts of the mouth and nose, and the anus develop from the ectoderm. Cells lining the airways and most of the digestive system originate in the endoderm. The epithelium that lines vessels in the lymphatic and cardiovascular system derives from the mesoderm and is called an endothelium.

All epithelia share some important structural and functional features. This tissue is highly cellular, with little or no extracellular material present between cells. Adjoining cells form a specialized intercellular connection between their cell membranes called a cell junction. The epithelial cells exhibit polarity with differences in structure and function between the exposed or apical facing surface of the cell and the basal surface close to the underlying body structures. The basal lamina, a mixture of glycoproteins and collagen, provides an attachment site for the epithelium, separating it from underlying connective tissue. The basal lamina attaches to a reticular lamina, which is secreted by the underlying connective tissue, forming a basement membrane that helps hold it all together.

Epithelial tissues are nearly completely avascular. For instance, no blood vessels cross the basement membrane to enter the tissue, and nutrients must come by diffusion or absorption from underlying tissues or the surface. Many epithelial tissues are capable of rapidly replacing damaged and dead cells. Sloughing off of damaged or dead cells is a characteristic of surface epithelium and allows our airways and digestive tracts to rapidly replace damaged cells with new cells.

Epithelial tissues provide the body's first line of protection from physical, chemical, and biological wear and tear. The cells of an epithelium act as gatekeepers of the body controlling permeability and allowing selective transfer of materials across a physical barrier. All substances that enter the body must cross an epithelium. Some epithelia often include structural features that allow the selective transport of molecules and ions across their cell membranes.

Many epithelial cells are capable of secretion and release mucous and specific chemical compounds onto their apical surfaces. The epithelium of the small intestine releases digestive enzymes, for example. Cells lining the respiratory tract secrete mucous that traps incoming microorganisms and particles. A glandular epithelium contains many secretory cells.

The Epithelial Cell

Epithelial cells are typically characterized by the polarized distribution of organelles and membrane-bound proteins between their basal and apical surfaces. Particular structures found in some epithelial cells are an adaptation to specific functions. Certain organelles are segregated to the basal sides, whereas other organelles and extensions, such as cilia, when present, are on the apical surface.

Cilia are microscopic extensions of the apical cell membrane that are supported by microtubules. They beat in unison and move fluids as well as trapped particles. Ciliated epithelium lines the ventricles of the brain where it helps circulate the cerebrospinal fluid. The ciliated epithelium of your airway forms a mucociliary escalator that sweeps particles of dust and pathogens trapped in the secreted mucous toward the throat. It is called an escalator because it continuously pushes mucous with trapped particles upward. In contrast, nasal cilia sweep the mucous blanket down towards your throat. In both cases, the transported materials are usually swallowed, and end up in the acidic environment of your stomach.

Cell to Cell Junctions

Cells of epithelia are closely connected and are not separated by intracellular material. Three basic types of connections allow varying degrees of interaction between the cells: tight junctions, anchoring junctions, and gap junctions (Figure 4.2.1).

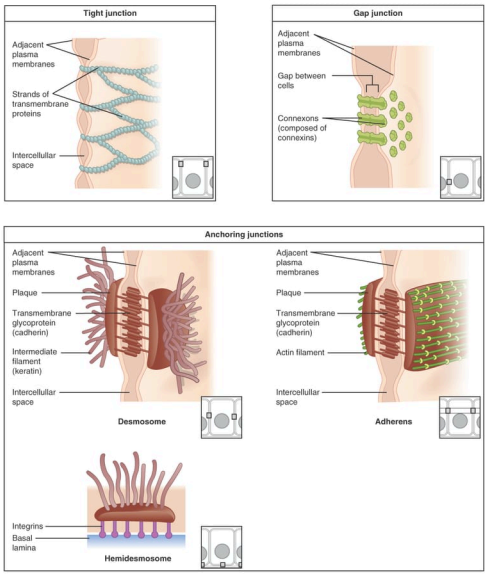


Figure 4.2.1: The three basic types of cell-to-cell junctions are tight junctions, gap junctions, and anchoring junctions. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.2.1.

At one end of the spectrum is the tight junction, which separates the cells into apical and basal compartments. When two adjacent epithelial cells form a tight junction, there is no extracellular space between them and the movement of substances through the extracellular space between the cells is blocked. This enables the epithelia to act as selective barriers. An anchoring junction includes several types of cell junctions that help stabilize epithelial tissues. Anchoring junctions are common on the lateral and basal surfaces of cells where they provide strong and flexible connections. There are three types of anchoring junctions: desmosomes, hemidesmosomes, and adherens. Desmosomes occur in patches on the membranes of cells. The patches are structural proteins on the inner surface of the cell's membrane. The adhesion molecule, cadherin, is embedded in these patches and projects through the cell membrane to link with the cadherin molecules of adjacent cells. These connections are especially important in holding cells together. Hemidesmosomes, which look like half a desmosome, link cells to the extracellular matrix, for example, the basal lamina. While similar in appearance to desmosomes, they include the adhesion proteins called integrins rather than cadherins. Adherens junctions use either cadherins or integrins depending on whether they are linking to other cells or matrix. The junctions are characterized by the presence of the contractile protein actin located on the cytoplasmic surface of the cell membrane. The actin can connect isolated patches or form a belt-like structure inside the cell. These junctions influence the shape and folding of the epithelial tissue.

In contrast with the tight and anchoring junctions, a gap junction forms an intercellular passageway between the membranes of adjacent cells to facilitate the movement of small molecules and ions between the cytoplasm of adjacent cells. These junctions allow electrical and metabolic coupling of adjacent cells, which coordinates function in large groups of cells.

Classification of Epithelial Tissues

Epithelial tissues are classified according to the shape of the cells and number of the cell layers formed (Figure 4.2.2). Cell shapes can be squamous (flattened and thin), cuboidal (boxy, as wide as it is tall), or columnar (rectangular, taller than it is wide). Similarly, the number of cell layers in the tissue can be one—where every cell rests on the basal lamina—which is a simple epithelium, or more than one, which is a stratified epithelium and only the basal layer of cells rests on the basal lamina. Pseudostratified (pseudo- = "false") describes tissue with a single layer of irregularly shaped cells that give the appearance of more than one layer. Transitional describes a form of specialized stratified epithelium in which the shape of the cells can vary.

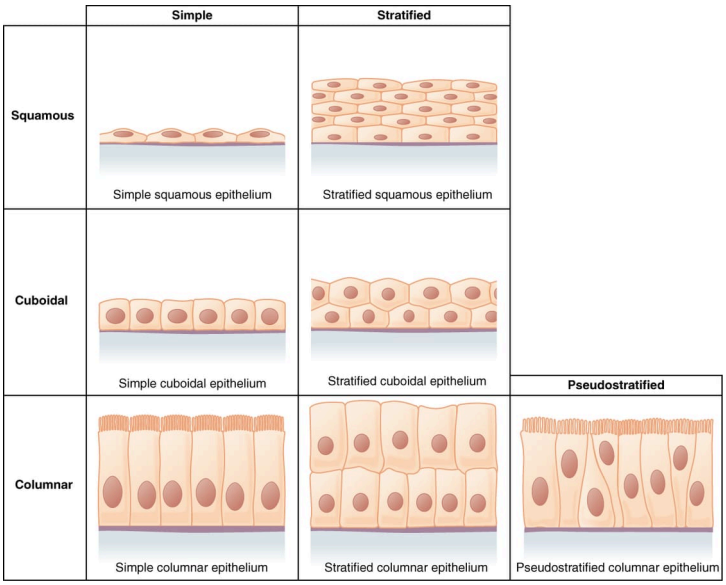


Figure 4.2.2: Simple epithelial tissue is organized as a single layer of cells and stratified epithelial tissue is formed by several layers of cells. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.2.2.

Simple Epithelium

The shape of the cells in the single cell layer of simple epithelium reflects the functioning of those cells. The cells in simple squamous epithelium have the appearance of thin scales. Squamous cell nuclei tend to be flat, horizontal, and elliptical, mirroring the form of the cell. The endothelium is the epithelial tissue that lines vessels of the lymphatic and cardiovascular system, and it is made up of a single layer of squamous cells. Simple squamous epithelium, because of the thinness of the cell, is present where rapid passage of chemical compounds is observed. The alveoli of lungs where gases diffuse, segments of kidney tubules, and the lining of capillaries are also made of simple squamous epithelial tissue. The mesothelium is a simple squamous epithelium that forms the surface layer of the serous membrane that lines body cavities and internal organs. Its primary function is to provide a smooth and protective surface. Mesothelial cells are squamous epithelial cells that secrete a fluid that lubricates the mesothelium.

In simple cuboidal epithelium, the nucleus of the box-like cells appears round and is generally located near the center of the cell. These epithelia are active in the secretion and absorptions of molecules. Simple cuboidal epithelia are observed in the lining of the kidney tubules and in the ducts of glands.

In simple columnar epithelium, the nucleus of the tall column-like cells tends to be elongated and located in the basal end of the cells. Like the cuboidal epithelia, this epithelium is active in the absorption and secretion of molecules. Simple columnar epithelium forms the lining of some sections of the digestive system and parts of the female reproductive tract. Ciliated columnar epithelium is composed of simple columnar epithelial cells with cilia on their apical surfaces. These epithelial cells are found in the lining of the fallopian tubes and parts of the respiratory system, where the beating of the cilia helps remove particulate matter.

Pseudostratified columnar epithelium is a type of epithelium that appears to be stratified but instead consists of a single layer of irregularly shaped and differently sized columnar cells. In pseudostratified epithelium, nuclei of neighboring cells appear at different levels rather than clustered in the basal end. The arrangement gives the appearance of stratification; but in fact all the cells are in contact with the basal lamina, although some do not reach the apical surface. Pseudostratified columnar epithelium is found in the respiratory tract, where some of these cells have cilia.

Both simple and pseudostratified columnar epithelia are heterogeneous epithelia because they include additional types of cells interspersed among the epithelial cells. For example, a goblet cell is a mucous-secreting unicellular “gland” interspersed between the columnar epithelial cells of mucous membranes.

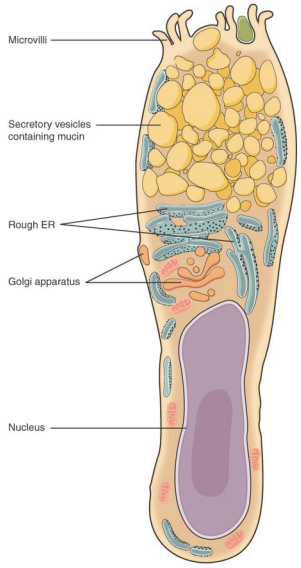


Figure 4.2.3: In the lining of the small intestine, columnar epithelium cells are interspersed with goblet cells. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.2.3.

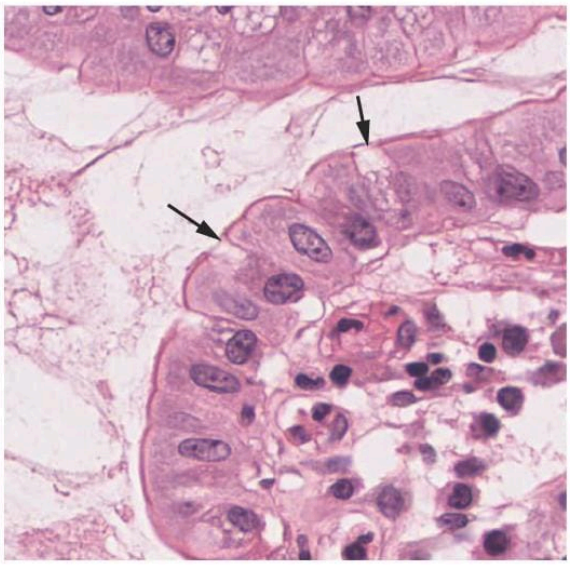


Figure 4.2.4: The arrows in this micrograph point to the mucous-secreting goblet cells. LM × 1600. (CC BY-SA 4.0; via OpenStax). Alternate text description of Figure 4.2.4.

Stratified Epithelium

A stratified epithelium consists of several stacked layers of cells. This epithelium protects against physical and chemical wear and tear. The stratified epithelium is named by the shape of the most apical layer of cells, closest to the free space. Stratified squamous epithelium is the most common type of stratified epithelium in the human body. The apical cells are squamous, whereas the basal layer contains either columnar or cuboidal cells. The top layer may be covered with dead cells filled with keratin. Mammalian skin is an example of this dry, keratinized, stratified squamous epithelium. The lining of the mouth cavity is an example of an unkeratinized, stratified squamous epithelium. Stratified cuboidal epithelium and stratified columnar epithelium can also be found in certain glands and ducts, but are uncommon in the human body.

Another kind of stratified epithelium is transitional epithelium, so-called because of the gradual changes in the shapes of the apical cells as the bladder fills with urine. It is found only in the urinary system, specifically the ureters and urinary bladder. When the bladder is empty, this epithelium is convoluted and has cuboidal apical cells with convex, umbrella shaped, apical surfaces. As the bladder fills with urine, this epithelium loses its convolutions and the apical cells transition from cuboidal to squamous. It appears thicker and more multi-layered when the bladder is empty, and more stretched out and less stratified when the bladder

is full and distended. Figure 4.2.5 summarizes the different categories of epithelial cell tissue cells.

Cells	Location	Function
Simple squamous epithelium	Air sacs of lungs and the lining of the heart, blood vessels, and lymphatic vessels	Allows materials to pass through by diffusion and filtration, and secretes lubricating substance
Simple cuboidal epithelium	In ducts and secretory portions of small glands and in kidney tubules	Secretes and absorbs
Simple columnar epithelium	Ciliated tissues are in larger bronchioles, uterine tubes, and uterus; smooth (nonciliated tissues) are in the digestive tract, bladder	Absorbs; it also secretes mucus and enzymes
Pseudostratified columnar epithelium	Ciliated tissue lines the bronchi, trachea, and much of the upper respiratory tract	Secretes mucus; ciliated tissue moves mucus
Stratified squamous epithelium	Lines the esophagus, mouth, and vagina	Protects against abrasion
Stratified cuboidal epithelium	Sweat glands, salivary glands, and the mammary glands	Protective tissue
Stratified columnar epithelium	The male and female urethrae and the ducts of some glands	Secretes and protects
Transitional epithelium	Lines the bladder, urethra, and the ureters	Allows the urinary organs to expand and stretch

Figure 4.2.5: Summary of Epithelial Tissue Cells. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.2.5.

In a simple cuboidal epithelium, the cells are cube shaped and single layered and located in ducts and secretory portions of small glands as well as in the kidney tubules. The function of simple cuboidal epithelium is to secrete and absorb. In a simple columnar epithelium, the cells are rectangular and are attached to the basement membrane on one of their narrow sides, so that each cell is standing up like a column. There is only one layer of cells. Simple columnar epithelium is found in ciliated tissues including the larger bronchioles, uterine tubes, and uterus, as well as in smooth, nonciliated tissues such as the digestive tract bladder.

The function of simple columnar epithelium is to absorb substances but also to secrete mucous and enzymes. In a pseudostratified columnar epithelium, the cells are column-like in appearance, but they vary in height. The taller cells bend over the tops of the shorter cells so that the top of the epithelial tissue is continuous. There is only one layer of cells. Pseudostratified columnar epithelium lines the bronchi, the trachea, and much of the upper respiratory tract. The function of pseudostratified columnar epithelium is to secrete mucous and also move that mucus using the hair like cilia projecting from the top of each cell.

A stratified squamous epithelium contains many layers of flattened cells. Stratified squamous epithelium lines the esophagus, mouth, and vagina. The function of stratified squamous epithelium is to protect against abrasion. Stratified cuboidal epithelium contains many layers of cube-shaped cells. Stratified cuboidal epithelium is found in the sweat glands, salivary glands, and mammary glands. The function of stratified cuboidal epithelium is to protect other tissues of the body. Stratified columnar epithelium contains many layers of rectangular, column-shaped cells. Stratified columnar epithelium is located in the male and female urethrae and the ducts of some glands. The function of stratified columnar epithelium is to secrete and protect. Transitional epithelium consists of many layers of irregularly shaped cells with diverse sizes. Transitional epithelium is found lining the bladder, urethra and ureters. The function of transitional epithelium is to allow the urinary organs to expand and stretch.

Glandular Epithelium

A gland is a structure made up of one or more cells modified to synthesize and secrete chemical substances. Most glands consist of groups of epithelial cells. A gland can be classified as an endocrine gland, a ductless gland that releases secretions directly into surrounding tissues and fluids (endo- = “inside”), or an exocrine gland whose secretions leave through a duct that opens directly, or indirectly, to the external environment (exo- = “outside”).

Endocrine Glands

The secretions of endocrine glands are called hormones. Hormones are released into the interstitial fluid, diffused into the bloodstream, and delivered to targets, in other words, cells that have receptors to bind the hormones. The endocrine system is part of a major regulatory system coordinating the regulation and integration of body responses. A few examples of endocrine glands include the anterior pituitary, thymus, adrenal cortex, and gonads.

Exocrine Glands

Exocrine glands release their contents through a duct that leads to the epithelial surface. Mucous, sweat, saliva, and breast milk are all examples of secretions from exocrine glands. They are all discharged through tubular ducts. Secretions into the lumen of the gastrointestinal tract, technically outside of the body, are of the exocrine category.

Glandular Structure

Exocrine glands are classified as either unicellular or multicellular. The unicellular glands are scattered single cells, such as goblet cells, found in the mucous membranes of the small and large intestine.

The multicellular exocrine glands known as serous glands develop from simple epithelium to form a secretory surface that secretes directly into an inner cavity. These glands line the internal cavities of the abdomen and chest and release their secretions directly into the cavities. Other multicellular exocrine glands release their contents through a tubular duct. The duct is single in a simple gland but in compound glands is divided into one or more branches (Figure 4.2.6). In tubular glands, the ducts can be straight or coiled, whereas tubes that form pockets are alveolar (acinar), such as the exocrine portion of the pancreas. Combinations of tubes and pockets are known as tubuloalveolar (tubuloacinar) compound glands. In a branched gland, a duct is connected to more than one secretory group of cells.

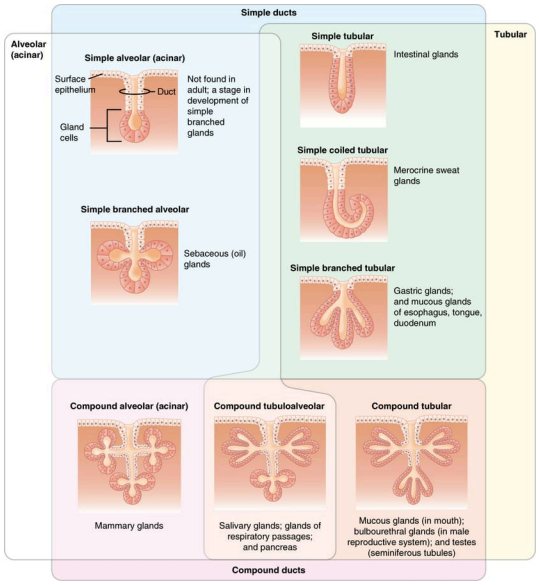


Figure 4.2.6: Exocrine glands are classified by their structure. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.2.6.

Methods and Types of Secretion

Exocrine glands can be classified by their mode of secretion and the nature of the substances released, as well as by the structure of the glands and shape of ducts (Figure 4.2.7). Merocrine secretion is the most common type of exocrine secretion. The secretions are enclosed in vesicles that move to the apical surface of the cell where the contents are released by exocytosis. For example, watery mucous containing the glycoprotein mucin, a lubricant that offers some pathogen protection is a merocrine secretion. The eccrine glands that produce and secrete sweat are another example.

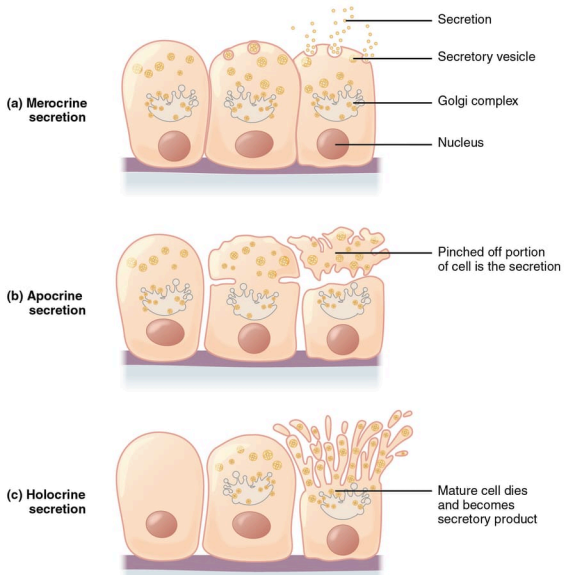


Figure 4.2.7: (a) In merocrine secretion, the cell remains intact. (b) In apocrine secretion, the apical portion of the cell is released, as well. (c) In holocrine secretion, the cell is destroyed as it releases its product and the cell itself becomes part of the secretion. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.2.7.

Apocrine secretion accumulates near the apical portion of the cell. That portion of the cell and its secretory contents pinch off from the cell and are released. Apocrine sweat glands in the axillary and genital areas release fatty secretions that local bacteria break down; this causes body odor. Both merocrine and apocrine glands continue to produce and secrete their contents with little damage caused to the cell because the nucleus and golgi regions remain intact after secretion.

In contrast, the process of holocrine secretion involves the rupture and destruction of the entire gland cell. The cell accumulates its secretory products and releases them only when it bursts. New gland cells differentiate from cells in the surrounding tissue to replace those lost by secretion. The sebaceous glands that produce the oils on the skin and hair are holocrine glands/cells Figure 4.2.8).

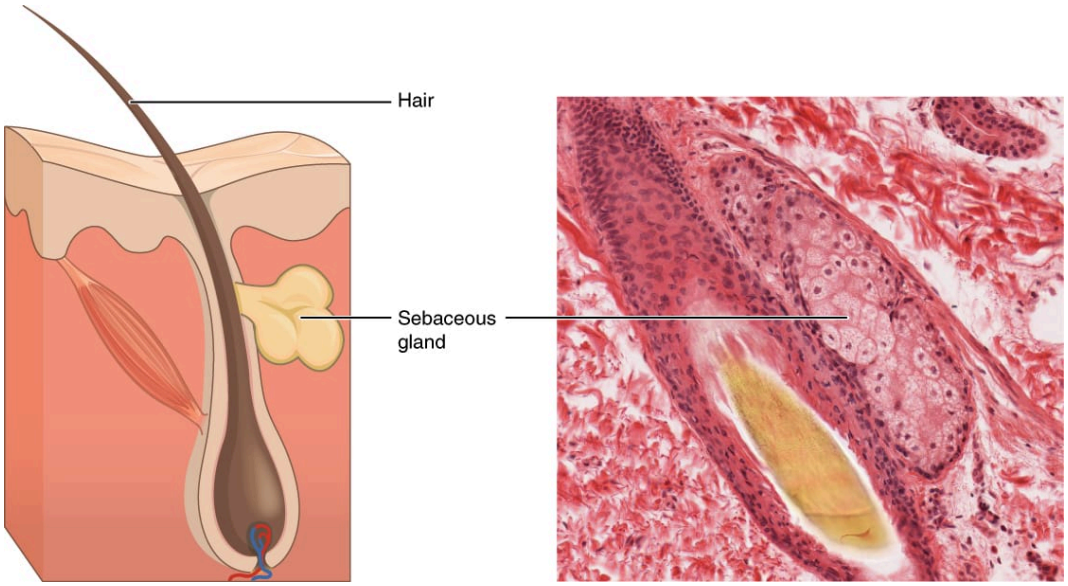


Figure 4.2.8: These glands secrete oils that lubricate and protect the skin. They are holocrine glands and they are destroyed after releasing their contents. New glandular cells form to replace the cells that are lost. LM × 400. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.2.8.

Glands are also named after the products they produce. The serous gland produces watery, blood-plasma-like secretions rich in enzymes such as alpha amylase, whereas the mucous gland releases watery to viscous products rich in the glycoprotein mucin.

Both serous and mucous glands are common in the salivary glands of the mouth. Mixed exocrine glands contain both serous and mucous glands and release both types of secretions.

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4.3: Connective Tissue Supports and Protects

Functions of Connective Tissues

As may be obvious from its name, one of the major functions of connective tissue is to connect tissues and organs. Unlike epithelial tissue, which is composed of cells closely packed with little or no extracellular space in between, connective tissue cells are dispersed in a matrix. The matrix usually includes a large amount of extracellular material produced by the connective tissue cells that are embedded within it. The matrix plays a major role in the functioning of this tissue. The major component of the matrix is a ground substance often crisscrossed by protein fibers. This ground substance is usually a fluid, but it can also be mineralized and solid, as in bones. Connective tissues come in a vast variety of forms, yet they typically have in common three characteristic components: cells, large amounts of amorphous ground substance, and protein fibers. The amount and structure of each component correlates with the function of the tissue, from the rigid ground substance in bones supporting the body to the inclusion of specialized cells; for example, a phagocytic cell that engulfs pathogens and also rids tissue of cellular debris.

Connective tissues perform many functions in the body, but most importantly, they support and connect other tissues; from the connective tissue sheath that surrounds muscle cells, to the tendons that attach muscles to bones, and to the skeleton that supports the positions of the body. Protection is another major function of connective tissue, in the form of fibrous capsules and bones that protect delicate organs and, of course, the skeletal system. Specialized cells in connective tissue defend the body from microorganisms that enter the body. Transport of fluid, nutrients, waste, and chemical messengers is ensured by specialized fluid connective tissues, such as blood and lymph. Adipose cells store surplus energy in the form of fat and contribute to the thermal insulation of the body.

Embryonic Connective Tissue

All connective tissues derive from the mesodermal layer of the embryo (see Figure 4.3). The first connective tissue to develop in the embryo is mesenchyme, the stem cell line from which all connective tissues are later derived. Clusters of mesenchymal cells are scattered throughout adult tissue and supply the cells needed for replacement and repair after a connective tissue injury. A second type of embryonic connective tissue forms in the umbilical cord, called mucous connective tissue or Wharton's jelly. This tissue is no longer present after birth, leaving only scattered mesenchymal cells throughout the body.

Classification of Connective Tissues

The three broad categories of connective tissue are classified according to the characteristics of their ground substance and the types of fibers found within the matrix (Table 4.3.1). Connective tissue proper includes loose connective tissue and dense connective tissue. Both tissues have a variety of cell types and protein fibers suspended in a viscous ground substance. Dense connective tissue is reinforced by bundles of fibers that provide tensile strength, elasticity, and protection. In loose connective tissue, the fibers are loosely organized, leaving large spaces in between. Supportive connective tissue—bone and cartilage—provide structure and strength to the body and protect soft tissues. A few distinct cell types and densely packed fibers in a matrix characterize these tissues. In bone, the matrix is rigid and described as calcified because of the deposited calcium salts. In fluid connective tissue, in other words, lymph and blood, various specialized cells circulate in a watery fluid containing salts, nutrients, and dissolved proteins.

Table 4.3.1: Connective Tissue Examples

Connective tissue proper	Supportive connective tissue	Fluid connective tissue
Loose connective tissue • Areolar • Adipose • Reticular Dense connective tissue • Dense regular • Elastic • Dense-irregular	Cartilage • Hyaline • Fibrocartilage • Elastic Bone	Blood Lymph

Connective Tissue Proper

Fibroblasts are present in all connective tissue proper (Figure 4.3.1). Fibrocytes, adipocytes, and mesenchymal cells are fixed cells, which means they remain within the connective tissue. Other cells move in and out of the connective tissue in response to chemical signals. Macrophages, mast cells, lymphocytes, plasma cells, and phagocytic cells are found in connective tissue proper but are actually part of the immune system protecting the body.

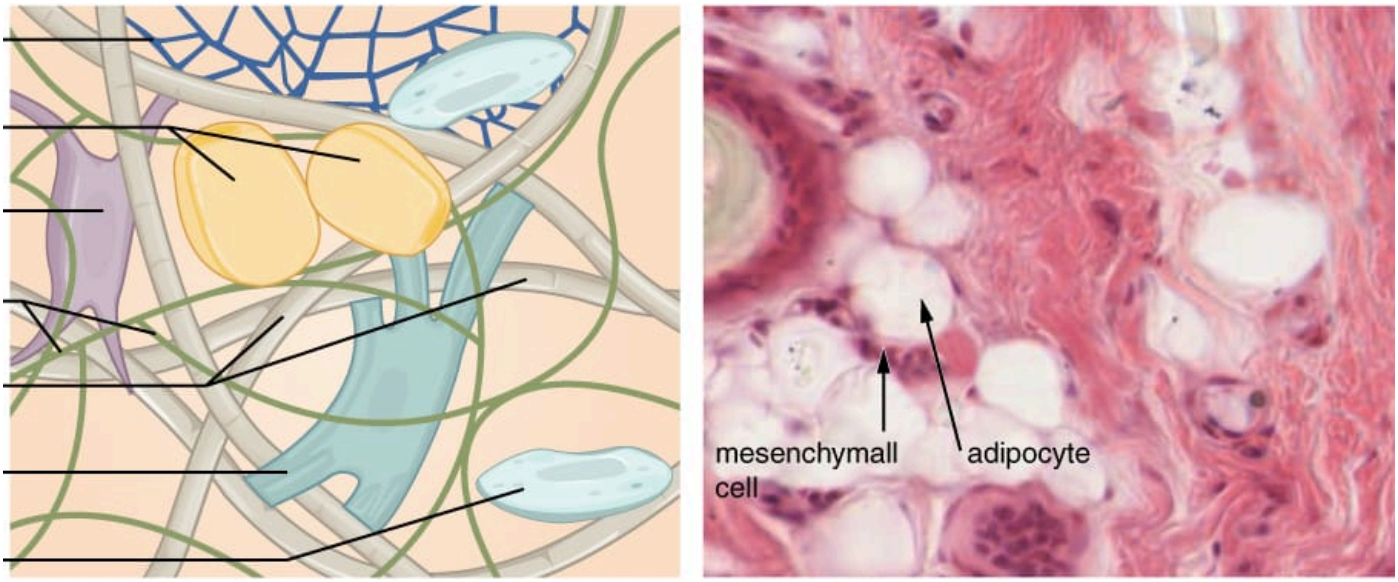


Figure 4.3.1: Connective tissue proper includes the fixed cells fibrocytes, adipocytes, and mesenchymal cells. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.3.1.

Cell Types

The most abundant cell in connective tissue proper is the fibroblast. Polysaccharides and proteins secreted by fibroblasts combine with extra-cellular fluids to produce a viscous ground substance that, with embedded fibrous proteins, forms the extra-cellular matrix. As you might expect, a fibrocyte, a less active form of fibroblast, is the second most common cell type in connective tissue proper.

Adipocytes are cells that store lipids as droplets that fill most of the cytoplasm. There are two basic types of adipocytes: white and brown. The brown adipocytes store lipids as many droplets, and have high metabolic activity. In contrast, white fat adipocytes store lipids as a single large drop and are metabolically less active. Their effectiveness at storing large amounts of fat is witnessed in obese individuals. The number and type of adipocytes depends on the tissue and location, and vary among individuals in the

population.

The mesenchymal cell is a multipotent adult stem cell. These cells can differentiate into any type of connective tissue cells needed for repair and healing of damaged tissue.

The macrophage cell is a large cell derived from a monocyte, a type of blood cell, which enters the connective tissue matrix from the blood vessels. The macrophage cells are an essential component of the immune system, which is the body's defense against potential pathogens and degraded host cells. When stimulated, macrophages release cytokines, small proteins that act as chemical messengers. Cytokines recruit other cells of the immune system to infected sites and stimulate their activities. Roaming, or free, macrophages move rapidly by amoeboid movement, engulfing infectious agents and cellular debris. In contrast, fixed macrophages are permanent residents of their tissues.

The mast cell, found in connective tissue proper, has many cytoplasmic granules. These granules contain the chemical signals histamine and heparin. When irritated or damaged, mast cells release histamine, an inflammatory mediator, which causes vasodilation and increased blood flow at a site of injury or infection, along with itching, swelling, and redness you recognize as an allergic response. Like blood cells, mast cells are derived from hematopoietic stem cells and are part of the immune system.

Connective Tissue Fibers and Ground Substance

Three main types of fibers are secreted by fibroblasts: collagen fibers, elastic fibers, and reticular fibers. Collagen fiber is made from fibrous protein subunits linked together to form a long and straight fiber. Collagen fibers, while flexible, have great tensile strength, resist stretching, and give ligaments and tendons their characteristic resilience and strength. These fibers hold connective tissues together, even during the movement of the body.

Elastic fiber contains the protein elastin along with lesser amounts of other proteins and glycoproteins. The main property of elastin is that after being stretched or compressed, it will return to its original shape. Elastic fibers are prominent in elastic tissues found in skin and the elastic ligaments of the vertebral column.

Reticular fiber is also formed from the same protein subunits as collagen fibers; however, these fibers remain narrow and are arrayed in a branching network. They are found throughout the body, but are most abundant in the reticular tissue of soft organs, such as liver and spleen, where they anchor and provide structural support to the parenchyma (the functional cells, blood vessels, and nerves of the organ).

All of these fiber types are embedded in ground substance. Secreted by fibroblasts, ground substance is made of polysaccharides, specifically hyaluronic acid, and proteins. These combine to form a proteoglycan with a protein core and polysaccharide branches. The proteoglycan attracts and traps available moisture forming the clear, viscous, colorless matrix you now know as ground substance.

Loose Connective Tissue

Loose connective tissue is found between many organs where it acts both to absorb shock and bind tissues together. It allows water, salts, and various nutrients to diffuse through to adjacent or imbedded cells and tissues.

Adipose tissue consists mostly of fat storage cells, with little extracellular matrix (Figure $4.3.2$). A large number of capillaries allow rapid storage and mobilization of lipid molecules. White adipose tissue is most abundant. It can appear yellow and owes its color to carotene and related pigments from plant food. White fat contributes mostly to lipid storage and can serve as insulation from cold temperatures and mechanical injuries. White adipose tissue can be found protecting the kidneys and cushioning the back of the eye. Brown adipose tissue is more common in infants, hence the term "baby fat." In adults, there is a reduced amount of brown fat and it is found mainly in the neck and clavicular regions of the body. The many mitochondria in the cytoplasm of brown adipose tissue help explain its efficiency at metabolizing stored fat. Brown adipose tissue is thermogenic, meaning that as it breaks down fats, it releases metabolic heat, rather than producing adenosine triphosphate (ATP), a key molecule used in metabolism.

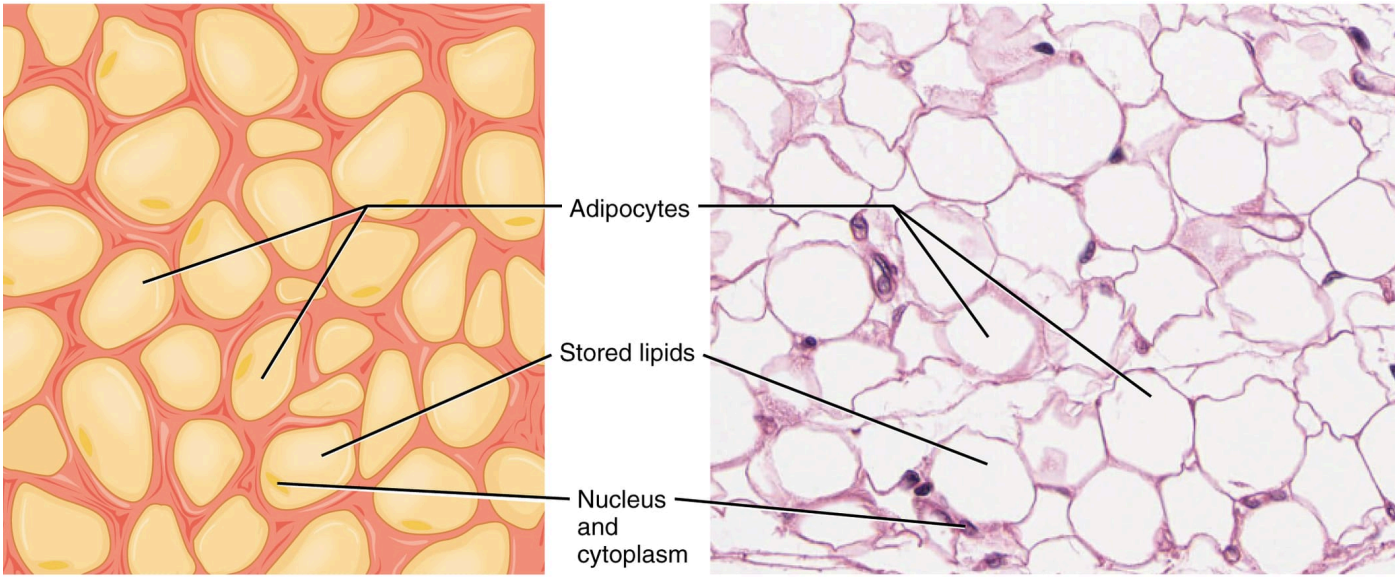


Figure 4.3.2: This is a loose connective tissue that consists of fat cells with little extracellular matrix. It stores fat for energy and provides insulation. LM × 800. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.3.2.

Areolar tissue shows little specialization. It contains all the cell types and fibers previously described and is distributed in a random, web-like fashion. It fills the spaces between muscle fibers, surrounds blood and lymph vessels, and supports organs in the abdominal cavity. Areolar tissue underlies most epithelia and represents the connective tissue component of epithelial membranes, which are described further in a later section.

Reticular tissue is a mesh-like, supportive framework for soft organs such as lymphatic tissue, the spleen, and the liver (Figure 4.3.3). Reticular cells produce the reticular fibers that form the network onto which other cells attach. It derives its name from the Latin *reticulus*, which means "little net."

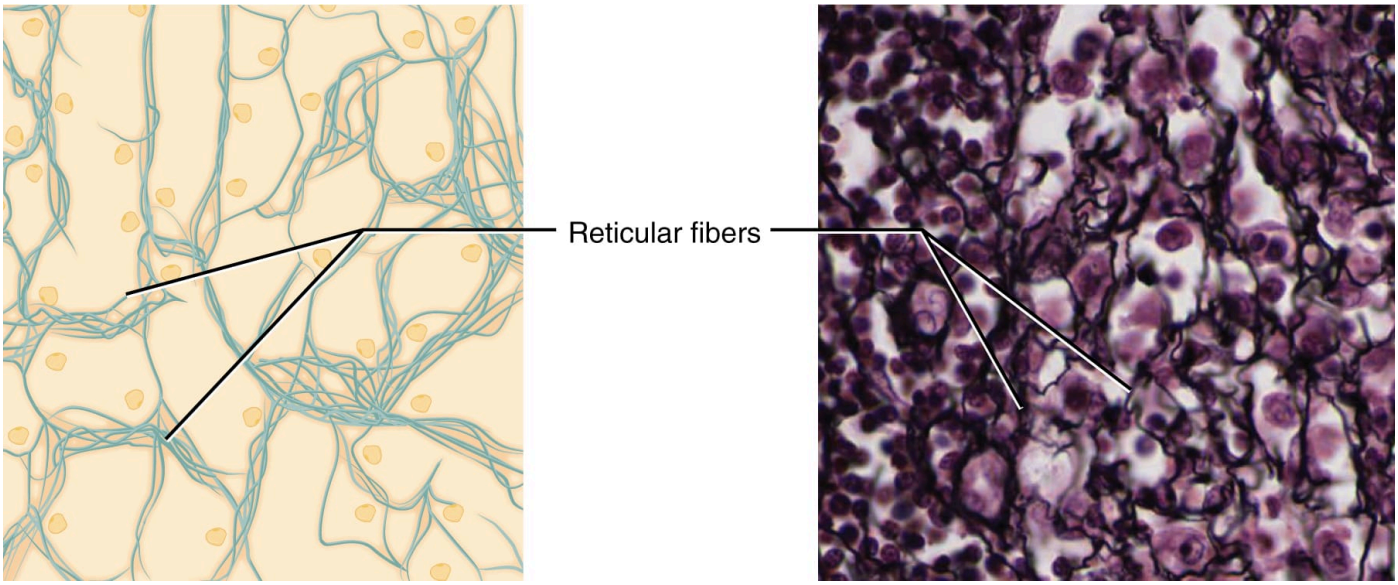


Figure 4.3.3: This is a loose connective tissue made up of a network of reticular fibers that provides a supportive framework for soft organs. LM × 1600. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.3.3.

Dense Connective Tissue

Dense connective tissue contains more collagen fibers than does loose connective tissue. As a consequence, it displays

greater resistance to stretching. There are two major categories of dense connective tissue: regular and irregular. Dense regular connective tissue fibers are parallel to each other, enhancing tensile strength and resistance to stretching in the direction of the fiber orientations. Ligaments and tendons are made of dense regular connective tissue, but in ligaments not all fibers are parallel. Dense regular elastic tissue contains elastin fibers in addition to collagen fibers, which allows the ligament to return to its original length after stretching. The ligaments in the vocal folds and between the vertebrae in the vertebral column are elastic.

In dense irregular connective tissue, the direction of fibers is random. This arrangement gives the tissue greater strength in all directions and less strength in one particular direction. In some tissues, fibers crisscross and form a mesh. In other tissues, stretching in several directions is achieved by alternating layers where fibers run in the same orientation in each layer, and it is the layers themselves that are stacked at an angle. The dermis of the skin is an example of dense irregular connective tissue rich in collagen fibers. Dense irregular elastic tissues give arterial walls the strength and the ability to regain original shape after stretching (Figure 4.3.4).

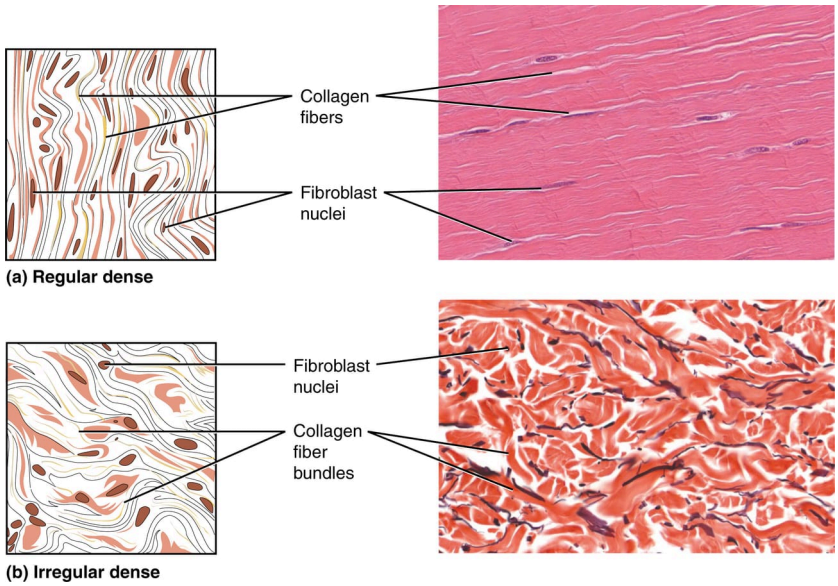


Figure 4.3.4: (a) Dense regular connective tissue consists of collagenous fibers packed into parallel bundles. (b) Dense irregular connective tissue consists of collagenous fibers interwoven into a mesh-like network. From top, LM × 1000, LM × 200. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.3.4.

Disorders of the...

Connective Tissue: Tendinitis

Your opponent stands ready as you prepare to hit the serve, but you are confident that you will smash the ball past your opponent. As you toss the ball high in the air, a burning pain shoots across your wrist and you drop the tennis racket. That dull ache in the wrist that you ignored through the summer is now an unbearable pain. The game is over for now.

After examining your swollen wrist, the doctor in the emergency room announces that you have developed wrist tendinitis. She recommends icing the tender area, taking non-steroidal anti-inflammatory medication to ease the pain and to reduce swelling, and complete rest for a few weeks. She interrupts your protests that you cannot stop playing. She issues a stern warning about the risk of aggravating the condition and the possibility of surgery. She consoles you by mentioning that well known tennis players such as Venus and Serena Williams and Rafael Nadal have also suffered from tendinitis related injuries.

What is tendinitis and how did it happen? Tendinitis is the inflammation of a tendon, the thick band of fibrous connective tissue that attaches a muscle to a bone. The condition causes pain and tenderness in the area around a joint. On rare occasions, a sudden serious injury will cause tendinitis. Most often, the condition results from repetitive motions over time that strain the tendons needed to perform the tasks.

Persons whose jobs and hobbies involve performing the same movements over and over again are often at the greatest risk of tendinitis. You hear of tennis and golfer's elbow, jumper's knee, and swimmer's shoulder. In all cases, overuse of the joint causes a microtrauma that initiates the inflammatory response. Tendinitis is routinely diagnosed through a clinical

examination. In case of severe pain, X-rays can be examined to rule out the possibility of a bone injury. Severe cases of tendinitis can even tear loose a tendon. Surgical repair of a tendon is painful. Connective tissue in the tendon does not have abundant blood supply and heals slowly.

While older adults are at risk for tendinitis because the elasticity of tendon tissue decreases with age, active people of all ages can develop tendinitis. Young athletes, dancers, and computer operators; anyone who performs the same movements constantly is at risk for tendinitis. Although repetitive motions are unavoidable in many activities and may lead to tendinitis, precautions can be taken that can lessen the probability of developing tendinitis. For active individuals, stretches before exercising and cross training or changing exercises are recommended. For the passionate athlete, it may be time to take some lessons to improve technique. All of the preventive measures aim to increase the strength of the tendon and decrease the stress put on it. With proper rest and managed care, you will be back on the court to hit that slice-spin serve over the net.

Supportive Connective Tissues

Two major forms of supportive connective tissue, cartilage and bone, allow the body to maintain its posture and protect internal organs.

Cartilage

The distinctive appearance of cartilage is due to polysaccharides called chondroitin sulfates, which bind with ground substance proteins to form proteoglycans. Embedded within the cartilage matrix are chondrocytes, or cartilage cells, and the space they occupy are called lacunae (singular = lacuna). A layer of dense irregular connective tissue, the perichondrium, encapsulates the cartilage. Cartilaginous tissue is avascular, thus all nutrients need to diffuse through the matrix to reach the chondrocytes. This is a factor contributing to the very slow healing of cartilaginous tissues.

The three main types of cartilage tissue are hyaline cartilage, fibrocartilage, and elastic cartilage (Figure $4.3.5$). Hyaline cartilage, the most common type of cartilage in the body, consists of short and dispersed collagen fibers and contains large amounts of proteoglycans. Under the microscope, tissue samples appear clear. The surface of hyaline cartilage is smooth. Both strong and flexible, it is found in the rib cage and nose and covers bones where they meet to form moveable joints. It makes up a template of the embryonic skeleton before bone formation. A plate of hyaline cartilage at the ends of bone allows continued growth until adulthood. Fibrocartilage is tough because it has thick bundles of collagen fibers dispersed through its matrix. Menisci in the knee joint and the intervertebral discs are examples of fibrocartilage. Elastic cartilage contains elastic fibers as well as collagen and proteoglycans. This tissue gives rigid support as well as elasticity. Tug gently at your ear lobes, and notice that the lobes return to their initial shape. The external ear contains elastic cartilage.

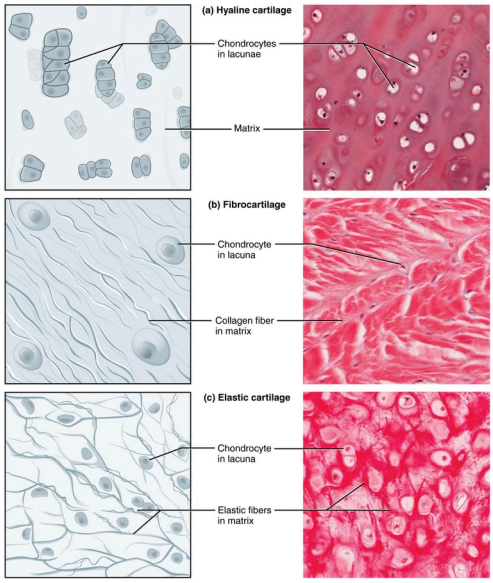


Figure 4.3.5: Cartilage is a connective tissue consisting of collagenous fibers embedded in a firm matrix of chondroitin sulfates. (a) Hyaline cartilage provides support with some flexibility. The example is from dog tissue. (b) Fibrocartilage provides some compressibility and can absorb pressure. (c) Elastic cartilage provides firm but elastic support. From top, LM × 300, LM × 1200, LM × 1016. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.3.5.

Bone

Bone is the hardest connective tissue. It provides protection to internal organs and supports the body. Bone's rigid extracellular matrix contains mostly collagen fibers embedded in a mineralized ground substance containing hydroxyapatite, a form of calcium phosphate. Both components of the matrix, organic and inorganic, contribute to the unusual properties of bone. Without collagen, bones would be brittle and shatter easily. Without mineral crystals, bones would flex and provide little support. Osteocytes, bone cells like chondrocytes, are located within lacunae. The histology of transverse tissue from long bone shows a typical arrangement of osteocytes in concentric circles around a central canal. Bone is a highly vascularized tissue. Unlike cartilage, bone tissue can recover from injuries in a relatively short time.

Cancellous bone looks like a sponge under the microscope and contains empty spaces between trabeculae, or arches of bone proper. It is lighter than compact bone and found in the interior of some bones and at the end of long bones. Compact bone is solid and has greater structural strength.

Fluid Connective Tissue

Blood and lymph are fluid connective tissues. Cells circulate in a liquid extracellular matrix. The formed elements circulating in blood are all derived from hematopoietic stem cells located in bone marrow (Figure 4.3.6). Erythrocytes, red blood cells, transport oxygen and some carbon dioxide. Leukocytes, white blood cells, are responsible for defending against potentially harmful microorganisms or molecules. Platelets are cell fragments involved in blood clotting. Some white blood cells have the ability to cross the endothelial layer that lines blood vessels and enter adjacent tissues. Nutrients, salts, and wastes are dissolved in the liquid matrix and transported through the body.

Lymph contains a liquid matrix and white blood cells. Lymphatic capillaries are extremely permeable, allowing larger molecules and excess fluid from interstitial spaces to enter the lymphatic vessels. Lymph drains into blood vessels, delivering molecules to the blood that could not otherwise directly enter the bloodstream. In this way, specialized lymphatic capillaries transport absorbed fats away from the intestine and deliver these molecules to the blood.

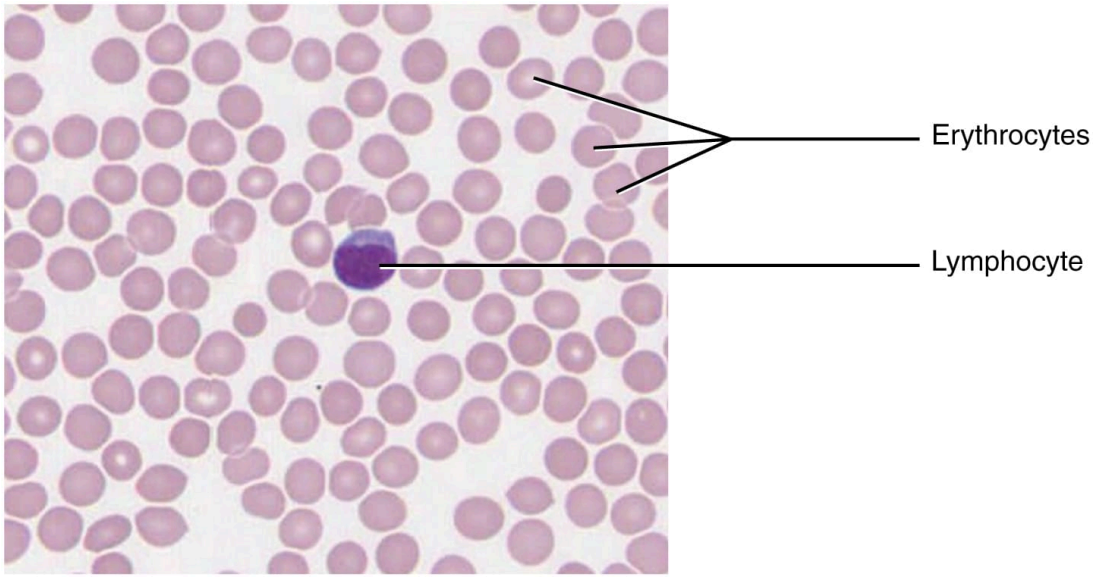


Figure 4.3.6: Tissue Blood is a fluid connective tissue containing erythrocytes and various types of leukocytes that circulate in a liquid extracellular matrix. LM × 1600. (CC BY-SA 4.0; via Wikimedia Commons). Alternate text description of Figure 4.3.6.

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4.4: Muscle Tissue and Motion

Overview of Muscle Tissue

Muscle tissue is characterized by properties that allow movement. Muscle cells are excitable; they respond to a stimulus. They are contractile, meaning they can shorten and generate a pulling force. When attached between two movable objects, in other words, bones, contractions of the muscles cause the bones to move. Some muscle movement is voluntary, which means it is under conscious control. For example, a person decides to open a book and read a chapter on anatomy. Other movements are involuntary, meaning they are not under conscious control, such as the contraction of your pupil in bright light. Muscle tissue is classified into three types according to structure and function: skeletal, cardiac, and smooth (Table 4.4.1).

Table 4.4.1: Comparison of Structure and Properties of Muscle Tissue Types

Tissue	Histology	Function	Location
Skeletal	Long cylindrical fiber, striated, many peripherally located nuclei	Voluntary movement, produces heat, protects organs	Attached to bones and around entrance points to body (e.g., mouth, anus)
Cardiac	Short, branched, striated, single central nucleus	Contracts to pump blood	Heart
Smooth	Short, spindle-shaped, no evident striation, single nucleus in each fiber	Involuntary movement, moves food, involuntary control of respiration, moves secretions, regulates flow of blood in arteries by contraction	Walls of major organs and passageways

Types of Muscle Tissue

Skeletal muscle is attached to bones and its contraction makes possible locomotion, facial expressions, posture, and other voluntary movements of the body. Forty percent of your body mass is made up of skeletal muscle. Skeletal muscles generate heat as a byproduct of their contraction and thus participate in thermal homeostasis. Shivering is an involuntary contraction of skeletal muscles in response to perceived lower than normal body temperature. The muscle cell, or myocyte, develops from myoblasts derived from the mesoderm. Myocytes and their numbers remain relatively constant throughout life. Skeletal muscle tissue is arranged in bundles surrounded by connective tissue. Under the light microscope, muscle cells appear striated with many nuclei squeezed along the membranes. The striation is due to the regular alternation of the contractile proteins actin and myosin, along with the structural proteins that couple the contractile proteins to connective tissues. The cells are multinucleated as a result of the fusion of the many myoblasts that fuse to form each long muscle fiber.

Cardiac muscle forms the contractile walls of the heart. The cells of cardiac muscle, known as cardiomyocytes, also appear striated under the microscope. Unlike skeletal muscle fibers, cardiomyocytes are single cells typically with a single centrally located nucleus. A principal characteristic of cardiomyocytes is that they contract on their own intrinsic rhythms without any external stimulation. Cardiomyocyte attach to one another with specialized cell junctions called intercalated discs. Intercalated discs have both anchoring junctions and gap junctions. Attached cells form long, branching cardiac muscle fibers that are, essentially, a mechanical and electrochemical syncytium allowing the cells to synchronize their actions. The cardiac muscle pumps blood through the body and is under involuntary control. The attachment junctions hold adjacent cells together across the dynamic pressures changes of the cardiac cycle.

Smooth muscle tissue contraction is responsible for involuntary movements in the internal organs. It forms the contractile component of the digestive, urinary, and reproductive systems as well as the airways and arteries. Each cell is spindle shaped with a single nucleus and no visible striations (Figure 4.4.1).

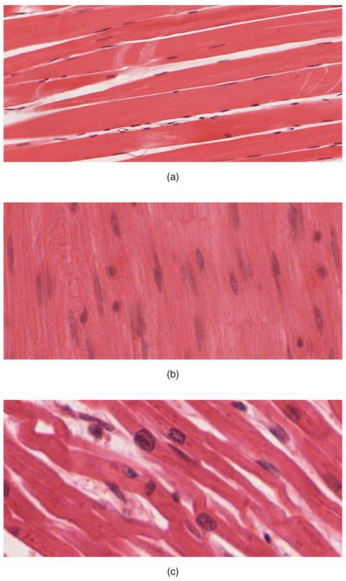


Figure 4.4.1: (a) Skeletal muscle cells have long cylindrical fiber, prominent striation, and many peripherally located nuclei. (b) Smooth muscle cells are short, spindle-shaped, no evident striation, single nucleus in each fiber. (c) Cardiac muscle cells are short, branched, striated, and have a single nucleus. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 4.4.1.

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4.5: Nervous Tissue Mediates Perception and Response

Structure and Organization of Nervous Tissue

Nervous tissue is characterized as being excitable and capable of sending and receiving electrochemical signals that provide the body with information. Two main classes of cells make up nervous tissue: the neuron and neuroglia (Figure 4.5.1). Neurons propagate information via electrochemical impulses, called action potentials, which are biochemically linked to the release of chemical signals. Neuroglia play an essential role in supporting neurons and modulating their information propagation.

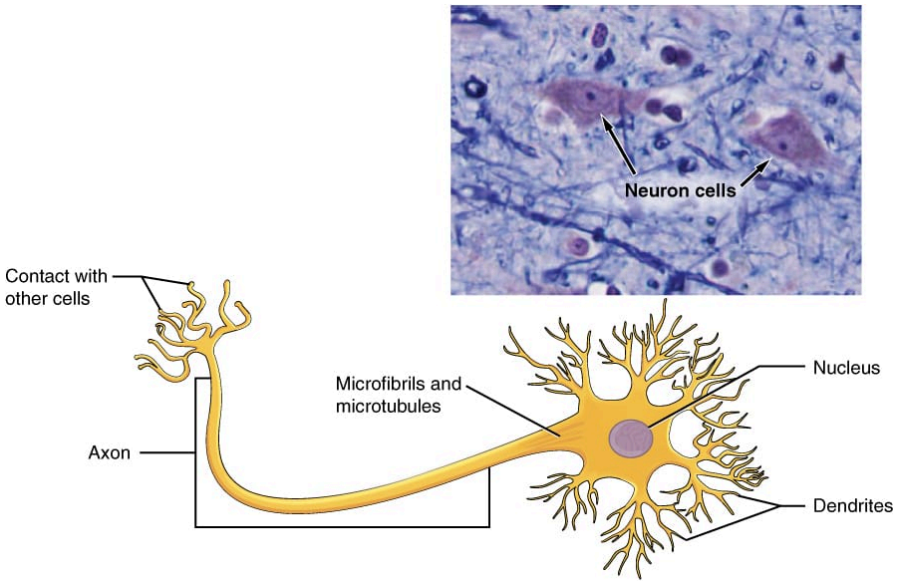


Figure 4.5.1: The cell body of a neuron, also called the soma, contains the nucleus and mitochondria. The dendrites transfer the nerve impulse to the soma. The axon carries the action potential away to another excitable cell. LM × 1600. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 4.5.1.

Neurons display distinctive morphology, well suited to their role as conducting cells, with three main parts. The cell body includes most of the cytoplasm, the organelles, and the nucleus. Dendrites branch off the cell body and appear as thin extensions. A long "tail," the axon, extends from the neuron body and can be wrapped in an insulating layer known as myelin, which is formed by accessory cells. The synapse is the gap between nerve cells, or between a nerve cell and its target, for example, a muscle or a gland, across which the impulse is transmitted by chemical compounds known as neurotransmitters. Neurons categorized as multipolar neurons have several dendrites and a single prominent axon. Bipolar neurons possess a single dendrite and axon with the cell body, while unipolar neurons have only a single process extending out from the cell body, which divides into a functional dendrite and into a functional axon. When a neuron is sufficiently stimulated, it generates an action potential that propagates down the axon towards the synapse. If enough neurotransmitters are released at the synapse to stimulate the next neuron or target, a response is generated.

Neuroglia: The Support Cells of the Nervous System

The second class of neural cells comprises the neuroglia or glial cells, which have been characterized as having a simple support role. The word "glia" comes from the Greek word for glue. Recent research is shedding light on the more complex role of neuroglia in the function of the brain and nervous system. Astrocyte cells, named for their distinctive star shape, are abundant in the central nervous system. The astrocytes have many functions, including regulation of ion concentration in the intercellular space, uptake and/or breakdown of some neurotransmitters, and formation of the blood-brain barrier, the membrane that separates the circulatory system from the brain. Microglia protect the nervous system against infection but are not nervous tissue because they are related to macrophages. Oligodendrocyte cells produce myelin in the central nervous system (brain and spinal cord) while the Schwann cell produces myelin in the peripheral nervous system (Figure 4.5.2).

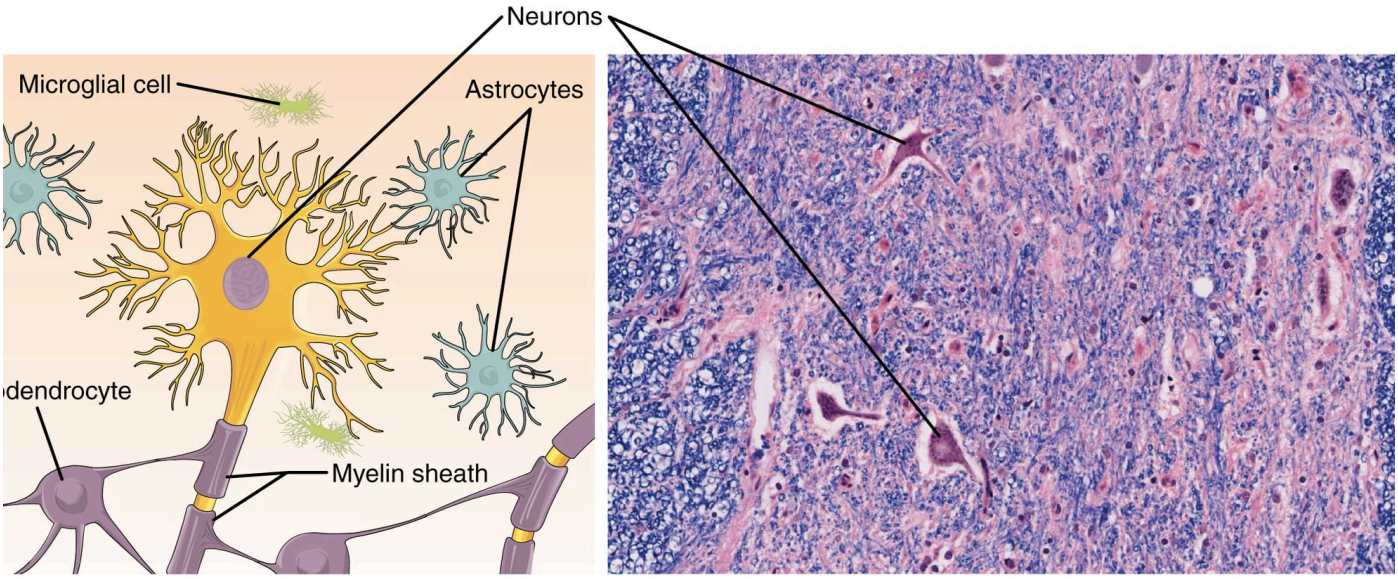


Figure 4.5.2: Nervous tissue is made up of neurons and neuroglia. The cells of nervous tissue are specialized to transmit and receive impulses. LM × 872. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 4.5.2.

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4.6: Terms and Definitions

Key Terms

Select to view definitions

Adipocytes
lipid storage cells

Adipose tissue
specialized areolar tissue rich in stored fat

Anchoring junction
mechanically attaches adjacent cells to each other or to the basement membrane

Apical
that part of a cell or tissue which, in general, faces an open space

Apocrine secretion
release of a substance along with the apical portion of the cell

Apoptosis
programmed cell death

Areolar tissue
(also, loose connective tissue) a type of connective tissue proper that shows little specialization with cells dispersed in the matrix

Astrocyte
star-shaped cell in the central nervous system that regulates ions and uptake and/or breakdown of some neurotransmitters and contributes to the formation of the blood-brain barrier

Atrophy
loss of mass and function

Basal lamina
thin extracellular layer that lies underneath epithelial cells and separates them from other tissues

Basement membrane
in epithelial tissue, a thin layer of fibrous material that anchors the epithelial tissue to the underlying connective tissue; made up of the basal lamina and reticular lamina

Cardiac muscle
heart muscle, under involuntary control, composed of striated cells that attach to form fibers, each cell contains a single nucleus, contracts autonomously

Cell junction
point of cell-to-cell contact that connects one cell to another in a tissue

Chondrocytes
cells of the cartilage

Clotting
also called coagulation; complex process by which blood components form a plug to stop bleeding

Collagen fiber
flexible fibrous proteins that give connective tissue tensile strength

Connective tissue
type of tissue that serves to hold in place, connect, and integrate the body's organs and systems

Connective tissue membrane
connective tissue that encapsulates organs and lines movable joints

Connective tissue proper
connective tissue containing a viscous matrix, fibers, and cells.

Cutaneous membrane
skin; epithelial tissue made up of a stratified squamous epithelial cells that cover the outside of the body

Dense connective tissue
connective tissue proper that contains many fibers that provide both elasticity and protection

Ectoderm
outermost embryonic germ layer from which the epidermis and the nervous tissue derive

Elastic cartilage
type of cartilage, with elastin as the major protein, characterized by rigid support as well as elasticity

Elastic fiber
fibrous protein within connective tissue that contains a high percentage of the protein elastin that allows the fibers to stretch and return to original size

Endocrine gland
groups of cells that release chemical signals into the intercellular fluid to be picked up and transported to their target organs by blood

Endoderm
innermost embryonic germ layer from which most of the digestive system and lower respiratory system derive

Endothelium
tissue that lines vessels of the lymphatic and cardiovascular system, made up of a simple squamous epithelium

Epithelial membrane
epithelium attached to a layer of connective tissue

Epithelial tissue
type of tissue that serves primarily as a covering or lining of body parts, protecting the body; it also functions in absorption, transport, and secretion

Exocrine gland
group of epithelial cells that secrete substances through ducts that open to the skin or to internal body surfaces that lead to the exterior of the body

Fibroblast
most abundant cell type in connective tissue, secretes protein fibers and matrix into the extracellular space

Fibrocartilage
tough form of cartilage, made of thick bundles of collagen fibers embedded in chondroitin sulfate ground substance

Fibrocyte
less active form of fibroblast

Fluid connective tissue
specialized cells that circulate in a watery fluid containing salts, nutrients, and dissolved proteins

Gap junction
allows cytoplasmic communications to occur between cells

Goblet cell
unicellular gland found in columnar epithelium that secretes mucous

Ground substance
fluid or semi-fluid portion of the matrix

Histamine
chemical compound released by mast cells in response to injury that causes vasodilation and endothelium permeability

Histology
microscopic study of tissue architecture, organization, and function

Holocrine secretion
release of a substance caused by the rupture of a gland cell, which becomes part of the secretion

Hyaline cartilage
most common type of cartilage, smooth and made of short collagen fibers embedded in a chondroitin sulfate ground substance

Inflammation
response of tissue to injury

Lacunae
(singular = lacuna) small spaces in bone or cartilage tissue that cells occupy

Lamina propria
areolar connective tissue underlying a mucous membrane

Loose connective tissue
(also, areolar tissue) type of connective tissue proper that shows little specialization with cells dispersed in the matrix

Mmatrix
extracellular material which is produced by the cells embedded in it, containing ground substance and fibers

Merocrine secretion
release of a substance from a gland via exocytosis

Mesenchymal cell
adult stem cell from which most connective tissue cells are derived

Mesenchyme
embryonic tissue from which connective tissue cells derive

Mesoderm
middle embryonic germ layer from which connective tissue, muscle tissue, and some epithelial tissue derive

Mesothelium
simple squamous epithelial tissue which covers the major body cavities and is the epithelial portion of serous membranes

Mucous connective tissue
specialized loose connective tissue present in the umbilical cord

Mucous gland
group of cells that secrete mucous, a thick, slippery substance that keeps tissues moist and acts as a lubricant

Mucous membrane
tissue membrane that is covered by protective mucous and lines tissue exposed to the outside environment

Muscle tissue
type of tissue that is capable of contracting and generating tension in response to stimulation; produces movement.

Myelin
layer of lipid inside some neuroglial cells that wraps around the axons of some neurons

Myocyte
muscle cells

Necrosis
accidental death of cells and tissues

Nervous tissue
type of tissue that is capable of sending and receiving impulses through electrochemical signals.

Neuroglia
supportive neural cells

Neuron
excitable neural cell that transfer nerve impulses

Oligodendrocyte
neuroglial cell that produces myelin in the brain

Parenchyma
functional cells of a gland or organ, in contrast with the supportive or connective tissue of a gland or organ

Primary union
condition of a wound where the wound edges are close enough to be brought together and fastened if necessary, allowing quicker and more thorough healing

Pseudostratified columnar epithelium
tissue that consists of a single layer of irregularly shaped and sized cells that give the appearance of multiple layers; found in ducts of certain glands and the upper respiratory tract

Reticular fiber
fine fibrous protein, made of collagen subunits, which cross-link to form supporting “nets” within connective tissue

Reticular lamina
matrix containing collagen and elastin secreted by connective tissue; a component of the basement membrane

Reticular tissue
type of loose connective tissue that provides a supportive framework to soft organs, such as lymphatic tissue, spleen, and the liver

Schwann cell
neuroglial cell that produces myelin in the peripheral nervous system

Secondary union
wound healing facilitated by wound contraction

Serous gland
group of cells within the serous membrane that secrete a lubricating substance onto the surface

Serous membrane
type of tissue membrane that lines body cavities and lubricates them with serous fluid

Simple columnar epithelium
tissue that consists of a single layer of column-like cells; promotes secretion and absorption in tissues and organs

Simple cuboidal epithelium
tissue that consists of a single layer of cube-shaped cells; promotes secretion and absorption in ducts and tubules

Simple squamous epithelium
tissue that consists of a single layer of flat scale-like cells; promotes diffusion and filtration across surface

Skeletal muscle
usually attached to bone, under voluntary control, each cell is a fiber that is multinucleated and striated

Smooth muscle
under involuntary control, moves internal organs, cells contain a single nucleus, are spindle-shaped, and do not appear striated; each cell is a fiber

Stratified columnar epithelium
tissue that consists of two or more layers of column-like cells, contains glands and is found in some ducts

Stratified cuboidal epithelium
tissue that consists of two or more layers of cube-shaped cells, found in some ducts

Stratified squamous epithelium
tissue that consists of multiple layers of cells with the most apical being flat scale-like cells; protects surfaces from abrasion

Striation
alignment of parallel actin and myosin filaments which form a banded pattern

Supportive connective tissue
type of connective tissue that provides strength to the body and protects soft tissue

Synovial membrane
connective tissue membrane that lines the cavities of freely movable joints, producing synovial fluid for lubrication

Tight junction
forms an impermeable barrier between cells

Tissue
group of cells that are similar in form and perform related functions

Tissue membrane
thin layer or sheet of cells that covers the outside of the body, organs, and internal cavities

Totipotent
embryonic cells that have the ability to differentiate into any type of cell and organ in the body

Transitional epithelium
form of stratified epithelium found in the urinary tract, characterized by an apical layer of cells that change shape in response to the presence of urine

Vasodilation
widening of blood vessels

Wound contraction
process whereby the borders of a wound are physically drawn together

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4.7: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. The process by which a less specialized cell becomes a more specialized cell type during development is called what?
   A. Differentiation
   B. Maturation
   C. Modification
   D. Specialization

2. In a developing embryo, all differentiated cells ultimately derive from which three primary germ layers?
   A. Endothelium, mesothelium, and epithelium
   B. Ectoderm, mesoderm, and endoderm
   C. Connective tissue, epithelial tissue, and muscle tissue
   D. Epidermis, mesoderm, and endothelium

3. A biopsy from the skin surface shows closely packed cells arranged in layers, with very little extracellular matrix and no blood vessels within the tissue. The tissue covers the body surface and lines body cavities. How should this sample be classified?
   A. Connective tissue
   B. Muscle tissue
   C. Nervous tissue
   D. Epithelial tissue

4. Under the microscope, a specimen shows a single layer of tall, narrow cells. The nuclei are located near the basal surface of each cell, and all cells contact the basement membrane. Which type of epithelial tissue is present?
   A. Simple columnar epithelium
   B. Stratified columnar epithelium
   C. Simple squamous epithelium
   D. Simple cuboidal epithelium

5. Which type of epithelial tissue lines the interior surface of blood vessels (endothelium)?
   A. Simple columnar epithelium
   B. Stratified columnar epithelium
   C. Simple squamous epithelium
   D. Simple cuboidal epithelium

6. A certain exocrine gland type stores its secretory product inside entire cells; the whole cell then disintegrates to release the secretion. Another gland type releases its product when only the apical portion of the cell pinches off and breaks down, while the basal portion remains and repairs itself. Which option correctly matches these two gland types in that order?
   A. Holocrine gland; apocrine gland
   B. Eccrine gland; endocrine gland
   C. Apocrine gland; holocrine gland
   D. Eccrine gland; apocrine gland

7. Mucous membranes (mucosae) are found in particular locations in the body. Which description best identifies where mucous membranes are located?
   A. Covering the outer surfaces of the lungs and heart in the thoracic cavity
   B. Lining body cavities and passageways that open to the exterior, such as the respiratory, digestive, urinary, and reproductive tracts
   C. Surrounding the kidneys in the retroperitoneal space
   D. Covering the articular surfaces of freely movable synovial joints

8. Which statement best distinguishes epithelial tissue from connective tissue?
   A. Epithelial tissue has abundant extracellular matrix, whereas connective tissue has very little.
   B. Epithelial tissue is highly vascular, whereas connective tissue is always avascular.
   C. Epithelial tissue forms continuous sheets covering surfaces and lining cavities; connective tissue mainly supports, binds, and fills spaces.
   D. Epithelial tissue cannot regenerate, whereas connective tissue cannot be repaired.

9. Most connective tissues are composed of which three essential components?
   A. Cells, ground substance, and carbohydrate fibers
   B. Cells, ground substance, and protein fibers
   C. Collagen, ground substance, and protein fibers only
   D. Matrix, ground substance, and fluid, without cells

10. The wall of the intestine contains a layer of tissue with spindle-shaped, non-striated cells that contract involuntarily to move food along. Which tissue type is this?
    A. Skeletal muscle
    B. Cardiac muscle
    C. Smooth muscle
    D. Dense connective tissue

11. Under the microscope, a tissue specimen shows chondrocytes located in lacunae scattered in a smooth, glassy, almost transparent extracellular matrix with fine collagen fibers that are not easily visible. This tissue is most likely which of the following?
    A. Loose areolar connective tissue
    B. Dense regular connective tissue
    C. Fibrocartilage
    D. Hyaline cartilage

12. Ligaments connect bones together and must withstand unidirectional tensile stress. Which connective tissue type predominantly makes up ligaments?
    A. Loose areolar connective tissue
    B. Dense regular connective tissue
    C. Fibrocartilage
    D. Hyaline cartilage

13. In adults, new connective tissue cells most directly originate from which cell population?
    A. Mesoderm
    B. Mesenchyme-derived stem or progenitor cells
    C. Ectoderm
    D. Endoderm

14. Fat droplets are stored in cells in a specialized form of loose connective tissue called adipose tissue.
    A. True
    B. False

15. In bone tissue, which cells are the mature cells located in lacunae that maintain the bone matrix?
    A. Fibroblasts
    B. Chondrocytes
    C. Lymphocytes
    D. Osteocytes

16. Striations, cylindrical (long, fiber-like) cells, and multiple peripheral nuclei per cell are characteristic of which muscle type?
    A. Skeletal muscle only
    B. Cardiac muscle only
    C. Smooth muscle only
    D. Both skeletal and cardiac muscles

17. The contractile cells of muscle tissue, called myocytes or muscle fibers, develop from which precursor cells during embryonic development?
    A. Myoblasts
    B. Endoderm cells
    C. Fibrocytes
    D. Chondrocytes

18. Skeletal muscle fibers are highly active cells. Which organelles would you expect to find in particularly high numbers in these cells to meet their energy demands?
    A. Nuclei
    B. Striations
    C. Golgi bodies
    D. Mitochondria

19. Which cells are primarily responsible for generating and conducting nerve impulses in nervous tissue?
    A. Neurons
    B. Oligodendrocytes
    C. Astrocytes
    D. Microglia

20. In a typical neuron, the nerve impulse travels away from the cell body along which structure?
    A. Dendrite
    B. Axon
    C. Microglia
    D. Collagen fiber

21. In the central nervous system, which neuroglial cells regulate extracellular ion concentrations, participate in the uptake and breakdown of some neurotransmitters, and contribute to the formation of the blood–brain barrier?
    A. Microglia
    B. Neuroglia as a general group
    C. Oligodendrocytes
    D. Astrocytes

22. Which of the following is not considered one of the classic cardinal signs of acute inflammation?
    A. Redness
    B. Heat
    C. Fever as a whole-body response
    D. Swelling

23. When a mast cell in connective tissue reacts to injury or irritation, which chemical mediator does it release in large amounts to promote vasodilation and increased vascular permeability?
    A. Collagen
    B. Histamine
    C. Hyaluronic acid
    D. Myelin

24. In the context of tissue changes, what does the term “atrophy” refer to?
    A. Loss of elasticity
    B. Loss of mass or size of a tissue or organ
    C. Loss of rigidity
    D. Loss of permeability

25. Individuals can slow some aspects of aging by modifying several lifestyle factors. Which of the following lifestyle aspects cannot be modified to slow the intrinsic rate of aging?
A. Diet
B. Exercise
C. Genetic factors
D. Stress management

26. Under the microscope, you observe an epithelial tissue that appears to have multiple layers of nuclei, but all cells actually contact the basement membrane. Goblet cells and cilia are present. Which epithelial tissue type is this most likely to be?
A. Simple cuboidal epithelium
B. Stratified squamous epithelium
C. Pseudostratified ciliated columnar epithelium
D. Transitional epithelium

27. Which statement correctly distinguishes endocrine glands from exocrine glands?
A. Endocrine glands release their products into ducts that open onto surfaces; exocrine glands release hormones into the bloodstream.
B. Endocrine glands are always unicellular; exocrine glands are always multicellular.
C. Endocrine glands release hormones directly into the interstitial fluid and blood; exocrine glands release secretions into ducts leading to body surfaces or lumens.
D. Endocrine glands never undergo mitosis; exocrine glands constantly proliferate.

28. Which tissue type has an abundant extracellular matrix with collagen and elastic fibers arranged irregularly, and is found in the dermis of the skin providing tensile strength in multiple directions?
A. Loose areolar connective tissue
B. Dense regular connective tissue
C. Dense irregular connective tissue
D. Elastic cartilage

29. Which muscle tissue contains branching cells, a single central nucleus per cell, striations, and intercalated discs?
A. Skeletal muscle
B. Cardiac muscle
C. Smooth muscle
D. All three muscle types

30. Which type of cartilage is especially well suited to resist compression and is found in intervertebral discs and the pubic symphysis?
A. Hyaline cartilage
B. Elastic cartilage
C. Fibrocartilage
D. Articular cartilage of long bones

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4.8: Applied Thinking Self-Assessment

Challenge Yourself

- Critical thinking is essential in a time of endless information and AI, helping you move from passive memorizing to actively making sense of what you learn.
- Use these critical thinking prompts for self-assessment after studying the tissue chapter. As you respond:

- Write your answers in your own words, using complete sentences. Organize your ideas into short paragraphs rather than lists or bullet points.
- Emphasize your reasoning process. Do not just state a brief “right answer”; explain why it is correct, how you know, and what evidence or examples support it.
- Use appropriate scientific vocabulary for this chapter (for example: epithelium, connective tissue, differentiation, diffusion, extracellular matrix, tight junctions). If you are not fully confident with a term, define it briefly in your own words as you use it.
- When a question asks you to compare, contrast, or explain why/how:
  - Clearly state the similarities and/or differences between the items.
  - Include at least one reason, mechanism, or concrete example to support each point you make.
- Treat these questions as a self-assessment tool:
  - First, try to answer from memory, without looking at your notes or textbook.
  - Then consult your notes, textbook, or other reliable resources and revise your answer to correct or deepen it.
  - Mark any questions where you felt uncertain, changed your answer a lot, or needed to look up many details. Use those marks to identify topics you should review again.
- By following these steps, you will use the critical thinking questions not just to check what you remember, but to build deeper, more flexible understanding of human tissues and how structure supports function.

1. A patient has a lump in the breast. Imaging (like ultrasound or mammogram) cannot clearly tell if it is cancerous. The doctor orders a biopsy and sends the tissue sample to a pathology lab. Explain why histology (looking at thin tissue sections under a microscope) is important in this situation.
2. Choose one organ (for example: skin, small intestine, heart, lung, kidney). Describe how each of the four basic tissue types is used in that organ. Explain how the relative amount, arrangement, and specialization of these four tissues allow this organ to do its main function(s). Be specific.
3. Synovial membranes produce synovial fluid in freely movable joints (such as the knee, shoulder, and fingers). Suppose a patient develops a disease that greatly reduces synovial fluid production at one major joint. Predict at least two functional consequences for that joint over time (for example: range of motion, pain, wear on cartilage, risk of arthritis). For each consequence you predict, explain the tissue-level mechanism. In your explanation, refer to at least one of the following: Articular cartilage; Synovial membrane; Joint capsule and ligaments.
4. The mucosa of the small intestine is highly folded (villi, microvilli) and richly supplied with blood and lymphatic vessels. Imagine a genetic condition in which intestinal epithelial cells lack microvilli. Predict how this would affect nutrient absorption, body weight, and overall health, and explain why using the structure–function relationship of this tissue.
5. An athlete tears the articular cartilage in her knee and, a year later, still has pain and limited healing. Another person breaks a bone and heals relatively quickly.
   - The main cells in each tissue (for example, chondrocytes, osteoblasts, osteocytes)
   - The extracellular matrix (what it is made of and how dense it is)
   - Vascularization (how much blood supply each tissue has)
6. You are observing cells growing in a dish in the lab. At first, each cell contracts alone, at its own time. Later, the cells form physical connections with each other, and then they start to contract together in a regular, coordinated rhythm. Based on what you know about tissue types:
   - Which specific tissue type do you think these cells most likely belong to (for example, cardiac muscle, skeletal muscle, smooth muscle)?
   - Give at least two reasons for your choice. You can mention how that tissue normally works in the body (for example, pumping blood, moving food, moving bones).
   - Explain what structural specializations allow these cells to contract together in a coordinated way.
     - Name and describe at least one specific structure that connects the cells (for example, a type of junction).

    - Explain how this structure helps electrical signals or ions pass quickly from one cell to another.
7. Neurons are often described as having “input” (dendrites), “integration” (cell body), and “output” (axon, synaptic terminals) regions. Choose a specific example of neural function (such as withdrawing your hand from a hot stove or forming a memory) and trace how this morphology enables that function. How might altering one part of the neuron’s structure change the way the circuit works?
8. After a deep cut in the skin, the wound fills with a blood clot and then gradually closes over the next several days to weeks. Explain how at least three different types of cells (for example: platelets, inflammatory cells such as neutrophils or macrophages, fibroblasts, endothelial cells, keratinocytes) work together over time to repair this wound. In your answer:
    - Describe the role of each cell type you choose (what it does and when it is most active).
    - Explain how the actions of these cells change the structure of the tissue from an open wound to healed skin (including scar formation, if relevant).
    - Briefly discuss one factor (such as diabetes, poor blood supply, or infection) that could interfere with one of these cell types and slow or prevent proper healing.
9. Aging affects all four tissue types but not in the same way. Choose two different tissues (for example, bone vs. cardiac muscle, skin vs. nervous tissue) and compare how aging changes their structure and function. Which specific age-related changes (e.g., reduced cell division, altered extracellular matrix, accumulated DNA damage) are most critical in each tissue, and why?
10. Many chronic diseases of aging - such as osteoarthritis, heart failure, and neurodegenerative disorders - can be viewed as problems of tissue homeostasis. Select one age-related disease and analyze it from a tissue-level perspective: Which tissue(s) are primarily involved? What structural changes occur? How do those changes disrupt normal function? Finally, suggest one plausible tissue-targeted strategy (not necessarily a drug) that might slow or partially reverse these changes.

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4.9: Alternate Text Descriptions

Figure 4.1: Micrograph of Cervical Tissue

This image shows tissue surrounding several empty spaces. The epithelial tissue occurs at the border between the rest of the tissue and the empty spaces. The normal epithelium is composed of rectangular-shaped cells neatly organized side by side. Dark purple nuclei are clear at the bottom of the epithelial cells, where they attach to the rest of the tissue. The abnormal epithelium appears as a tangled area of purple nuclei, much thicker than the normal epithelium although no distinct cells are discernible.

Figure 4.1.1: The Four Primary Tissue Types

This image shows the four primary tissue types in the body. A central human body diagram is surrounded by four micrographs, and arrows connect each tissue image to example anatomical locations where that tissue is found.

- The upper left micrograph represents nervous tissue. Arrows point to the brain, spinal cord, and nerves. The micrograph shows irregularly shaped cells embedded in supporting tissue, representing the specialized structure of nervous tissue.
- The upper right micrograph represents muscle tissue. Arrows identify cardiac muscle, smooth muscle, and skeletal muscle. The body diagram points to examples such as the heart, the walls of internal organs, and skeletal muscles attached to bones. The micrograph shows elongated cells with prominent nuclei.
- The lower left micrograph represents epithelial tissue. Arrows point to the lining of gastrointestinal tract organs and other hollow organs and to the skin surface, or epidermis. The micrograph shows many closely packed cells forming a continuous sheet.
- The lower right micrograph represents connective tissue. Arrows point to fat and other soft padding tissue, bone, and tendon. The micrograph shows scattered cells and fibers with more open space between structures than in the other tissue types.

Figure 4.1.2: The Three Primary Germ Layers

This image is a two-column table with the headers Germ Layer and Gives rise to. The table has three main rows: ectoderm, mesoderm, and endoderm. Each row lists examples of tissues or structures derived from that germ layer and includes small illustrations of representative cell or tissue types.

Ectoderm: The first row is ectoderm. The table states that ectoderm gives rise to the epidermis, glands on the skin, some cranial bones, the pituitary and adrenal medulla, the nervous system, the tissue between the cheeks and gums, and the anus. This row includes three example illustrations:

- Skin cells, shown as many flattened cells arranged in layers
- Neurons, shown as branching nerve cells with a central cell body and a long projection
- Pigment cell, shown beneath surrounding skin cells with branching extensions reaching between nearby cells

Mesoderm: The second row is mesoderm. The table states that mesoderm gives rise to connective tissues proper, bone, cartilage, blood, the endothelium of blood vessels, muscle, synovial membranes, serous membranes lining body cavities, kidneys, and the lining of gonads. This row includes five example illustrations:

- Cardiac muscle, shown as branching muscle fibers
- Skeletal muscle, shown as long parallel fibers with clear striping
- Tubule cell of kidney, shown as epithelial cells lining a tubule
- Red blood cells, shown as rounded cells with central indentations
- Smooth muscle, shown as closely packed elongated cells with central nuclei

Endoderm: The third row is endoderm. The table states that endoderm gives rise to the lining of the airways and the digestive system except the mouth and distal part of the digestive system, as well as glands, including digestive glands, endocrine glands, and the adrenal cortex. This row includes three example illustrations:

- Lung cell

- Thyroid cell
- Pancreatic cell

Figure 4.1.3: Tissue Membranes

This image identifies four major body membranes and the locations where they line or cover body structures. Callout boxes point to representative locations on the body.

- Mucous membranes line the digestive, respiratory, urinary, and reproductive tracts. The callout points to the mouth and trachea and notes that mucous membranes are coated with secretions from mucous glands.
- Serous membranes line body cavities that are closed to the exterior. The callout identifies the pleural, pericardial, and peritoneal cavities and points to regions associated with the lungs, heart, and abdominal cavity.
- Cutaneous membrane, also called the skin, covers the body surface. The callout points to the skin on the arm and hand.
- Synovial membranes line joint cavities and produce the fluid within joints. The callout points to a knee joint.

Figure 4.2.1: Types of Cell Junctions

This image compares several types of cell junctions, which connect cells to each other or to surrounding structures.

- The image is divided into sections showing tight junctions, gap junctions, and anchoring junctions, including desmosomes, adherens junctions, and hemidesmosomes. Each diagram shows adjacent plasma membranes and how they are connected.
- In the tight junction diagram, two adjacent cell membranes are connected by strands of transmembrane proteins. These proteins form continuous connections between the membranes. Tight junctions seal the space between cells, preventing substances from passing between them, and they help maintain separate environments on either side of a tissue.
- In the gap junction diagram, the junction is formed by protein channels called connexons. Each connexon is made of two units from neighboring cells, and the channels align to create a continuous passage between cells. Gap junctions allow small molecules and ions to pass directly between cells, which enables cell-to-cell communication.
- The anchoring junction diagrams show structures that provide mechanical connections that hold cells in place. In the desmosome diagram, each cell membrane contains a plaque on its inner surface. The plaques are connected by transmembrane proteins, labeled cadherins, and intermediate filaments extend from the plaques into the cell interior. Desmosomes provide strong attachment between cells and help tissues resist mechanical stress, such as stretching.
- In the adherens junction diagram, the structure is similar to a desmosome, but it is connected to actin filaments instead of intermediate filaments. The filaments form a network along the inside of the cell membrane. Adherens junctions provide flexible connections between cells and allow tissues to change shape while remaining connected.
- In the hemidesmosome diagram, the structure is located between a cell and the basement membrane, rather than between two cells. It contains a plaque connected to intermediate filaments inside the cell, and on the outside, proteins called integrins attach to the basement membrane. Hemidesmosomes anchor cells to the underlying surface and provide stability and attachment to tissues.

Figure 4.2.2: Cells of Epithelial Tissue

This image is a table showing the appearance of squamous, cuboidal, and columnar epithelial tissues. The rows are organized by cell shape, and the columns show simple, stratified, and pseudostratified forms.

- In simple squamous epithelium, the cells are flattened and arranged in a single layer. In simple cuboidal epithelium, the cells are cube-shaped and arranged in a single layer. In simple columnar epithelium, the cells are tall and rectangular, attached to the basement membrane on one narrow side so they stand like columns in a single layer.
- In pseudostratified columnar epithelium, the cells are column-like but vary in height. All cells contact the basement membrane, but the differing heights and uneven nuclei make the tissue appear layered even though it is only one layer.
- In stratified squamous epithelium, there are many layers of flattened cells. In stratified cuboidal epithelium, there are multiple layers of cube-shaped cells. In stratified columnar epithelium, there are multiple layers of tall, rectangular cells.

Figure 4.2.3: Goblet Cell

This image shows a goblet cell, a specialized epithelial cell that produces and secretes mucus.

- The cell is shown as tall and narrow, with a wider upper region and a narrower base. The top surface faces the external environment, and the lower region contains the nucleus and major organelles. This overall shape supports secretion of mucus toward the cell surface.
- At the top of the cell, the apical surface contains microvilli, which are small projections extending outward. These microvilli increase the surface area, helping with secretion and interaction with the surrounding environment.
- The upper part of the cell is filled with secretory vesicles containing mucin. These vesicles store mucin, which is released outside the cell and forms mucus. Mucus helps protect and lubricate surfaces, such as those in the digestive or respiratory systems.
- Below the vesicles is the rough endoplasmic reticulum, often abbreviated as RER. It appears as folded membranes in the middle region of the cell. The rough endoplasmic reticulum produces the proteins that will become part of mucin and is responsible for protein synthesis and initial processing.
- Below the rough endoplasmic reticulum is the Golgi apparatus. The Golgi modifies and packages proteins into secretory vesicles and prepares mucin for transport and release.
- Near the base of the cell is a large nucleus. The nucleus contains DNA and controls the production of proteins and vesicles.

Figure 4.2.4: Columnar Epithelium Tissue

This image is a micrograph of the innermost lining of the small intestine. This innermost lining is a simple columnar epithelium, with a single layer of rectangular cells oriented in a line. Occasionally, the line of epithelial cells is interrupted by a goblet cell. Goblet cells are thinner than the epithelial cells and appear roughly pill shaped. In this micrograph, the cells did not stain as darkly as the epithelial cells.

Figure 4.2.5: Epithelial Tissues

This image is three-column table with the headers Cells, Location, and Function. Each row lists a type of epithelial tissue, where it is found, and what it does. This is a classification chart of epithelial tissues organized by cell shape and layering. Rows represent squamous, cuboidal, and columnar cell shapes. Columns represent simple, stratified, and pseudostratified arrangements. Each illustration shows the relative cell shape and number of layers characteristic of the tissue type.

Row 1: Simple squamous epithelium:

- Location: Air sacs of lungs and the lining of the heart, blood vessels, and lymphatic vessels
- Function: Allows materials to pass through by diffusion and filtration, and secretes lubricating substance

Row 2: Simple cuboidal epithelium:

- Location: In ducts and secretory portions of small glands and in kidney tubules
- Function: Secretes and absorbs

Row 3: Simple columnar epithelium:

- Location: Ciliated tissues are in bronchi, uterine tubes, and uterus; smooth, nonciliated tissues are in the digestive tract and bladder
- Function: Absorbs; also secretes mucus and enzymes

Row 4: Pseudostratified columnar epithelium:

- Location: Ciliated tissue lines the trachea and much of the upper respiratory tract
- Function: Secretes mucus; ciliated tissue moves mucus

Row 5: Stratified squamous epithelium:

- Location: Lines the esophagus, mouth, and vagina
- Function: Protects against abrasion

Row 6: Stratified cuboidal epithelium

- Location: Sweat glands, salivary glands, and mammary glands

- Function: Protective tissue

Row 7: Stratified columnar epithelium:

- Location: The male urethra and the ducts of some glands
- Function: Secretes and protects

Row 8: Transitional epithelium:

- Location: Lines the bladder, urethra, and ureters
- Function: Allows the urinary organs to expand and stretch

Figure 4.2.6: Exocrine Glands

This image classifies exocrine glands based on the shape of their secretory units and the complexity of their ducts. The diagram is divided into two main categories, simple glands and compound glands, with multiple gland types shown in each category.

- The diagram is organized into two major groups: simple glands, which have single unbranched ducts, and compound glands, which have branched duct systems. Within each group, glands are further classified by shape as alveolar, also called acinar, meaning sac-like structures, and tubular, meaning tube-like structures. This classification helps explain how gland structure relates to how substances are produced, stored, and delivered.
- In the simple gland group, the duct remains a single pathway from the secretory unit to the surface. A simple alveolar, or simple acinar, gland is shown as a single sac-like secretory unit connected to one duct. It represents an early developmental stage of glands and is not typically found in adult tissues.
- A simple branched alveolar gland is shown with multiple sac-like units connected to a single unbranched duct. This type produces and releases substances such as oil in sebaceous glands.
- A simple tubular gland is shown as a straight, tube-like secretory structure connected to a duct. It is found in intestinal glands, where the structure supports secretion along a defined path.
- A simple coiled tubular gland is shown as a long tubular gland that is coiled. It is found in sweat glands, where the coiling allows more secretory surface in a small space.
- A simple branched tubular gland is shown with multiple tubular branches connected to a single duct. It is found in glands that produce mucus or digestive secretions, allowing increased secretion.
- In the compound gland group, the glands have multiple duct branches, increasing complexity. A compound alveolar, or compound acinar, gland is shown with many sac-like secretory units connected by branching ducts. It is found in mammary glands, allowing large-scale secretion such as milk production.
- A compound tubuloalveolar gland is shown as a combination of tubular and sac-like structures connected through branched ducts. It is found in salivary glands and the pancreas, supporting both enzyme secretion and fluid production.
- A compound tubular gland is shown with branched ducts connected to tubular secretory units. It is found in glands producing mucus or reproductive fluids, supporting continuous secretion along tubular structures.

Figure 4.2.7: Modes of Glandular Secretion

This image compares three types of exocrine gland secretion mechanisms: merocrine, apocrine, and holocrine. Each type is shown as a sequence of cells releasing substances.

- The diagram is divided into three labeled sections: (a) merocrine secretion, (b) apocrine secretion, and (c) holocrine secretion. Each section shows epithelial cells arranged in a layer above a base surface, and the diagrams illustrate how secretory products leave the cell.
- In merocrine secretion, the cells contain secretory vesicles inside the cytoplasm. The vesicles move toward the cell membrane at the top surface. The nucleus is located near the base of the cell, and the Golgi complex is visible within the cytoplasm. In this mechanism, vesicles fuse with the cell membrane and release their contents outside the cell. The cell remains intact and unchanged after secretion. This is the most common secretion method and is used in glands such as sweat glands and salivary glands.
- In apocrine secretion, the upper portion of the cell contains secretory material. The top part of the cell pinches off and separates from the rest of the cell. In this mechanism, a portion of the cell membrane and cytoplasm is released along with the secretion. The remaining part of the cell repairs itself and continues functioning. This method is used in glands such as mammary glands.

- In holocrine secretion, cells accumulate secretory products throughout the entire cytoplasm, and the cells enlarge as they fill with material. In this mechanism, the entire cell breaks down and releases its contents. The cell becomes part of the secretion and is destroyed. New cells replace the lost cells. This type of secretion occurs in sebaceous, or oil, glands.
- The main comparison shown in the image is that merocrine secretion releases products by vesicles while the cell stays intact, apocrine secretion releases products by pinching off part of the cell, and holocrine secretion releases products when the entire cell breaks down.

Figure 4.2.8: Sebaceous Glands

This image contains two images showing the structure of the skin. Labels include: hair and sebaceous gland.

In Image A, the skin is shown in cross section with two layers: an outer layer at the top and a deeper inner layer below. The boundary between the layers is uneven rather than flat. A hair follicle extends downward into the inner layer, and the outer layer folds inward around the follicle to form a sheath. At the base of the follicle is a bulb connected to blood vessels. A hair shaft grows from this bulb and travels upward through the follicle to the surface. A sebaceous gland is attached to the side of the follicle, and a duct connects the gland directly into the follicle. The hair follicle produces and supports the growth of hair, the bulb receives nutrients from nearby blood vessels, and the sebaceous gland produces an oily substance called sebum. Sebum is released into the follicle and helps lubricate and protect the hair and skin.

In Image B, a magnified microscopic image shows a hair follicle surrounded by layers of cells. A central structure represents the growing hair. Next to the follicle is a cluster of cells forming the sebaceous gland. These cells are tightly packed and arranged in a rounded mass. The follicle continues to produce the hair shaft seen at the center, and the sebaceous gland cells synthesize and release sebum. The connection between the gland and follicle allows sebum to enter the follicle.

Figure 4.3.1: Fibroblasts

This image produce this fibrous tissue contains two images comparing the structure of connective tissue: a diagram on the left and a micrograph on the right. The left image is a labeled diagram showing different components of connective tissue. The right image is a microscopic view of similar tissue. Both images highlight the relationship between cells and extracellular fibers

1. Left Image – Connective tissue diagram shows a network of fibers and scattered cells embedded in a matrix
    - Several types of fibers are labeled:
        - Collagen fibers, which appear as thick strands
        - Elastic fibers, which appear as thinner, branching strands
        - Reticular fibers, forming a fine supporting network
    - Multiple cell types are present:
        - Fibroblasts, elongated cells associated with fiber production
        - Mesenchymal cells, less specialized cells
        - Adipocytes, large cells that store fat
        - Macrophages, cells involved in defense
    - The fibers provide structural support and flexibility
    - Fibroblasts produce and maintain the fiber network
    - Adipocytes store energy and insulation
    - Macrophages participate in immune defense
    - Mesenchymal cells can differentiate into other connective tissue cells
2. Right Image – Connective Tissue Micrograph
    - The microscopic image shows:
        - A dense background of fibrous material
        - Rounded spaces corresponding to adipocytes
    - Smaller cells with visible nuclei, including:
        - Fibrocytes (mature fibroblasts)
        - Mesenchymal-like cells
    - The fibers appear arranged in an irregular pattern throughout the tissue
    - The fibrous background provides strength and support
    - Adipocytes function in fat storage
    - Fibrocytes maintain the connective tissue matrix
    - The mixture of cells and fibers supports tissue repair and structural integrity

Figure 4.3.2: Adipose Tissue

This image shows adipose tissue, or fat tissue, in two formats: a diagram on the left and a micrograph on the right. Both the diagrams have callouts labels Adipocytes, Stored lipids, Nucleus and cytoplasm.

Both images illustrate the structure of adipocytes, which are specialized cells for storing lipids. The images show how adipocytes are arranged in groups within connective tissue, so the main purpose of the figure is to compare a simplified diagram with a microscopic view of the same tissue type.

In the left image, the diagram shows many closely packed adipocytes. Each adipocyte contains a large central region representing stored lipids. The nucleus and cytoplasm are compressed to the outer edge of the cell. The cells appear tightly grouped with minimal space between them. These adipocytes store energy in the form of lipids, and the large storage region allows efficient accumulation of energy reserves. The arrangement of cells also supports insulation and cushioning of tissues.

Figure 4.3.3: Reticular Tissue

This image illustrates reticular tissue alongside a micrograph. The diagram shows a series of small, oval cells embedded in a matrix. Thin reticular fibers spread and crisscross throughout the matrix. In the micrograph, the reticular fibers are thin, dark, and seem to travel between the many deeply stained cells.

Figure 4.3.4: Dense Connective Tissue

In Figure $4.9.4$ compares two types of dense connective tissue: regular tissue and irregular tissue. Each type is shown as both a diagram and a micrograph. The left image is a simplified diagram and the right image is a microscopic view. In both sections, the labeled structures are collagen fibers and fibroblast nuclei.

In panel (a) regular tissue , the collagen fibers are arranged in parallel bundles running in the same direction. The fibroblast nuclei are located between the collagen fibers and appear elongated. The fibers form tightly packed, linear structures with minimal variation in orientation. This parallel arrangement provides strong resistance to tension in one direction. This type of tissue is found in structures such as tendons and ligaments, where forces are applied along a single axis.

In panel (b) irregular tissue the collagen fiber bundles are arranged in multiple directions rather than parallel. The fibroblast nuclei are scattered among the fibers. The fibers form a dense, interconnected network with varied orientation. This irregular arrangement provides strength in multiple directions. This tissue is found in areas such as the dermis of the skin, where forces come from different directions.

Figure 4.3.5: Types of Cartilage

This image compares three types of cartilage: hyaline cartilage, fibrocartilage, and elastic cartilage. Each type is shown as both a diagram on the left and a micrograph on the right.

The figure is divided into three labeled sections. The labels are (a) Hyaline cartilage, (b) Fibrocartilage, and (c) Elastic cartilage. For each type, the left image is a simplified diagram and the right image is a microscopic view. In all three sections, the labeled cell structures are chondrocytes in lacunae, meaning cartilage cells located in small spaces within the matrix.

In section (a) Hyaline cartilage, the labeled structures include chondrocytes in lacunae and the matrix. The chondrocytes are grouped together within lacunae, and the surrounding matrix appears smooth and uniform. Fibers are present but are not visibly distinct as separate bundles. The smooth matrix provides support with some flexibility. This structure allows the tissue to resist compression while maintaining shape. Hyaline cartilage is found in areas such as joints, the trachea, and the nose.

In section (b) Fibrocartilage, the labeled structures include chondrocytes in lacunae and thick collagen fiber bundles. The chondrocytes are located within lacunae and are arranged among thick collagen fiber bundles. The collagen fibers are prominent and run in organized strands throughout the matrix. The tissue appears more densely packed with fibers than hyaline cartilage. The presence of dense collagen fibers provides high tensile strength and resistance to compression. This structure allows fibrocartilage to absorb shock. It is found in areas such as intervertebral discs and the pubic symphysis.

In section (c) Elastic cartilage, the labeled structures include chondrocytes in lacunae, the matrix, and a network of elastic fibers. The chondrocytes are located in lacunae and are distributed throughout the tissue. The matrix contains a network of elastic fibers that form an interconnected structure. These fibers are more flexible compared to collagen. Elastic fibers allow the tissue to bend and return to its original shape. This cartilage provides flexible support. It is found in structures such as the external ear and epiglottis.

Figure 4.3.6: Blood: A Fluid Connective

This image shows a microscopic view of a blood smear, highlighting many erythrocytes, or red blood cells, and one labeled lymphocyte, which is a white blood cell.

The image contains many small, circular cells spread across the field. Most of these cells are labeled as erythrocytes (red blood cells), and one larger cell labeled lymphocyte is present among them.

The erythrocytes are numerous, small, round cells distributed throughout the image. Each erythrocyte appears flattened with a central area that is thinner than the edges, giving it a biconcave shape. These cells do not contain a nucleus. Their function is to transport oxygen and carbon dioxide through the bloodstream, and their shape increases surface area and supports efficient gas exchange.

The labeled lymphocyte is a single larger cell visible among the erythrocytes. It contains a large nucleus that occupies most of its interior, with a small amount of surrounding cytoplasm. Lymphocytes are part of the immune system and help recognize and respond to pathogens such as viruses and bacteria.

Figure 4.4.1: Muscle Tissue

This image shows three types of muscle tissue, (a) skeletal muscle, (b) smooth muscle, and (c) cardiac muscle. Each image shows a microscopic view of muscle cells, also called muscle fibers. The figure is organized into three sections, and each section compares the arrangement of muscle fibers and the appearance of cell nuclei.

In section (a) Skeletal muscle, the muscle fibers are long, cylindrical, and run parallel to each other. The fibers show visible striations, which are repeating bands along the length of each fiber. Multiple nuclei are present in each fiber, and these nuclei are located near the outer edges of the cells. The fibers are unbranched and aligned in a uniform direction. Skeletal muscle produces voluntary movement of the body. The parallel arrangement and striations support strong, coordinated contractions. These muscles attach to bones and enable movement such as walking and lifting.

In section (b) Smooth muscle, the cells are shorter and spindle-shaped, tapering at both ends. The fibers are arranged in overlapping layers rather than strict parallel alignment. There are no visible striations. Each cell contains a single centrally located nucleus. Smooth muscle controls involuntary movements within internal organs. It is found in structures such as the digestive tract and blood vessels. The arrangement allows for slow, sustained contractions, such as moving food through the intestines.

In section (c) Cardiac muscle, the muscle fibers are branched and interconnected. Striations are present, similar to skeletal muscle. Each cell typically contains one centrally located nucleus. Specialized connections between cells, called intercalated discs, join adjacent fibers. Cardiac muscle forms the walls of the heart. The branching and connections allow cells to contract together as a coordinated unit. This structure supports rhythmic, involuntary contractions that pump blood.

Figure 4.5.1: The Neuron

This image shows the structure of a neuron, or nerve cell, using both a micrograph and a diagram.

The image contains two main parts. The top image is a micrograph labeled neuron cells in tissue, and the bottom image is a diagram illustrating the structure of a single neuron. The labels identified in the figure include nucleus, dendrites, and axon. The diagram also has labels microfibrils and microtubules inside the axon.

In the top image, the micrograph shows several neuron cells embedded within tissue. Each neuron has a cell body with a central region that contains the nucleus. The surrounding area contains many thin extensions and supporting structures. These cells are specialized for receiving, processing, and transmitting signals within the nervous system.

In the bottom image, the diagram shows a single neuron with three main parts. The first part is the cell body, also called the soma. This central region contains the nucleus, and multiple short, branching extensions extend outward from it. The second part is the dendrites, which are many short, branched extensions surrounding the cell body. The diagram explicitly labels these structures as dendrites. The third part is the axon, which is a single long extension that extends away from the cell body. The axon ends in branching terminals that contact other cells. Internal structures within the axon are labeled as microfibrils and microtubules.

The functions shown in the figure are that dendrites receive incoming signals from other cells, the cell body integrates and processes these signals, and the axon carries electrical signals away from the cell body to other cells. The terminal branches allow communication with other neurons or target cells.

Figure 4.5.2: Nervous Tissue

This image shows nervous tissue, including neurons and supporting cells, presented as a diagram on the left and a micrograph on the right.

The image is divided into two main parts. The left image is a diagram illustrating different types of cells in nervous tissue, and the right image is a micrograph showing neurons within actual tissue. The labels in the figure include neurons, astrocytes, oligodendrocytes, microglial cells, and myelin sheath.

In the left image, the diagram shows a large central cell labeled neuron. The neuron has a cell body with a nucleus and multiple branching extensions extending outward. Several smaller surrounding cells represent glial cells. These labeled supporting cells include astrocytes, which have many branching processes, microglial cells, which are smaller and more irregular in shape, and oligodendrocytes, which are located along nerve fibers. Segments wrapped around the neuron's long extension are labeled myelin sheath.

The functions shown in the left image are that the neuron is specialized for transmitting electrical signals throughout the nervous system, astrocytes support neurons by maintaining the surrounding environment and assisting with nutrient exchange, oligodendrocytes produce the myelin sheath, which insulates nerve fibers and increases the speed of signal transmission, and microglial cells provide immune defense by removing debris and pathogens. The myelin sheath allows signals to travel more efficiently along the neuron.

In the right image, the micrograph shows neuron cell bodies embedded in a dense network of surrounding tissue. The neurons appear larger than surrounding cells and contain a visible central region corresponding to the nucleus. The surrounding tissue contains many smaller supporting cells and fiber-like structures. The neurons form part of a network that transmits information, while the surrounding supporting cells maintain tissue health, provide structural support, and assist in communication.

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5: MORE THAN SKIN DEEP - THE INTEGUMENTARY SYSTEM

Overview



Figure 5.1: Your skin is a vital part of your life and appearance (a–b). Some people choose to embellish it with tattoos (a) or makeup (b). (CC BY 4.0; via Introduction).

Integumentary system

The integumentary system is the largest organ system in the human body, forming a protective barrier between the external environment and the internal structures it safeguards. It is composed of the skin—including the epidermis, dermis, and hypodermis—along with accessory structures such as hair, nails, sweat glands, and sebaceous glands

The skin is composed of two major layers: a superficial epidermis and a deeper dermis. The epidermis consists of several layers beginning with the innermost (deepest) stratum basale (germinatum), followed by the stratum spinosum, stratum granulosum, stratum lucidum (when present), and ending with the outermost layer, the stratum corneum. The topmost layer, the stratum corneum, consists of dead cells that shed periodically and is progressively replaced by cells formed from the basal layer. The stratum basale also contains melanocytes, cells that produce melanin, the pigment primarily responsible for giving skin its color. Melanin is transferred to keratinocytes in the stratum spinosum to protect cells from UV rays.

The dermis connects the epidermis to the hypodermis, and provides strength and elasticity due to the presence of collagen and elastin fibers. It has only two layers: the papillary layer with papillae that extend into the epidermis and the lower, reticular layer composed of loose connective tissue. The hypodermis, deep to the dermis of skin, is the connective tissue that connects the dermis to underlying structures; it also harbors adipose tissue for fat storage and protection.

Accessory Structures of the Skin

Accessory structures of the skin include hair, nails, sweat glands, and sebaceous glands. Hair is made of dead keratinized cells, and gets its color from melanin pigments. Nails, also made of dead keratinized cells, protect the extremities of our fingers and toes from mechanical damage. Sweat glands and sebaceous glands produce sweat and sebum, respectively. Each of these fluids has a role to play in maintaining homeostasis. Sweat cools the body surface when it gets overheated and helps excrete small amounts of metabolic waste. Sebum acts as a natural moisturizer and keeps the dead, flaky, outer keratin layer healthy.

The skin plays important roles in protection, sensing stimuli, thermoregulation, and vitamin D synthesis. It is the first layer of defense to prevent dehydration, infection, and injury to the rest of the body. Sweat glands in the skin allow the skin surface to cool when the body gets overheated. Thermoregulation is also accomplished by the dilation or constriction of heat-carrying blood vessels in the skin. Immune cells present among the skin layers patrol the areas to keep them free of foreign materials. Fat stores in the hypodermis aid in both thermoregulation and protection. Finally, the skin plays a role in the synthesis of vitamin D, which is necessary for our well-being but not easily available in natural foods.

Disorders and Injuries of the Integumentary System

Skin cancer is a result of damage to the DNA of skin cells, often due to excessive exposure to UV radiation. Basal cell carcinoma and squamous cell carcinoma are highly curable, and arise from cells in the stratum basale and stratum spinosum, respectively. Melanoma is the most dangerous form of skin cancer, affecting melanocytes, which can spread/metastasize to other organs. Burns are an injury to the skin that occur as a result of exposure to extreme heat, radiation, or chemicals. First-degree and second-degree burns usually heal quickly, but third-degree burns can be fatal because they penetrate the full thickness of the skin. Scars occur when there is repair of skin damage. Fibroblasts generate scar tissue in the form of collagen, which forms a basket-weave pattern that looks different from normal skin.

Bedsores and stretch marks are the result of excessive pressure on the skin and underlying tissue. Bedsores are characterized by necrosis of tissue due to immobility, whereas stretch marks result from rapid growth. Eczema is an allergic reaction that manifests as a rash, and acne results from clogged sebaceous glands. Eczema and acne are usually long-term skin conditions that may be treated successfully in mild cases. Calluses and corns are the result of abrasive pressure on the skin.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own.

By the end of this chapter, students should be able to:

1. Describe the integumentary system and the role it plays in homeostasis
   - Major components (epidermis, dermis, hypodermis, glands, hair, nails), skin micro biome, acid mantle, vitamin D synthesis.
   - Explain how skin helps regulate temperature (sweating, vasodilation/constriction), fluid balance (barrier to water loss), protection (UV, pathogens), sensation, immune surveillance, and excretion.
   - Trace a stimulus–response pathway (e.g., heat -> sweat -> evaporative cooling) and predict what happens if one step fails (e.g., anhidrosis, extensive burns).
2. Describe the layers of the skin and the functions of each layer
   - Epidermal strata (basale, spinosum, granulosum, lucidum—palms/soles, corneum); cell types (keratinocytes, melanocytes, Langerhans, Merkel). Dermis (papillary vs reticular; collagen/elastin, vessels, nerves). Hypodermis (adipose/areolar).
   - Match structures to functions (barrier, renewal, strength/elasticity, sensation, thermoregulation, energy storage). Relate histology to function.
   - Label a diagram/histology slide and explain how a second-degree vs third-degree burn alters functions at specific layers.
3. Describe the accessory structures of the skin and the functions of each
   - Hair and follicles (arrector pili), nails, glands (eccrine, apocrine, sebaceous; ceruminous/mammary as modified glands), innervation and myoepithelial cells.
   - Link structure to role (cooling via eccrine sweat; sebum for barrier; hair for protection/sensation; nails for protection/fine motor).
   - Compare eccrine vs apocrine glands by secretion, location, and function; predict effects of blocked sebaceous ducts (acne).
4. Describe the changes that occur in the integumentary system during the aging process
   - Epidermal/dermal thinning, reduced melanocytes and Langerhans cells, decreased collagen/elastin, slower wound healing, reduced sweat/sebum, impaired thermoregulation, increased cancer risk.
   - Connect these changes to signs/symptoms (dryness, wrinkles, bruising, heat/cold intolerance, pressure ulcer risk) and safety/clinical implications.
   - Propose skincare and environmental strategies to reduce ulcer risk in an older adult; justify with physiology.
5. Discuss several common diseases, disorders, and injuries that affect the integumentary system (Identify structures/layers involved, key clinical features, risk factors, and basic pathophysiology).
   - Infectious: impetigo, cellulitis.
   - Inborn errors of metabolism: albinism.
   - Inflammatory/immune: dermatitis/eczema, psoriasis.

- Pigment disorders: vitiligo, melasma.
- Neoplasms: basal cell carcinoma, squamous cell carcinoma, melanoma (ABCDE).
- Injuries: abrasions, lacerations, burns (degrees, Rule of Nines), pressure injuries, frostbite.

6. Explain protection/treatments for some common diseases, disorders, and injuries of the integumentary system such as burn management priorities, sun protection, pressure ulcer prevention.

What do you think when you look at your skin in the mirror? Do you think about covering it with makeup, adding a tattoo, or maybe a body piercing? Or do you think about the fact that the skin belongs to one of the body's most essential and dynamic systems: the integumentary system? The integumentary system refers to the skin and its accessory structures, and it is responsible for much more than simply lending to your outward appearance. In the adult human body, the skin makes up about 16 percent of body weight and covers an area of 1.5 to 2 m^2. In fact, the skin and accessory structures are the largest organ system in the human body. As such, the skin protects your inner organs and it is in need of daily care and protection to maintain its health. This chapter will introduce the structure and functions of the integumentary system, as well as some of the diseases, disorders, and injuries that can affect this system.

5.1: Layers of the Skin

5.2: Accessory Structures of the Skin

5.3: Functions of the Integumentary System

5.4: Diseases, Disorders, and Injuries of the Integumentary System

5.5: Terms and Definitions

5.6: Chapter Review Questions

5.7: Applied Thinking Self-Check

5.8: Alternate Text Descriptions

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5.1: Layers of the Skin

Histology and Structure of the Skin Layers

Although you may not typically think of the skin as an organ, it is in fact made of tissues that work together as a single structure to perform unique and critical functions. The skin and its accessory structures make up the integumentary system, which provides the body with overall protection. The skin is made of multiple layers of cells and tissues, which are held to underlying structures by connective tissue (Figure 5.1.1). The deeper layer of skin is well vascularized (has numerous blood vessels). It also has numerous sensory, and autonomic and sympathetic nerve fibers ensuring communication to and from the brain.

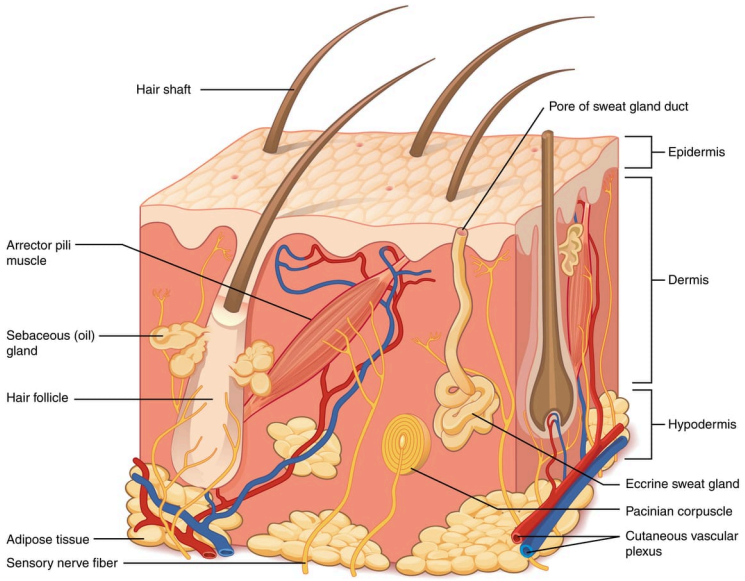


Figure 5.1.1: The skin is composed of two main layers: the epidermis, made of closely packed epithelial cells, and the dermis, made of dense, irregular connective tissue that houses blood vessels, hair follicles, sweat glands, and other structures. Beneath the dermis lies the hypodermis, which is composed mainly of loose connective and fatty tissues. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 5.1.1.

The Epidermis

The epidermis is composed of keratinized, stratified squamous epithelium. It is made of four or five layers of epithelial cells, depending on its location in the body. It does not have any blood vessels within it (i.e., it is avascular). Skin that has four layers of cells is referred to as “thin skin.” From deep to superficial, these layers are the stratum basale, stratum spinosum, stratum granulosum, and stratum corneum. Most of the skin can be classified as thin skin. “Thick skin” is found only on the palms of the hands and the soles of the feet. It has a fifth layer, called the stratum lucidum, located between the stratum corneum and the stratum granulosum (Figure 5.1.2).

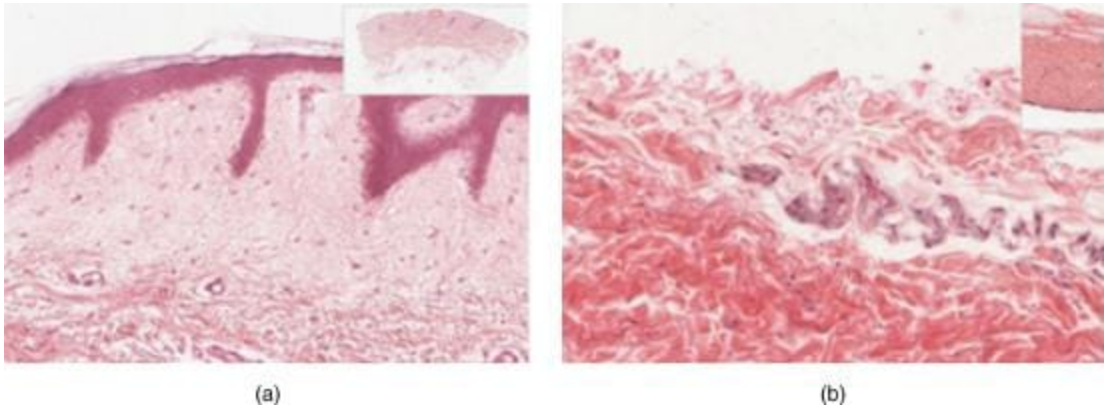


Figure 5.1.2: Comparison of two histology samples showing differences in epithelial thickness over connective tissue. (CC BY 4.0; via Layers of the Skin). Alternate text description of Figure 5.1.2.

The cells in all of the layers except the stratum basale are called keratinocytes. A keratinocyte is a cell that manufactures and stores the protein keratin. Keratin is an intracellular fibrous protein that gives hair, nails, and skin their hardness and water-resistant properties. The keratinocytes in the stratum corneum are dead and regularly slough away, being replaced by cells from the deeper layers (Figure 5.1.3).

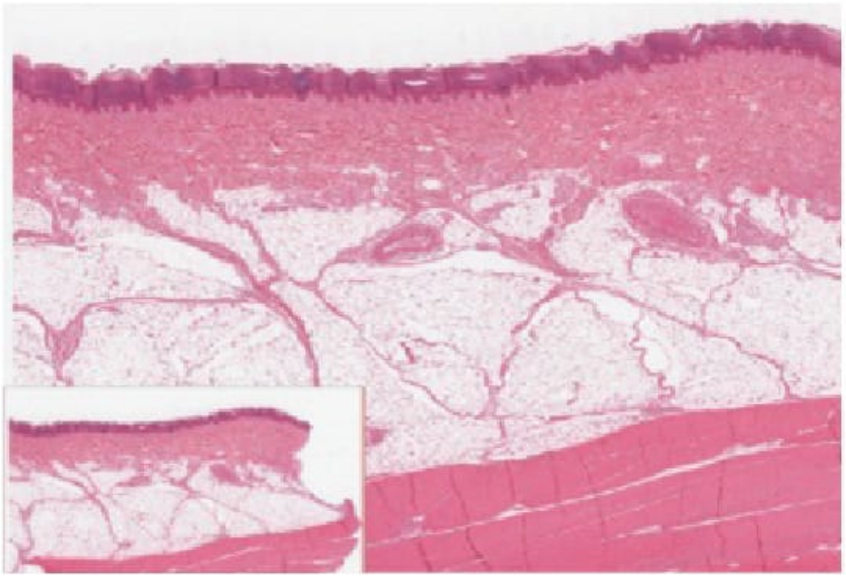


Figure 5.1.3: The epidermis is epithelium composed of multiple layers of cells. The basal layer consists of cuboidal cells, whereas the outer layers are squamous, keratinized cells, so the whole epithelium is often described as being keratinized stratified squamous epithelium. LM × 40. (CC BY 4.0; via Layers of the Skin). Alternate text description of Figure 5.1.3.

Stratum Basale

The stratum basale (also called the stratum germinativum) is the deepest epidermal layer and attaches the epidermis to the basal lamina, below which lie the layers of the dermis. The cells in the stratum basale bond to the dermis via intertwining collagen fibers, referred to as the basement membrane. A finger-like projection, or fold, known as the dermal papilla (plural = dermal papillae) is found in the superficial portion of the dermis. Dermal papillae increase the strength of the connection between the epidermis and dermis; the greater the folding, the stronger the connections made (Figure 5.1.4).

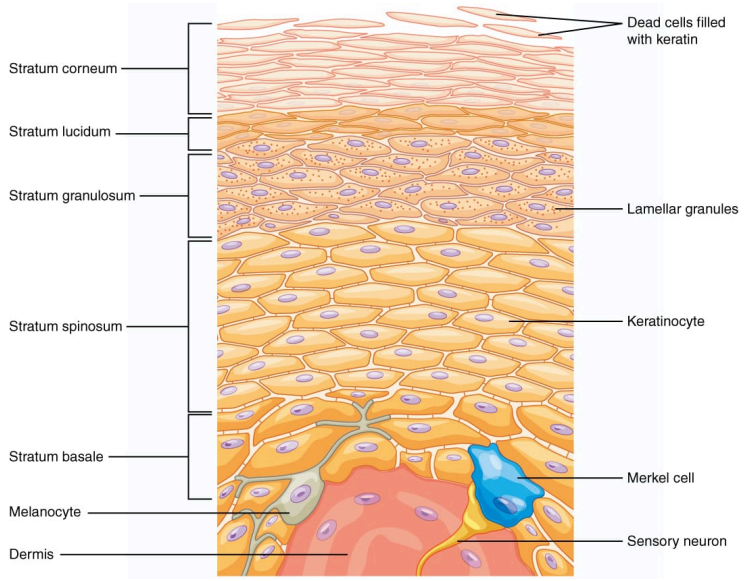


Figure 5.1.4: The epidermis of thick skin has five layers: stratum basale, stratum spinosum, stratum granulosum, stratum lucidum, and stratum corneum. (CC BY 4.0; via Layers of the Skin). Alternate text description of Figure 5.1.4.

The stratum basale is a single layer of cells primarily made of basal cells. A basal cell is a cuboidal-shaped stem cell that is a precursor of the keratinocytes of the epidermis. All of the keratinocytes are produced from this single layer of cells, which are constantly going through mitosis to produce new cells. As new cells are formed, the existing cells are pushed superficially away from the stratum basale. Two other cell types are found dispersed among the basal cells in the stratum basale. The first is a Merkel cell, which functions as a receptor and is responsible for stimulating sensory nerves that the brain perceives as touch. These cells are especially abundant on the surfaces of the hands and feet. The second is a melanocyte, a cell that produces the pigment melanin. Melanin gives hair and skin its color, and also helps protect the living cells of the epidermis from ultraviolet (UV) radiation damage.

In a growing fetus, fingerprints form where the cells of the stratum basale meet the papillae of the underlying dermal layer (papillary layer), resulting in the formation of the ridges on your fingers that you recognize as fingerprints. Fingerprints are unique to each individual and are used for forensic analyses because the patterns do not change with the growth and aging processes.

Stratum Spinosum

As the name suggests, the stratum spinosum is spiny in appearance due to the protruding cell processes that join the cells via a structure called a desmosome. The desmosomes interlock with each other and strengthen the bond between the cells. It is interesting to note that the “spiny” nature of this layer is an artifact of the staining process. Unstained epidermis samples do not exhibit this characteristic appearance. The stratum spinosum is composed of eight to 10 layers of keratinocytes, formed as a result of cell division in the stratum basale (Figure 5.1.5). Interspersed among the keratinocytes of this layer is a type of dendritic cell called the Langerhans cell, which functions as a macrophage by engulfing bacteria, foreign particles, and damaged cells that occur in this layer.

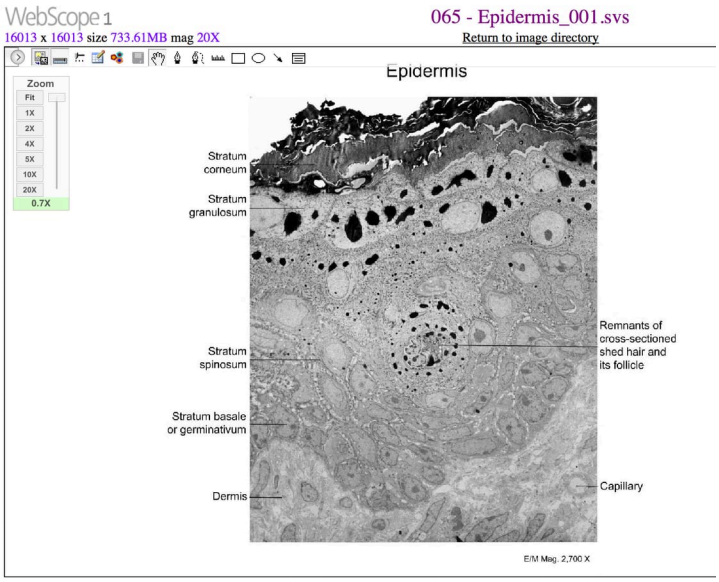


Figure 5.1.5: The cells in the different layers of the epidermis originate from basal cells located in the stratum basale, yet the cells of each layer are distinctively different. EM × 2700. (Micrograph provided by the Regents of University of Michigan Medical School © 2012). (CC BY 4.0; via Layers of the Skin). Alternate text description of Figure 5.1.5.

Stratum Granulosum

The stratum granulosum has a grainy appearance due to further changes to the keratinocytes as they are pushed from the stratum spinosum. The cells (three to five layers deep) become flatter, their cell membranes thicken, and they generate large amounts of the proteins keratin, which is fibrous, and keratohyalin, which accumulates as lamellar granules within the cells as represented in Figure 5.1.5. These two proteins make up the bulk of the keratinocyte mass in the stratum granulosum and give the layer its grainy appearance. The nuclei and other cell organelles disintegrate as the cells die, leaving behind the keratin, keratohyalin, and cell membranes that will form the stratum lucidum, the stratum corneum, and the accessory structures of hair and nails.

Stratum Lucidum

The stratum lucidum is a smooth, seemingly translucent layer of the epidermis located just above the stratum granulosum and below the stratum corneum. This thin layer of cells is found only in the thick skin of the palms, soles, and digits. The keratinocytes that compose the stratum lucidum are dead and flattened as shown in Figure 5.1.5. These cells are densely packed with eleidin, a clear protein, derived from keratohyalin, which gives these cells their transparent (i.e., lucid) appearance.

Stratum Corneum

The stratum corneum is the most superficial layer of the epidermis and is the layer exposed to the outside environment Figure 5.1.5. The increased keratinization (also called cornification) of the cells in this layer gives it its name. There are usually 15 to 30 layers of cells in the stratum corneum. This dry, dead layer helps prevent the penetration of microbes and the dehydration of underlying tissues, and provides a mechanical protection against abrasion for the more delicate, underlying layers. Cells in this layer are shed periodically and are replaced by cells pushed up from the stratum granulosum (or stratum lucidum in the case of the palms and soles of feet). The entire layer is replaced during a period of about 4 weeks. Cosmetic procedures, such as micro dermabrasion, help remove some of the dry, upper layer and aim to keep the skin looking “fresh” and healthy.

Dermis

The dermis might be considered the “core” of the integumentary system (derma- = “skin”), as distinct from the epidermis (epi- = “upon” or “over”) and hypodermis (hypo- = “below”). It contains blood and lymph vessels, nerves, and other structures, such as hair follicles and sweat glands. The dermis is made of two layers of connective tissue that compose an interconnected mesh of elastin and collagenous fibers, produced by fibroblasts (Figure 5.1.6).

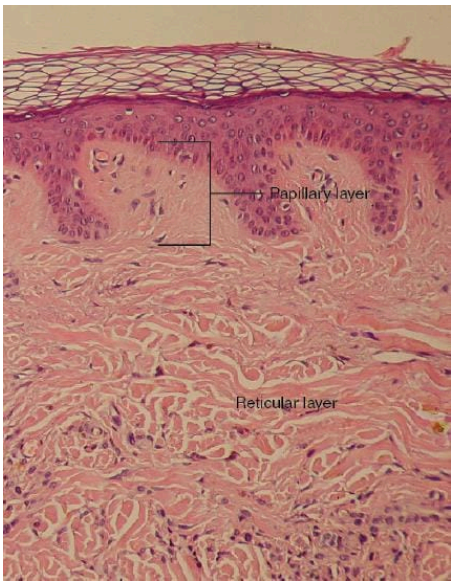


Figure 5.1.6: This stained slide shows the two components of the dermis—the papillary layer and the reticular layer. Both are made of connective tissue with fibers of collagen extending from one to the other, making the border between the two somewhat indistinct. The dermal papillae extending into the epidermis belong to the papillary layer, whereas the dense collagen fiber bundles below belong to the reticular layer. LM × 10. (CC BY 4.0; via Layers of the Skin). Alternate text description of Figure 5.1.6.

Papillary Layer

The papillary layer is made of loose, areolar connective tissue, which means the collagen and elastin fibers of this layer form a loose mesh. This superficial layer of the dermis projects into the stratum basale of the epidermis to form finger-like dermal papillae Figure 5.1.6. Within the papillary layer are fibroblasts, a small number of fat cells (adipocytes), and an abundance of small blood vessels. In addition, the papillary layer contains phagocytes, defensive cells that help fight bacteria or other infections that have breached the skin. This layer also contains lymphatic capillaries, nerve fibers, and touch receptors called the Meissner corpuscles.

Reticular Layer

Underlying the papillary layer is the much thicker reticular layer, composed of dense, irregular connective tissue. This layer is well vascularized and has a rich sensory and sympathetic nerve supply. The reticular layer appears reticulated (net-like) due to a tight meshwork of fibers. Elastin fibers provide some elasticity to the skin, enabling movement. Collagen fibers provide structure and tensile strength, with strands of collagen extending into both the papillary layer and the hypodermis. In addition, collagen binds water to keep the skin hydrated. Collagen injections and Retin-A creams help restore skin turgor by either introducing collagen externally or stimulating blood flow and repair of the dermis, respectively.

Hypodermis

The hypodermis (also called the subcutaneous layer or superficial fascia) is a layer directly below the dermis and serves to connect the skin to the underlying fascia (fibrous tissue) of the bones and muscles. It is not strictly a part of the skin, although the border between the hypodermis and dermis can be difficult to distinguish. The hypodermis consists of well-vascularized, loose, areolar connective tissue and adipose tissue, which functions as a mode of fat storage and provides insulation and cushioning for the integument.

Everyday Connection

Lipid Storage

The hypodermis is home to most of the fat that concerns people when they are trying to keep their weight under control. Adipose tissue present in the hypodermis consists of fat-storing cells called adipocytes. This stored fat can serve as an energy reserve, insulate the body to prevent heat loss, and act as a cushion to protect underlying structures from trauma.

Where the fat is deposited and accumulates within the hypodermis depends on hormones (testosterone, estrogen, insulin, glucagon, leptin, and others), as well as genetic factors. Fat distribution changes as our bodies mature and age. Males tend to accumulate fat in different areas (neck, arms, lower back, and abdomen) than do females (breasts, hips, thighs, and buttocks).

Pigmentation

The color of skin is influenced by a number of pigments, including melanin, carotene, and hemoglobin. Recall that melanin is produced by cells called melanocytes, which are found scattered throughout the stratum basale of the epidermis. The melanin is transferred into the keratinocytes via a cellular vesicle called a melanosome (Figure 5.1.7).

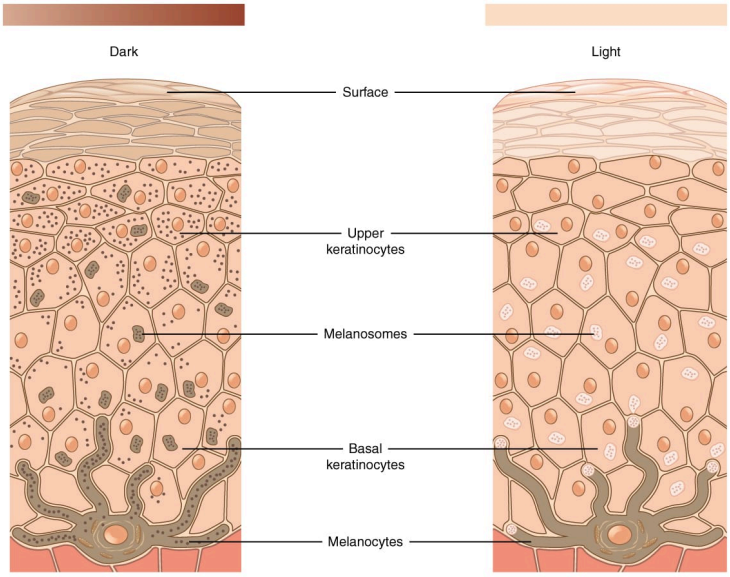


Figure 5.1.7: The relative coloration of the skin depends of the amount of melanin produced by melanocytes in the stratum basale and taken up by keratinocytes. (CC BY 4.0; via LibreTexts). Alternate text description of Figure 5.1.7.

Melanin occurs in two primary forms. Eumelanin exists as black and brown, whereas pheomelanin provides a red color. Dark-skinned individuals produce more melanin than those with pale skin. Exposure to the UV rays of the sun or a tanning salon causes melanin to be manufactured and built up in keratinocytes, as sun exposure stimulates keratinocytes to secrete chemicals that stimulate melanocytes. The accumulation of melanin in keratinocytes results in the darkening of the skin, or a tan. This increased melanin accumulation protects the DNA of epidermal cells from UV ray damage and the breakdown of folic acid, a nutrient necessary for our health and well-being. In contrast, too much melanin can interfere with the production of vitamin D, an important nutrient involved in calcium absorption. Thus, the amount of melanin present in our skin is dependent on a balance between available sunlight and folic acid destruction, and protection from UV radiation and vitamin D production.

It requires about 10 days after initial sun exposure for melanin synthesis to peak, which is why pale-skinned individuals tend to suffer sunburns of the epidermis initially. Dark-skinned individuals can also get sunburns, but are more protected than are pale-skinned individuals. Melanosomes are temporary structures that are eventually destroyed by fusion with lysosomes; this fact, along with melanin-filled keratinocytes in the stratum corneum sloughing off, makes tanning impermanent.

Too much sun exposure can eventually lead to wrinkling due to the destruction of the cellular structure of the skin, and in severe cases, can cause sufficient DNA damage to result in skin cancer. When there is an irregular accumulation of melanocytes in the skin, freckles appear. Moles are larger masses of melanocytes, and although most are benign, they should be monitored for changes that might indicate the presence of cancer (Figure 5.1.8).



Figure 5.1.8: Moles range from benign accumulations of melanocytes to melanomas. These structures populate the landscape of our skin. (Public Domain; via Wikimedia Commons). Alternate text description of Figure 5.1.8.

Disorders of the...

Integumentary System

The first thing a clinician sees is the skin, and so the examination of the skin should be part of any thorough physical examination. Most skin disorders are relatively benign, but a few, including melanomas, can be fatal if untreated. A couple of the more noticeable disorders, albinism and vitiligo, affect the appearance of the skin and its accessory organs. Although neither is fatal, it would be hard to claim that they are benign, at least to the individuals so afflicted.

Albinism is a genetic disorder that affects (completely or partially) the coloring of skin, hair, and eyes. The defect is primarily due to the inability of melanocytes to produce melanin. Individuals with albinism tend to appear white or very pale due to the lack of melanin in their skin and hair. Recall that melanin helps protect the skin from the harmful effects of UV radiation. Individuals with albinism tend to need more protection from UV radiation, as they are more prone to sunburns and skin cancer. They also tend to be more sensitive to light and have vision problems due to the lack of pigmentation on the retinal wall. Treatment of this disorder usually involves addressing the symptoms, such as limiting UV light exposure to the skin and eyes. In vitiligo, the melanocytes in certain areas lose their ability to produce melanin, possibly due to an autoimmune reaction. This leads to a loss of color in patches (Figure 5.1.9). Neither albinism nor vitiligo directly affects the lifespan of an individual.



(a) (b)

Figure 5.1.9: Individuals with vitiligo experience depigmentation that results in lighter colored patches of skin. The condition is especially noticeable. (CC BY 4.0; via Layers of the Skin).

Other changes in the appearance of skin coloration can be indicative of diseases associated with other body systems. Liver disease or liver cancer can cause the accumulation of bile and the yellow pigment bilirubin, leading to the skin appearing yellow or jaundiced (*jaune* is the French word for “yellow”). Tumors of the pituitary gland can result in the secretion of large amounts of melanocyte-stimulating hormone (MSH), which results in a darkening of the skin. Similarly, Addison’s disease can stimulate the release of excess amounts of adrenocorticotropic hormone (ACTH), which can give the skin a deep bronze color. A sudden drop in oxygenation can affect skin color, causing the skin to initially turn ashen (white). With a prolonged reduction in oxygen levels, dark red deoxyhemoglobin becomes dominant in the blood, making the skin appear blue, a condition referred to as cyanosis (*kyanos* is the Greek word for “blue”). This happens when the oxygen supply is restricted, as when someone is experiencing difficulty in breathing because of asthma or a heart attack. However, in these cases the effect on skin color has nothing do with the skin’s pigmentation.

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5.2: Accessory Structures of the Skin

Structures and Function of Hair, Nails and Glands

Accessory structures of the skin include hair, nails, sweat glands, and sebaceous glands. These structures embryologically originate from the epidermis and can extend down through the dermis into the hypodermis.

Hair

Hair is a keratinous filament growing out of the epidermis. It is primarily made of dead, keratinized cells. Strands of hair originate in an epidermal penetration of the dermis called the hair follicle. The hair shaft is the part of the hair not anchored to the follicle, and much of this is exposed at the skin's surface. The rest of the hair, which is anchored in the follicle, lies below the surface of the skin and is referred to as the hair root. The hair root ends deep in the dermis at the hair bulb, and includes a layer of mitotically active basal cells called the hair matrix. The hair bulb surrounds the hair papilla, which is made of connective tissue and contains blood capillaries and nerve endings from the dermis (Figure 5.2.1).

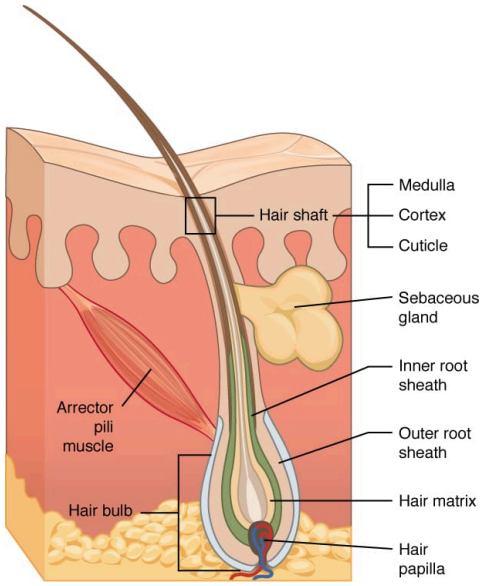


Figure 5.2.1: Hair follicles originate in the epidermis and have many different parts. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 5.2.1.

Just as the basal layer of the epidermis forms the layers of epidermis that get pushed to the surface as the dead skin on the surface sheds, the basal cells of the hair bulb divide and push cells outward in the hair root and shaft as the hair grows. The medulla forms the central core of the hair, which is surrounded by the cortex, a layer of compressed, keratinized cells that is covered by an outer layer of very hard, keratinized cells known as the cuticle. These layers are depicted in a longitudinal cross-section of the hair follicle (Figure 5.2.2), although not all hair has a medullary layer. Hair texture (straight, curly) is determined by the shape and structure of the cortex, and to the extent that it is present, the medulla. The shape and structure of these layers are, in turn, determined by the shape of the hair follicle. Hair growth begins with the production of keratinocytes by the basal cells of the hair bulb. As new cells are deposited at the hair bulb, the hair shaft is pushed through the follicle toward the surface. Keratinization is completed as the cells are pushed to the skin surface to form the shaft of hair that is externally visible. The external hair is completely dead and composed entirely of keratin. For this reason, our hair does not have sensation. Furthermore, you can cut your hair or shave without damaging the hair structure because the cut is superficial. Most chemical hair removers also act superficially; however, electrolysis and yanking both attempt to destroy the hair bulb so hair cannot grow.

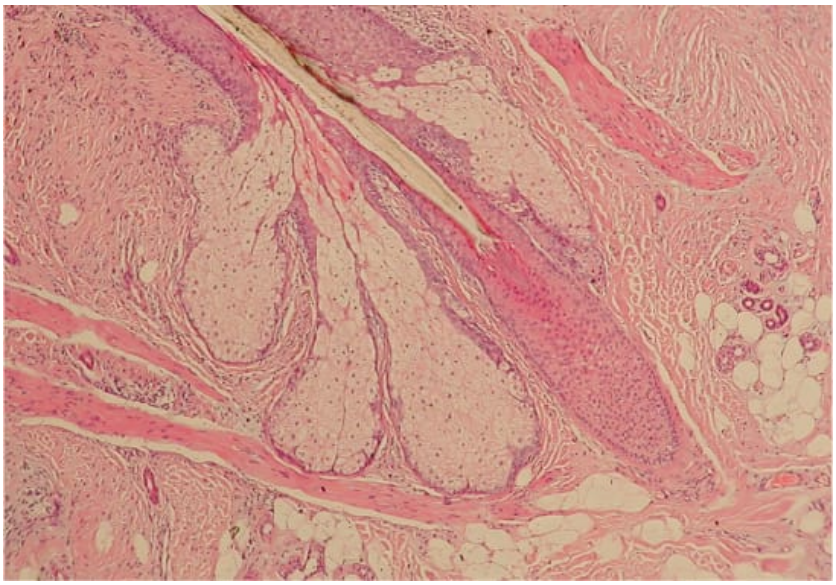


Figure 5.2.2: The slide shows a cross-section of a hair follicle. Basal cells of the hair matrix in the center differentiate into cells of the inner root sheath. Basal cells at the base of the hair root form the outer root sheath. LM × 4. (CC BY 4.0; via OpenStax). Alternate text description of Figure 5.2.2.

The wall of the hair follicle is made of three concentric layers of cells. The cells of the internal root sheath surround the root of the growing hair and extend just up to the hair shaft. They are derived from the basal cells of the hair matrix. The external root sheath, which is an extension of the epidermis, encloses the hair root. It is made of basal cells at the base of the hair root and tends to be more keratinous in the upper regions. The glassy membrane is a thick, clear connective tissue sheath covering the hair root, connecting it to the tissue of the dermis.

Hair serves a variety of functions, including protection, sensory input, thermoregulation, and communication. For example, hair on the head protects the skull from the sun. The hair in the nose and ears, and around the eyes (eyelashes) defends the body by trapping and excluding dust particles that may contain allergens and microbes. Hair of the eyebrows prevents sweat and other particles from dripping into and bothering the eyes. Hair also has a sensory function due to sensory innervation by a hair root plexus surrounding the base of each hair follicle. Hair is extremely sensitive to air movement or other disturbances in the environment, much more so than the skin surface. This feature is also useful for the detection of the presence of insects or other potentially damaging substances on the skin surface. Each hair root is connected to a smooth muscle called the arrector pili that contracts in response to nerve signals from the sympathetic nervous system, making the external hair shaft “stand up.” The primary purpose for this is to trap a layer of air to add insulation. This is visible in humans as goose bumps and even more obvious in animals, such as when a frightened cat raises its fur. Of course, this is much more obvious in organisms with a heavier coat than most humans, such as dogs and cats.

Hair Growth

Hair grows and is eventually shed and replaced by new hair. This occurs in three phases. The first is the anagen phase, during which cells divide rapidly at the root of the hair, pushing the hair shaft up and out. The length of this phase is measured in years, typically from 2 to 7 years. The catagen phase lasts only 2 to 3 weeks, and marks a transition from the hair follicle’s active growth. Finally, during the telogen phase, the hair follicle is at rest and no new growth occurs. At the end of this phase, which lasts about 2 to 4 months, another anagen phase begins. The basal cells in the hair matrix then produce a new hair follicle, which pushes the old hair out as the growth cycle repeats itself. Hair typically grows at the rate of 0.3 mm per day during the anagen phase. On average, 50 hairs are lost and replaced per day. Hair loss occurs if there is more hair shed than what is replaced and can happen due to hormonal or dietary changes. Hair loss can also result from the aging process, or the influence of hormones.

Hair Color

Similar to the skin, hair gets its color from the pigment melanin, produced by melanocytes in the hair papilla. Different hair color results from differences in the type of melanin, which is genetically determined. As a person ages, the melanin production decreases, and hair tends to lose its color and becomes gray and/or white.

Nails

The nail bed is a specialized structure of the epidermis that is found at the tips of our fingers and toes. The nail body is formed on the nail bed, and protects the tips of our fingers and toes as they are the farthest extremities and the parts of the body that experience the maximum mechanical stress (Figure 5.2.3). In addition, the nail body forms a back-support for picking up small objects with the fingers. The nail body is composed of densely packed dead keratinocytes. The epidermis in this part of the body has evolved a specialized structure upon which nails can form. The nail body forms at the nail root, which has a matrix of proliferating cells from the stratum basale that enables the nail to grow continuously. The lateral nail fold overlaps the nail on the sides, helping to anchor the nail body. The nail fold that meets the proximal end of the nail body forms the nail cuticle, also called the eponychium. The nail bed is rich in blood vessels, making it appear pink, except at the base, where a thick layer of epithelium over the nail matrix forms a crescent-shaped region called the lunula (the “little moon”). The area beneath the free edge of the nail, furthest from the cuticle, is called the hyponychium. It consists of a thickened layer of stratum corneum.

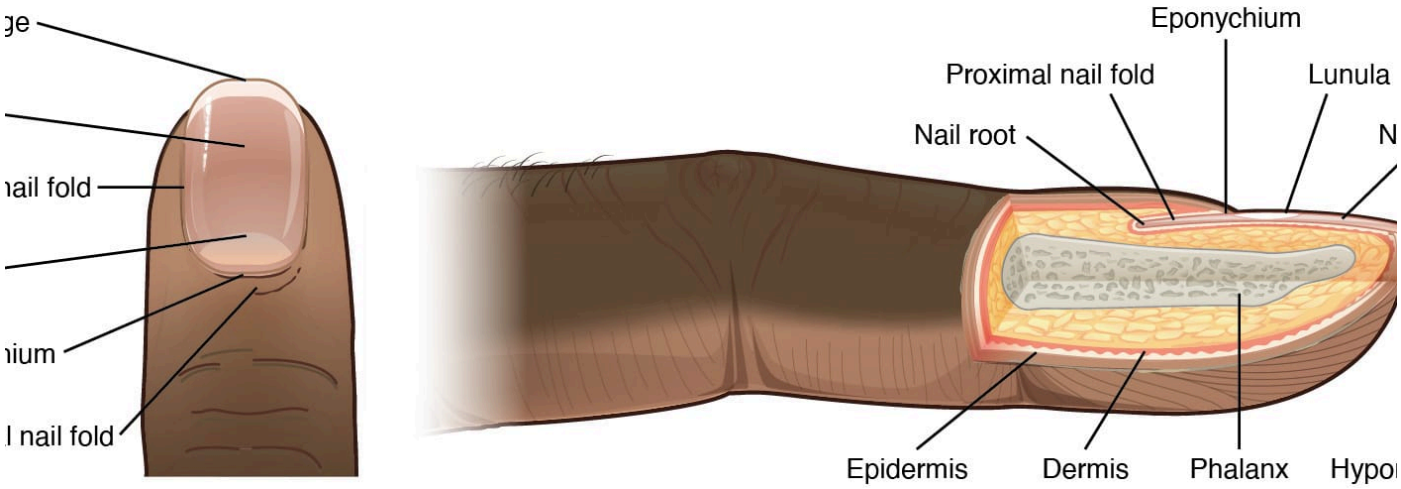


Figure 5.2.3: The nail is an accessory structure of the integumentary system. (CC BY 4.0; via OpenStax). Alternate text description of Figure 5.2.3.

Sweat Glands

When the body becomes warm, sudoriferous glands produce sweat to cool the body. Sweat glands develop from epidermal projections into the dermis and are classified as merocrine glands; that is, the secretions are excreted by exocytosis through a duct without affecting the cells of the gland. There are two types of sweat glands, each secreting slightly different products.

An eccrine sweat gland is type of gland that produces a hypotonic sweat for thermoregulation. These glands are found all over the skin’s surface, but are especially abundant on the palms of the hand, the soles of the feet, and the forehead (Figure 5.2.4). They are coiled glands lying deep in the dermis, with the duct rising up to a pore on the skin surface, where the sweat is released. This type of sweat, released by exocytosis, is hypotonic and composed mostly of water, with some salt, antibodies, traces of metabolic waste, and dermicidin, an antimicrobial peptide. Eccrine glands are a primary component of thermoregulation in humans and thus help to maintain homeostasis.

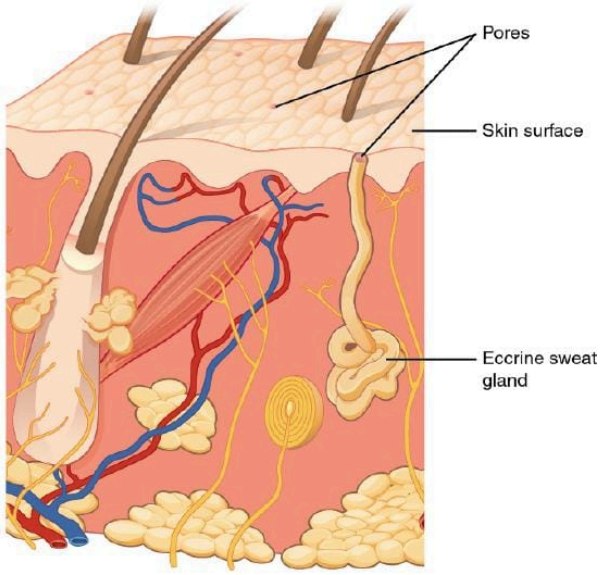


Figure 5.2.4: Eccrine glands are coiled glands in the dermis that release sweat that is mostly water. (CC BY 4.0; via Wikimedia Commons).
Alternate text description of Figure 5.2.4.

An apocrine sweat gland is usually associated with hair follicles in densely hairy areas, such as armpits and genital regions. Apocrine sweat glands are larger than eccrine sweat glands and lie deeper in the dermis, sometimes even reaching the hypodermis, with the duct normally emptying into the hair follicle. In addition to water and salts, apocrine sweat includes organic compounds that make the sweat thicker and subject to bacterial decomposition and subsequent smell. The release of this sweat is under both nervous and hormonal control, and plays a role in the poorly understood human pheromone response. Most commercial antiperspirants use an aluminum-based compound as their primary active ingredient to stop sweat. When the antiperspirant enters the sweat gland duct, the aluminum-based compounds precipitate due to a change in pH and form a physical block in the duct, which prevents sweat from coming out of the pore.

Sebaceous Glands

A sebaceous gland is a type of oil gland that is found all over the body and helps to lubricate and waterproof the skin and hair. Most sebaceous glands are associated with hair follicles. They generate and excrete sebum, a mixture of lipids, onto the skin surface, thereby naturally lubricating the dry and dead layer of keratinized cells of the stratum corneum, keeping it pliable. The fatty acids of sebum also have antibacterial properties, and prevent water loss from the skin in low-humidity environments. The secretion of sebum is stimulated by hormones, many of which do not become active until puberty. Thus, sebaceous glands are relatively inactive during childhood.

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5.3: Functions of the Integumentary System

Protection

The skin and accessory structures perform a variety of essential functions, such as protecting the body from invasion by microorganisms, chemicals, and other environmental factors; preventing dehydration; acting as a sensory organ; modulating body temperature and electrolyte balance; and synthesizing vitamin D. The underlying hypodermis has important roles in storing fats, forming a “cushion” over underlying structures, and providing insulation from cold temperatures.

The skin protects the rest of the body from the basic elements of nature such as wind, water, and UV sunlight. It acts as a protective barrier against water loss, due to the presence of layers of keratin and glycolipids in the stratum corneum. It also is the first line of defense against abrasive activity due to contact with grit, microbes, or harmful chemicals. Sweat excreted from sweat glands deters microbes from over-colonizing the skin surface by generating dermicidin, which has antibiotic properties.

Everyday Connection

Tattoos and Piercings

The word “armor” evokes several images. You might think of a Roman centurion or a medieval knight in a suit of armor. The skin, in its own way, functions as a form of armor—body armor. It provides a barrier between your vital, life-sustaining organs and the influence of outside elements that could potentially damage them.

For any form of armor, a breach in the protective barrier poses a danger. The skin can be breached when a child skins a knee or an adult has blood drawn—one is accidental and the other medically necessary. However, you also breach this barrier when you choose to “accessorize” your skin with a tattoo or body piercing. Because the needles involved in producing body art and piercings must penetrate the skin, there are dangers associated with the practice. These include allergic reactions; skin infections; blood-borne diseases, such as tetanus, hepatitis C, and hepatitis D; and the growth of scar tissue. Despite the risk, the practice of piercing the skin for decorative purposes has become increasingly popular. According to the American Academy of Dermatology, 24 percent of people from ages 18 to 50 have a tattoo.

Sensory Function

The fact that you can feel an ant crawling on your skin, allowing you to flick it off before it bites, is because the skin, and especially the hairs projecting from hair follicles in the skin, can sense changes in the environment. The hair root plexus surrounding the base of the hair follicle senses a disturbance, and then transmits the information to the central nervous system (brain and spinal cord), which can then respond by activating the skeletal muscles of your eyes to see the ant and the skeletal muscles of the body to act against the ant.

The skin acts as a sense organ because the epidermis, dermis, and the hypodermis contain specialized sensory nerve structures that detect touch, surface temperature, and pain. These receptors are more concentrated on the tips of the fingers, which are most sensitive to touch, especially the Meissner corpuscle (tactile corpuscle) (Figure 5.3.1), which responds to light touch, and the Pacinian corpuscle (lamellated corpuscle), which responds to vibration. Merkel cells, seen scattered in the stratum basale, are also touch receptors. In addition to these specialized receptors, there are sensory nerves connected to each hair follicle, pain and temperature receptors scattered throughout the skin, and motor nerves innervate the arrector pili muscles and glands. This rich innervation helps us sense our environment and react accordingly.

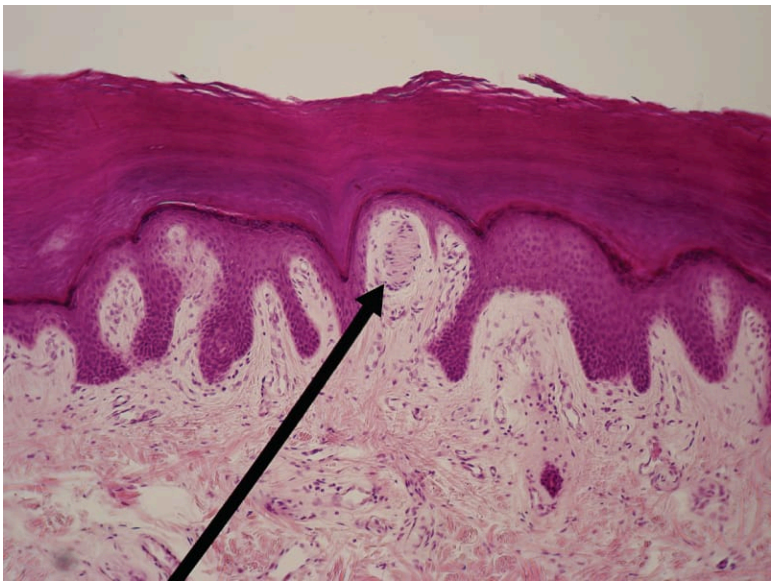


Figure 5.3.1: In this micrograph of a skin cross-section, you can see a Meissner corpuscle (arrow), a type of touch receptor located in a dermal papilla adjacent to the basement membrane and stratum basale of the overlying epidermis. LM × 100. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 5.3.1.

Thermoregulation

The integumentary system helps regulate body temperature through its tight association with the sympathetic nervous system, the division of the nervous system involved in our fight-or-flight responses. The sympathetic nervous system is continuously monitoring body temperature and initiating appropriate motor responses. Recall that sweat glands, accessory structures to the skin, secrete water, salt, and other substances to cool the body when it becomes warm. Even when the body does not appear to be noticeably sweating, approximately 500 mL of sweat (insensible perspiration) are secreted a day. If the body becomes excessively warm due to high temperatures, vigorous activity (5.3.2*a*,5.3.2*c*), or a combination of the two, sweat glands will be stimulated by the sympathetic nervous system to produce large amounts of sweat, as much as 0.7 to 1.5 L per hour for an active person. When the sweat evaporates from the skin surface, the body is cooled as body heat is dissipated.

In addition to sweating, arterioles in the dermis dilate so that excess heat carried by the blood can dissipate through the skin and into the surrounding environment (Figure 5.3.2*b*). This accounts for the skin redness that many people experience when exercising.

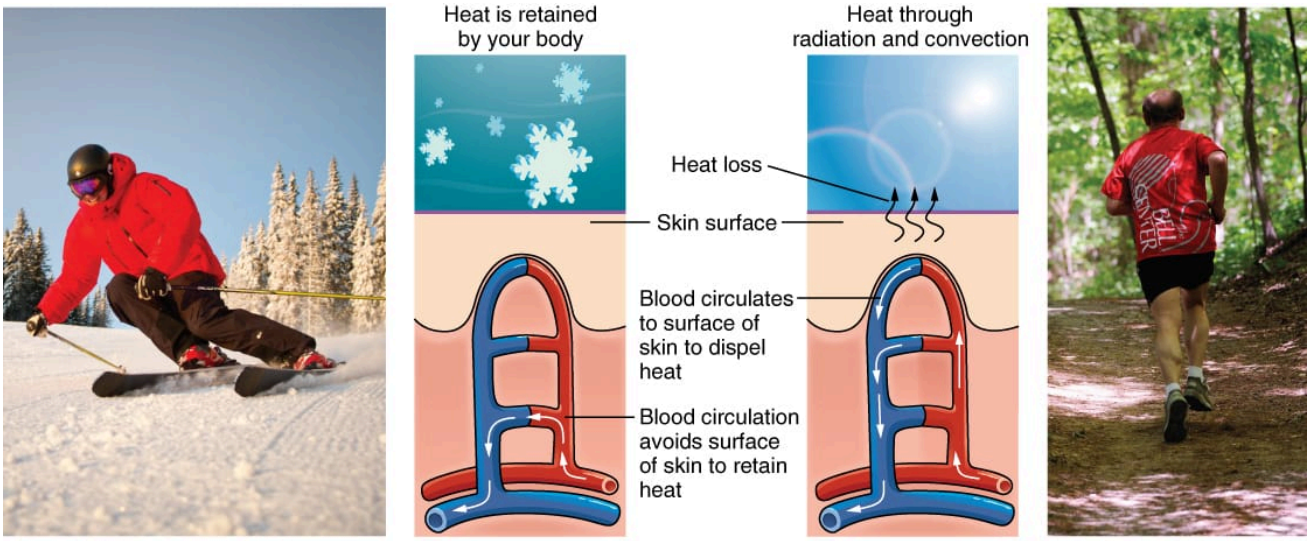


Figure 5.3.2: During strenuous physical activities, such as skiing (a) or running (c), the dermal blood vessels dilate and sweat secretion increases (b). These mechanisms prevent the body from overheating. In contrast, the dermal blood vessels constrict to minimize heat loss in response to low temperatures (b). (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 5.3.2.

When body temperatures drop, the arterioles constrict to minimize heat loss, particularly in the ends of the digits and tip of the nose. This reduced circulation can result in the skin taking on a whitish hue. Although the temperature of the skin drops as a result, passive heat loss is prevented, and internal organs and structures remain warm. If the temperature of the skin drops too much (such as environmental temperatures below freezing), the conservation of body core heat can result in the skin actually freezing, a condition called frostbite.

Aging and the...

Integumentary System

All systems in the body accumulate subtle and some not-so-subtle changes as a person ages. Among these changes are reductions in cell division, metabolic activity, blood circulation, hormonal levels, and muscle strength (Figure 5.3.3). In the skin, these changes are reflected in decreased mitosis in the stratum basale, leading to a thinner epidermis. The dermis, which is responsible for the elasticity and resilience of the skin, exhibits a reduced ability to regenerate, which leads to slower wound healing. The hypodermis, with its fat stores, loses structure due to the reduction and redistribution of fat, which in turn contributes to the thinning and sagging of skin.



Figure 5.3.3: Generally, skin, especially on the face and hands, starts to display the first noticeable signs of aging, as it loses its elasticity over time. (CC BY 4.0; Janet Ramsden via OpenStax).

The accessory structures also have lowered activity, generating thinner hair and nails, and reduced amounts of sebum and sweat. A reduced sweating ability can cause some elderly to be intolerant to extreme heat. Other cells in the skin, such as melanocytes and dendritic cells, also become less active, leading to a paler skin tone and lowered immunity. Wrinkling of the skin occurs due to breakdown of its structure, which results from decreased collagen and elastin production in the dermis, weakening of muscles lying under the skin, and the inability of the skin to retain adequate moisture.

Many anti-aging products can be found in stores today. In general, these products try to rehydrate the skin and thereby fill out the wrinkles, and some stimulate skin growth using hormones and growth factors. Additionally, invasive techniques include collagen injections to plump the tissue and injections of BOTOX® (the name brand of the botulinum neurotoxin) that paralyze the muscles that crease the skin and cause wrinkling.

Vitamin D Synthesis

The epidermal layer of human skin synthesizes vitamin D when exposed to UV radiation. In the presence of sunlight, a form of vitamin D_3 called cholecalciferol is synthesized from a derivative of the steroid cholesterol in the skin. The liver converts cholecalciferol to calcidiol, which is then converted to calcitriol (the active chemical form of the vitamin) in the kidneys. Vitamin D is essential for normal absorption of calcium and phosphorous, which are required for healthy bones. The absence of sun exposure can lead to a lack of vitamin D in the body, leading to a condition called rickets, a painful condition in children where the bones are misshapen due to a lack of calcium, causing bowleggedness. Elderly individuals who suffer from vitamin D deficiency can develop a condition called osteomalacia, a softening of the bones. In present day society, vitamin D is added as a supplement to many foods, including milk and orange juice, compensating for the need for sun exposure.

In addition to its essential role in bone health, vitamin D is essential for general immunity against bacterial, viral, and fungal infections. Recent studies are also finding a link between insufficient vitamin D and cancer.

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5.4: Diseases, Disorders, and Injuries of the Integumentary System

Clinical Conditions of Integumentary System

The integumentary system is susceptible to a variety of diseases, disorders, and injuries. These range from annoying but relatively benign bacterial or fungal infections that are categorized as disorders, to skin cancer and severe burns, which can be fatal. In this section, you will learn several of the most common skin conditions.

Diseases

One of the most talked about diseases is skin cancer. Cancer is a broad term that describes diseases caused by abnormal cells in the body dividing uncontrollably. Most cancers are identified by the organ or tissue in which the cancer originates. One common form of cancer is skin cancer. The Skin Cancer Foundation reports that one in five Americans will experience some type of skin cancer in their lifetime. The degradation of the ozone layer in the atmosphere and the resulting increase in exposure to UV radiation has contributed to its rise. Overexposure to UV radiation damages DNA, which can lead to the formation of cancerous lesions. Although melanin offers some protection against DNA damage from the sun, often it is not enough. The fact that cancers can also occur on areas of the body that are normally not exposed to UV radiation suggests that there are additional factors that can lead to cancerous lesions.

In general, cancers result from an accumulation of DNA mutations. These mutations can result in cell populations that do not die when they should and uncontrolled cell proliferation that leads to tumors. Although many tumors are benign (harmless), some produce cells that can mobilize and establish tumors in other organs of the body; this process is referred to as metastasis. Cancers are characterized by their ability to metastasize.

Basal Cell Carcinoma

Basal cell carcinoma is a form of cancer that affects the mitotically active stem cells in the stratum basale of the epidermis. It is the most common of all cancers that occur in the United States and is frequently found on the head, neck, arms, and back, which are areas that are most susceptible to long-term sun exposure. Although UV rays are the main culprit, exposure to other agents, such as radiation and arsenic, can also lead to this type of cancer. Wounds on the skin due to open sores, tattoos, burns, etc. may be predisposing factors as well. Basal cell carcinomas start in the stratum basale and usually spread along this boundary. At some point, they begin to grow toward the surface and become an uneven patch, bump, growth, or scar on the skin surface (Figure 5.4.1). Like most cancers, basal cell carcinomas respond best to treatment when caught early. Treatment options include surgery, freezing (cryosurgery), and topical ointments (Mayo Clinic 2012).



Figure 5.4.1: Basal Cell Carcinoma Basal cell carcinoma can take several different forms. Similar to other forms of skin cancer, it is readily cured if caught early and treated. (CC BY 4.0; John Hendrix, MD via OpenStax).

Squamous Cell Carcinoma

Squamous cell carcinoma is a cancer that affects the keratinocytes of the stratum spinosum and presents as lesions commonly found on the scalp, ears, and hands (Figure 5.4.2). It is the second most common skin cancer. The American Cancer Society reports that two of 10 skin cancers are squamous cell carcinomas, and it is more aggressive than basal cell carcinoma. If not removed, these carcinomas can metastasize. Surgery and radiation are used to cure squamous cell carcinoma.



Figure 5.4.2: Squamous Cell Carcinoma Squamous cell carcinoma presents here as a lesion on an individual's nose. (CC BY 4.0; The National Cancer Institute via OpenStax).

Melanoma

A melanoma is a cancer characterized by the uncontrolled growth of melanocytes, the pigment-producing cells in the epidermis. Typically, a melanoma develops from a mole. It is the most fatal of all skin cancers, as it is highly metastatic and can be difficult to detect before it has spread to other organs. Melanomas usually appear as asymmetrical brown and black patches with uneven

borders and a raised surface (Figure 5.4.3). Treatment typically involves surgical excision and immunotherapy.



Figure 5.4.3: Melanomas typically present as large brown or black patches with uneven borders and a raised surface. (CC BY 4.0; The National Cancer Institute via OpenStax). Alternate text description of Figure 5.4.3.

Skin Disorders

Two common skin disorders are eczema and acne. Eczema is an inflammatory condition and occurs in individuals of all ages. Acne involves the clogging of pores, which can lead to infection and inflammation, and is often seen in adolescents. Other disorders, not discussed here, include seborrheic dermatitis (on the scalp), psoriasis, cold sores, impetigo, scabies, hives, and warts.

Eczema

Eczema is an allergic reaction that manifests as dry, itchy patches of skin that resemble rashes (Figure 5.4.4. It may be accompanied by swelling of the skin, flaking, and in severe cases, bleeding. Many who suffer from eczema have antibodies against dust mites in their blood, but the link between eczema and allergy to dust mites has not been proven. Symptoms are usually managed with moisturizers, corticosteroid creams, and immunosuppressants.



Figure 5.4.4: Eczema is a common skin disorder that presents as a red, flaky rash. (CC BY 4.0; via OpenStax). Alternate text description of Figure 5.4.4.

Acne

Acne is a skin disturbance that typically occurs on areas of the skin that are rich in sebaceous glands (face and back). It is most common along with the onset of puberty due to associated hormonal changes, but can also occur in infants and continue into adulthood. Hormones, such as androgens, stimulate the release of sebum. An overproduction and accumulation of sebum along

with keratin can block hair follicles. This plug is initially white. The sebum, when oxidized by exposure to air, turns black. Acne results from infection by acne-causing bacteria (*Propionibacterium* and *Staphylococcus*), which can lead to redness and potential scarring due to the natural wound healing process (Figure 5.4.5).

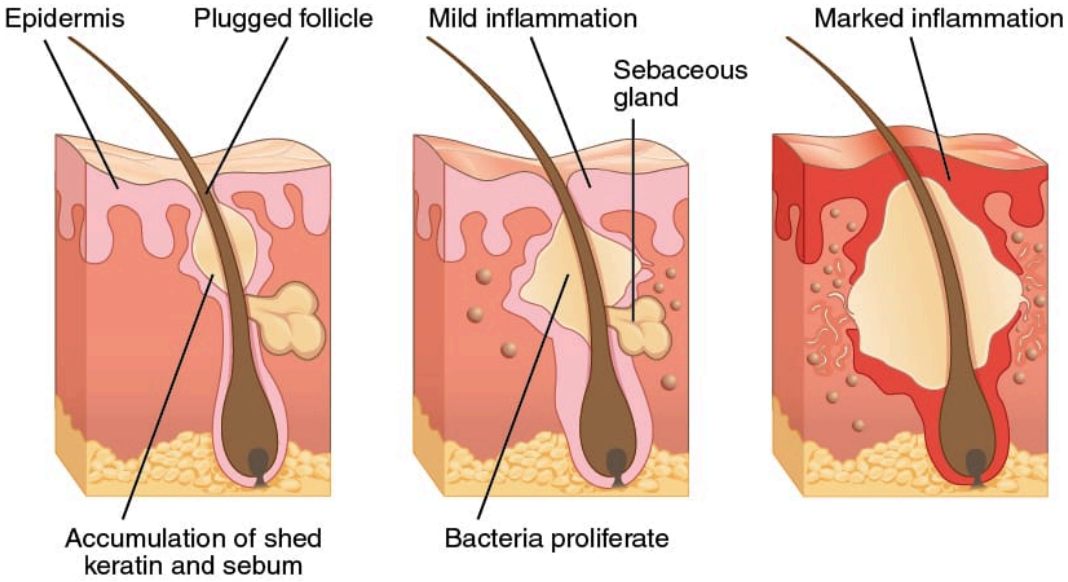


Figure 5.4.5: Acne is a result of over-productive sebaceous glands, which leads to formation of blackheads and inflammation of the skin. (CC BY 4.0; via OpenStax). Alternate text description of Figure 5.4.5.

Career Connection

Dermatologist

Have you ever had a rash that did not respond to over-the-counter creams, or a mole that you were concerned about? Dermatologists help patients with these types of problems and more, on a daily basis. Dermatologists are medical doctors who specialize in diagnosing and treating skin disorders. Like all medical doctors, dermatologists earn a medical degree and then complete several years of residency training. In addition, dermatologists may then participate in a dermatology fellowship or complete additional, specialized training in a dermatology practice. If practicing in the United States, dermatologists must pass the United States Medical Licensing Exam (USMLE), become licensed in their state of practice, and be certified by the American Board of Dermatology.

Most dermatologists work in a medical office or private-practice setting. They diagnose skin conditions and rashes, prescribe oral and topical medications to treat skin conditions, and may perform simple procedures, such as mole or wart removal. In addition, they may refer patients to an oncologist if skin cancer that has metastasized is suspected. Recently, cosmetic procedures have also become a prominent part of dermatology. Botox injections, laser treatments, and collagen and dermal filler injections are popular among patients, hoping to reduce the appearance of skin aging.

Dermatology is a competitive specialty in medicine. Limited openings in dermatology residency programs mean that many medical students compete for a few select spots. Dermatology is an appealing specialty to many prospective doctors, because unlike emergency room physicians or surgeons, dermatologists generally do not have to work excessive hours or be “on-call” weekends and holidays. Moreover, the popularity of cosmetic dermatology has made it a growing field with many lucrative opportunities. It is not unusual for dermatology clinics to market themselves exclusively as cosmetic dermatology centers, and for dermatologists to specialize exclusively in these procedures.

Consider visiting a dermatologist to talk about why they entered the field and what the field of dermatology is like. Visit this site for additional information.

Injuries

Because the skin is the part of our bodies that meets the world most directly, it is especially vulnerable to injury. Injuries include

burns and wounds, as well as scars and calluses. They can be caused by sharp objects, heat, or excessive pressure or friction to the skin.

Skin injuries set off a healing process that occurs in several overlapping stages. The first step to repairing damaged skin is the formation of a blood clot that helps stop the flow of blood and scabs over with time. Many different types of cells are involved in wound repair, especially if the surface area that needs repair is extensive. Before the basal stem cells of the stratum basale can recreate the epidermis, fibroblasts mobilize and divide rapidly to repair the damaged tissue by collagen deposition, forming granulation tissue. Blood capillaries follow the fibroblasts and help increase blood circulation and oxygen supply to the area. Immune cells, such as macrophages, roam the area and engulf any foreign matter to reduce the chance of infection.

Burns

A burn results when the skin is damaged by intense heat, radiation, electricity, or chemicals. The damage results in the death of skin cells, which can lead to a massive loss of fluid. Dehydration, electrolyte imbalance, and renal and circulatory failure follow, which can be fatal. Burn patients are treated with intravenous fluids to offset dehydration, as well as intravenous nutrients that enable the body to repair tissues and replace lost proteins. Another serious threat to the lives of burn patients is infection. Burned skin is extremely susceptible to bacteria and other pathogens, due to the loss of protection by intact layers of skin.

Burns are sometimes measured in terms of the size of the total surface area affected. This is referred to as the “rule of nines,” which associates specific anatomical areas with a percentage that is a factor of nine (Figure 5.4.6). Burns are also classified by the degree of their severity. A first-degree burn is a superficial burn that affects only the epidermis. Although the skin may be painful and swollen, these burns typically heal on their own within a few days. Mild sunburn fits into the category of a first-degree burn. A second-degree burn goes deeper and affects both the epidermis and a portion of the dermis. These burns result in swelling and a painful blistering of the skin. It is important to keep the burn site clean and sterile to prevent infection. If this is done, the burn will heal within several weeks. A third-degree burn fully extends into the epidermis and dermis, destroying the tissue and affecting the nerve endings and sensory function. These are serious burns that may appear white, red, or black; they require medical attention and will heal slowly without it. A fourth-degree burn is even more severe, affecting the underlying muscle and bone. Oddly, third and fourth-degree burns are usually not as painful because the nerve endings themselves are damaged. Full-thickness burns cannot be repaired by the body, because the local tissues used for repair are damaged and require excision (debridement), or amputation in severe cases, followed by grafting of the skin from an unaffected part of the body, or from skin grown in tissue culture for grafting purposes.

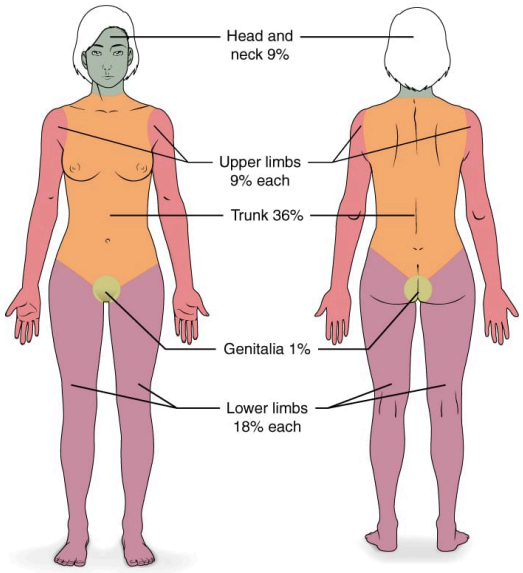


Figure 5.4.6: The size of a burn will guide decisions made about the need for specialized treatment. Specific parts of the body are associated with a percentage of body area. (CC BY 4.0; via OpenStax). Alternate text description of Figure 5.4.6.

Scars and Keloids

Most cuts or wounds, with the exception of ones that only scratch the surface (the epidermis), lead to scar formation. A scar is

collagen-rich skin formed after the process of wound healing that differs from normal skin. Scarring occurs in cases in which there is repair of skin damage, but the skin fails to regenerate the original skin structure. Fibroblasts generate scar tissue in the form of collagen, and the bulk of repair is due to the basket-weave pattern generated by collagen fibers and does not result in regeneration of the typical cellular structure of skin. Instead, the tissue is fibrous in nature and does not allow for the regeneration of accessory structures, such as hair follicles, sweat glands, or sebaceous glands.

Sometimes, there is an overproduction of scar tissue, because the process of collagen formation does not stop when the wound is healed; this results in the formation of a raised or hypertrophic scar called a keloid. In contrast, scars that result from acne and chickenpox have a sunken appearance and are called atrophic scars.

Scarring of skin after wound healing is a natural process and does not need to be treated further. Application of mineral oil and lotions may reduce the formation of scar tissue. However, modern cosmetic procedures, such as dermabrasion, laser treatments, and filler injections have been invented as remedies for severe scarring. All of these procedures try to reorganize the structure of the epidermis and underlying collagen tissue to make it look more natural.

Bedsores and Stretch Marks

Skin and its underlying tissue can be affected by excessive pressure. One example of this is called a bedsore. Bedsores, also called decubiti ulcers, are caused by constant, long-term, unrelieved pressure on certain body parts that are bony, reducing blood flow to the area and leading to necrosis (tissue death). Bedsores are most common in elderly patients who have debilitating conditions that cause them to be immobile. Most hospitals and long-term care facilities have the practice of turning the patients every few hours to prevent the incidence of bedsores. If left untreated by removal of necrotized tissue, bedsores can be fatal if they become infected.

The skin can also be affected by pressure associated with rapid growth. A stretch mark results when the dermis is stretched beyond its limits of elasticity, as the skin stretches to accommodate the excess pressure. Stretch marks usually accompany rapid weight gain during puberty and pregnancy. They initially have a reddish hue, but lighten over time. Other than for cosmetic reasons, treatment of stretch marks is not required. They occur most commonly over the hips and abdomen.

Calluses

When you wear shoes that do not fit well and are a constant source of abrasion on your toes, you tend to form a callus at the point of contact. This occurs because the basal stem cells in the stratum basale are triggered to divide more often to increase the thickness of the skin at the point of abrasion to protect the rest of the body from further damage. This is an example of a minor or local injury, and the skin manages to react and treat the problem independent of the rest of the body. Calluses can also form on your fingers if they are subject to constant mechanical stress, such as long periods of writing, playing string instruments, or video games. A corn is a specialized form of callus. Corns form from abrasions on the skin that result from an elliptical-type motion.

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5.5: Terms and Definitions

Key Terms

Select to view definitions

Acne
skin condition due to infected sebaceous glands

Albinism
genetic disorder that affects the skin, in which there is no melanin production

Apocrine sweat gland
type of sweat gland that is associated with hair follicles in the armpits and genital regions

Arrector pili
smooth muscle that is activated in response to external stimuli that pull on hair follicles and make the hair “stand up”

Basal cell
type of stem cell found in the stratum basale and in the hair matrix that continually undergoes cell division, producing the keratinocytes of the epidermis

Basal cell carcinoma
cancer that originates from basal cells in the epidermis of the skin

Bedsore
sore on the skin that develops when regions of the body start necrotizing due to constant pressure and lack of blood supply; also called decubitis ulcers

Callus
thickened area of skin that arises due to constant abrasion

Corn
type of callus that is named for its shape and the elliptical motion of the abrasive force

Cortex
in hair, the second or middle layer of keratinocytes originating from the hair matrix, as seen in a cross-section of the hair bulb

Cuticle
in hair, the outermost layer of keratinocytes originating from the hair matrix, as seen in a cross-section of the hair bulb

Dermal papilla
(plural = dermal papillae) extension of the papillary layer of the dermis that increases surface contact between the epidermis and dermis

Dermis
layer of skin between the epidermis and hypodermis, composed mainly of connective tissue and containing blood vessels, hair follicles, sweat glands, and other structures

Desmosome
structure that forms an impermeable junction between cells

Eccrine sweat gland
type of sweat gland that is common throughout the skin surface; it produces a hypotonic sweat for

thermoregulation

Eczema
skin condition due to an allergic reaction, which resembles a rash

Elastin fibers
fibers made of the protein elastin that increase the elasticity of the dermis

Eleiden
clear protein-bound lipid found in the stratum lucidum that is derived from keratohyalin and helps to prevent water loss

Epidermis
outermost tissue layer of the skin

Eponychium
nail fold that meets the proximal end of the nail body, also called the cuticle

External root sheath
outer layer of the hair follicle that is an extension of the epidermis, which encloses the hair root

First-degree burn
superficial burn that injures only the epidermis

Fourth-degree burn
burn in which full thickness of the skin and underlying muscle and bone is damaged

Hair
keratinous filament growing out of the epidermis

Hair bulb
structure at the base of the hair root that surrounds the dermal papilla

Hair follicle
cavity or sac from which hair originates

Hair matrix
layer of basal cells from which a strand of hair grows

Hair papilla
mass of connective tissue, blood capillaries, and nerve endings at the base of the hair follicle

Hair root
part of hair that is below the epidermis anchored to the follicle

Hair shaft
part of hair that is above the epidermis but is not anchored to the follicle

Hypodermis
connective tissue connecting the integument to the underlying bone and muscle

Hyponychium
thickened layer of stratum corneum that lies below the free edge of the nail

Integumentary system
skin and its accessory structures

Internal root sheath
innermost layer of keratinocytes in the hair follicle that surround the hair root up to the hair shaft

Keloid
type of scar that has layers raised above the skin surface

Keratin
type of structural protein that gives skin, hair, and nails its hard, water-resistant properties

Keratinocyte
cell that produces keratin and is the most predominant type of cell found in the epidermis

Keratohyalin
granulated protein found in the stratum granulosum

Langerhans cell
specialized dendritic cell found in the stratum spinosum that functions as a macrophage

Lunula
basal part of the nail body that consists of a crescent-shaped layer of thick epithelium

Medulla
in hair, the innermost layer of keratinocytes originating from the hair matrix

Meissner corpuscle
(also, tactile corpuscle) receptor in the skin that responds to light touch

Melanin
pigment that determines the color of hair and skin

Melanocyte
cell found in the stratum basale of the epidermis that produces the pigment melanin

Melanoma
type of skin cancer that originates from the melanocytes of the skin

Melanosome
intercellular vesicle that transfers melanin from melanocytes into keratinocytes of the epidermis

Merkel cell
receptor cell in the stratum basale of the epidermis that responds to the sense of touch

Metastasis
spread of cancer cells from a source to other parts of the body

Nail bed
layer of epidermis upon which the nail body forms

Nail body
main keratinous plate that forms the nail

Nail cuticle
fold of epithelium that extends over the nail bed, also called the eponychium

Nail fold
fold of epithelium at that extend over the sides of the nail body, holding it in place

Nail root
part of the nail that is lodged deep in the epidermis from which the nail grows

Pacinian corpuscle
(also, lamellated corpuscle) receptor in the skin that responds to vibration

Papillary layer
superficial layer of the dermis, made of loose, areolar connective tissue

Reticular layer
deeper layer of the dermis; it has a reticulated appearance due to the presence of abundant collagen and elastin

fibers

Rickets
disease in children caused by vitamin D deficiency, which leads to the weakening of bones

Scar
collagen-rich skin formed after the process of wound healing that is different from normal skin

Sebaceous gland
type of oil gland found in the dermis all over the body and helps to lubricate and waterproof the skin and hair by secreting sebum

Sebum
oily substance that is composed of a mixture of lipids that lubricates the skin and hair

Second-degree burn
partial-thickness burn that injures the epidermis and a portion of the dermis

Squamous cell carcinoma
type of skin cancer that originates from the stratum spinosum of the epidermis

Stratum basale
deepest layer of the epidermis, made of epidermal stem cells

Stratum corneum
most superficial layer of the epidermis

Stratum granulosum
layer of the epidermis superficial to the stratum spinosum

Stratum lucidum
layer of the epidermis between the stratum granulosum and stratum corneum, found only in thick skin covering the palms, soles of the feet, and digits

Stratum spinosum
layer of the epidermis superficial to the stratum basale, characterized by the presence of desmosomes

Stretch mark
mark formed on the skin due to a sudden growth spurt and expansion of the dermis beyond its elastic limits

Sudoriferous gland
sweat gland

Third-degree burn
burn that penetrates and destroys the full thickness of the skin (epidermis and dermis)

Vitamin D
compound that aids absorption of calcium and phosphates in the intestine to improve bone health

Vitiligo
skin condition in which melanocytes in certain areas lose the ability to produce melanin, possibly due an autoimmune reaction that leads to loss of color in patches

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5.6: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. The papillary layer of the dermis lies immediately deep to which specific layer of the epidermis?
   A. Stratum spinosum
   B. Stratum corneum
   C. Stratum granulosum
   D. Stratum basale

2. Langerhans cells, which participate in immune surveillance of the skin, are most commonly found in which epidermal layer?
   A. Stratum spinosum
   B. Stratum corneum
   C. Stratum granulosum
   D. Stratum basale

3. The papillary and reticular layers together make up the dermis. These layers are composed mainly of which type of tissue?
   A. Melanocytes
   B. Keratinocytes
   C. Connective tissue
   D. Adipose tissue

4. Collagen fibers in the dermis primarily provide which property to the skin?
   A. Elasticity
   B. Structural strength and support
   C. Pigmented color
   D. Ultraviolet radiation protection

5. Which of the following is not a major function of the hypodermis (subcutaneous layer)?
   A. Protecting underlying organs
   B. Helping to maintain body temperature via insulation
   C. Serving as a primary source of blood vessels that directly supply the epidermis
   D. Serving as a site for long-term energy storage in adipose cells

6. In response to sympathetic nervous system stimulation, which action of the arrector pili muscles is observed?
   A. They function as glands on the skin surface.
   B. They produce excessive sweating.
   C. They contract and produce “goose bumps.”
   D. They secrete sebum onto the skin surface.

7. The hair matrix, where hair growth occurs, contains which of the following?
   A. The entire hair follicle
   B. The hair shaft above the skin surface

C. The glassy membrane of the follicle wall
D. A layer of actively dividing basal cells

8. Eccrine (merocrine) sweat glands have which characteristic?
A. They open primarily into hair follicles.
B. They are widely distributed in the skin and produce a watery secretion important for thermoregulation.
C. They primarily produce sebum.
D. They act mainly as an oil-based moisturizer.

9. Which statement about sebaceous glands is correct?
A. They are a type of sweat gland.
B. They are typically associated with hair follicles and secrete sebum.
C. They normally function in response to light touch.
D. They release a watery solution of salt and metabolic waste.

10. Nails grow continuously from a specific region. Which of the following structures is farthest from the site of nail growth (the nail matrix in the nail root)?
A. Nail bed
B. Hyponychium
C. Nail root
D. Eponychium (cuticle)

11. In humans, exposure of the skin to ultraviolet light from sunlight is required for which physiological process?
A. Vitamin D synthesis
B. Arteriole constriction in the dermis
C. Folate production in the liver
D. Thermoregulation via sweating

12. One function of the integumentary system is protection. Which of the following does not directly contribute to the protective function of the skin?
A. Stratum lucidum in thick skin
B. Desmosomes connecting keratinocytes
C. Folic acid (folate) synthesis
D. Merkel (tactile) cells

13. A person cuts a finger with a sharp knife and notices bleeding. Which of the following skin layers must have been penetrated for bleeding to occur?
A. Stratum corneum only
B. Stratum basale only
C. Papillary layer of the dermis
D. Stratum granulosum only

14. While walking on a hot, dry beach, your skin does not desiccate like a dried fish. Which epidermal layer primarily prevents water loss from the body surface?
A. Stratum corneum
B. Stratum basale
C. Stratum spinosum
D. Stratum granulosum

15. If a cut becomes contaminated with bacteria, which epidermal-derived cell type plays the greatest role in initiating an immune response against the invading microbes?
A. Merkel cells
B. Keratinocytes
C. Langerhans (dendritic) cells
D. Melanocytes

16. Which of the following general statements about skin cancer is most accurate?
A. Skin cancers are easily treated in all cases and rarely a major health concern.

B. Skin cancers occur primarily because of poor hygiene.
C. The risk of some skin cancers can be reduced by limiting excessive exposure to ultraviolet radiation from the sun or tanning beds.
D. Skin cancers affect only the epidermal layers and never spread.

17. Pressure ulcers (bedsores) most directly result from which of the following conditions?
A. Frequent application of topical moisturizers
B. Repeated deep tissue massage
C. Unrelieved pressure that impairs blood flow to the skin and underlying tissues
D. Excessively dry skin alone

18. A person presents with a painful sunburn that has developed small, clear blisters. Which layers of the integument have most likely been damaged?
A. Epidermis only
B. Hypodermis only
C. Epidermis and hypodermis
D. Epidermis and dermis

19. After a skin injury that causes bleeding, the body initiates a wound-healing response. A blood clot forms first to stop bleeding. Which event typically occurs next in the sequence of wound healing?
A. Increased production of melanin by melanocytes
B. Migration and proliferation of fibroblasts and other cells to form granulation tissue and new extracellular matrix
C. Increased number of Pacinian corpuscles around the wound
D. Increased activity limited to the stratum lucidum

20. Squamous cell carcinoma is the second most common type of skin cancer and can metastasize if left untreated. This cancer most often arises from which specific epidermal cells?
A. Basal cells of the stratum basale
B. Melanocytes of the stratum basale
C. Keratinocytes of the stratum spinosum
D. Langerhans cells of the stratum corneum

21. Which component of the skin is primarily responsible for sensing light touch and texture?
A. Pacinian (lamellated) corpuscles in the hypodermis
B. Merkel cells in the stratum basale associated with sensory nerve endings
C. Langerhans cells in the stratum spinosum
D. Melanocytes in the stratum basale

22. Which of the following best explains why superficial cuts that damage only the epidermis typically do not leave scars, whereas deeper dermal injuries do?
A. The epidermis has no cells capable of division.
B. The epidermis heals by regeneration of keratinocytes without significant collagen deposition, whereas dermal repair involves fibroblasts laying down collagen, producing scar tissue.
C. The dermis contains fewer blood vessels than the epidermis.
D. The epidermis contains more melanocytes that prevent scar formation.

23. A patient has a burn that destroys the full thickness of the epidermis and part of the dermis. Which of the following is most likely impaired as a result?
A. Keratinocyte division in the stratum basale
B. Sweat secretion from eccrine glands in the region
C. Adipose storage in the hypodermis
D. Production of melanin by melanocytes in adjacent, unburned areas

24. Which factor most directly determines differences in normal skin color between individuals?
A. The number of melanocytes per unit area of skin
B. The type and amount of melanin produced and transferred to keratinocytes
C. The total thickness of the stratum corneum
D. The presence of Merkel cells in the epidermis

25. Which of the following is most characteristic of a superficial (first-degree) burn?

A. Damage to the entire dermis and epidermis
B. Blister formation and mottled appearance
C. Erythema and pain limited to the epidermis
D. Painless, dry, white or charred skin

26. A patient has painful blisters and moist, red skin after spilling boiling water on the forearm. Which burn classification best fits this description?

A. Superficial (first-degree) burn

B. Superficial partial-thickness (second-degree) burn

C. Deep partial-thickness (second-degree) burn

D. Full-thickness (third-degree) burn

27. Which feature is typical of a full-thickness (third-degree) burn?

A. Severe pain throughout the injured area
B. Complete destruction of epidermis and dermis, often with absent sensation
C. Involvement of only the stratum corneum
D. Spontaneous healing within 3–5 days without scarring

28. Which of the following is the most life-threatening immediate complication of extensive full-thickness burns?

A. Bacterial infection within 24 hours
B. Loss of body hair
C. Massive fluid loss and hypovolemic shock
D. Hyperthermia due to increased sweating

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5.7: Applied Thinking Self-Check

Challenge Yourself

- Critical thinking is essential in a time of endless information and AI, helping you move from passive memorizing to actively making sense of what you learn.
- Use the questions below as a self-assessment tool to deepen your understanding of the integumentary system (skin, hair, nails, and glands) and to practice critical thinking. They are designed to help you explain, connect, and apply ideas, not just memorize facts.
- First, answer each question without looking at your notes or textbook. Then write your answers in complete sentences and short paragraphs, aiming for about 5–10 sentences per question unless your instructor gives a different guideline.
- Each answer should start with a clear main idea that directly answers the question in one or two sentences. Follow this with explanations that show why and how, rather than just listing terms. Add examples when useful, such as specific skin layers, glands, or real-life situations.
- Apply correct anatomy and physiology terms from the integumentary chapter, such as epidermis, dermis, keratinocyte, melanocyte, vasodilation, barrier, and thermoregulation. If you use a term you are unsure about, briefly define it in your own words.
- After writing, check your answers against your notes, textbook, or other reliable resources. Revise or expand your answers if needed, and mark any questions that still feel uncertain. Use those marks to plan what to review so that these questions help you build a deeper, more flexible understanding of how integument structure supports its functions.

1. A hiker develops a painful blister on the heel. Later, after repeated friction in the same spot, a callus forms there. Describe how a keratinocyte changes (differentiates) as it moves from the stratum basale to the stratum corneum.
    - Mention at least two layers by name and describe what happens to the cells in each layer.
    - Explain how keratins, epidermal lipids, and desmosomes/corneodesmosomes help form the skin's barrier.
    - Connect each of these structures to one barrier function (for example, preventing water loss, resisting mechanical stress, blocking pathogens).
2. A fair-skinned student moves from a northern country to a tropical region. Within a few weeks, the student's skin becomes noticeably darker (tans), even though they use sunscreen every day.
    - Explain how melanocytes respond to increased UV exposure. Include changes in melanosome production, melanin type (especially eumelanin), and transfer of melanosomes to keratinocytes.
    - Explain how UV-triggered signaling (for example, DNA damage and signals from keratinocytes) can increase melanocyte activity.
    - Evaluate the trade-offs of having more eumelanin in the skin:
        - One benefit for UV protection
        - One effect on vitamin D synthesis
        - One effect on skin cancer risk
3. Comparing eccrine and apocrine sweat glands. Answer all parts in complete sentences.
    - Describe two similarities between eccrine and apocrine sweat glands. Think about basic structure and the fact that both are exocrine glands.
    - Describe at least three differences between eccrine and apocrine sweat glands.
        - Where they are found on the body
        - What they secrete (type of fluid)
        - When they become active (age, type of stimulus)
        - What their main functions are (for example, thermoregulation vs scent/communication)
4. Why do teenagers often experience acne?
5. Why do people sweat excessively during hot exercise? Imagine a person running outside on a hot day.
    - Explain why eccrine sweat glands become very active during exercise in the heat.
        - Include the role of body temperature, sympathetic nervous system, and thermoregulation.
        - Describe how sweating and increased skin blood flow help the body lose heat.

        - Be sure to include evaporation and convection in your answer.
6. Two patients come to clinic:
    - Patient A has very sweaty palms that make paper wet during exams.
    - Patient B produces only a small amount of sweat but has strong armpit (axillary) odor that started at puberty.
        - For each patient (A and B), identify which sweat gland type (eccrine or apocrine) is most important in their symptoms.
        - Justify your answers by discussing each of the following points:
            - Typical location of each gland type (for example, palms/soles vs axilla/groin)
            - Type of innervation (sympathetic cholinergic vs adrenergic)
            - Where the duct opens (onto the skin surface vs into a hair follicle)
            - Main composition of the secretion (watery vs more protein/lipid-rich, leading to odor)
7. Changes in the skin can give early clues about problems in other body systems. Describe a specific example where a change in the integumentary system (for example, jaundice, cyanosis, clubbing of nails, hair loss) reflects disease in another organ system (for example, liver, heart, lungs, endocrine).
    - Explain the underlying physiological reason for this change in the skin, hair, or nails.
    - Discuss why it is important for healthcare professionals to recognize and interpret these integumentary signs during physical examination.
8. As people age, both the structure and function of the skin change. Describe at least three age-related structural changes in the integumentary system (for example, thinner epidermis, reduced collagen and elastic fibers, fewer melanocytes, decreased gland activity).
    - Explain how each of these changes affects skin function (for example, barrier strength, temperature regulation, sensitivity, wound healing).
    - Suggest one lifestyle factor (such as sun exposure, smoking, nutrition, or hydration) that can speed up or slow down these changes, and explain how it acts at the tissue level.
9. Why does cutting your hair or clipping your nails cause no physical pain, whereas pulling a hair out by the root hurts intensely?

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5.8: Alternate Text Descriptions

Figure 5.1.1: Layers of Skin

This image is a cross-sectional diagram of the skin showing the three major layers: the epidermis, dermis, and hypodermis, along with associated structures.

Epidermis (outer layer)

- The epidermis forms the thin outer surface of the skin.
- Hair shafts extend upward through the epidermis and project above the skin surface.
- The pore of a sweat gland duct opens onto the skin surface, providing an exit for sweat produced deeper in the skin.

Dermis (middle layer)

- The dermis is located beneath the epidermis and contains most of the skin's glands, nerves, blood vessels, and hair structures.
- Hair follicles extend through the dermis and surround the roots of hairs.
- Sebaceous (oil) glands are attached to hair follicles and release oil into the follicle.
- Arrector pili muscles connect to hair follicles and extend toward the upper dermis.
- Eccrine sweat glands are coiled glands located in the deeper dermis; their ducts travel upward to the skin surface.
- Sensory nerve fibers branch throughout the dermis.
- Blood vessels are present throughout the dermis and connect with deeper vascular networks.

Hypodermis (deepest layer)

- The hypodermis lies below the dermis and contains large amounts of adipose (fat) tissue.
- Adipose tissue forms clusters throughout this layer.
- Pacinian corpuscles, which detect deep pressure and vibration, are located near the boundary between the dermis and hypodermis.
- The cutaneous vascular plexus, a network of larger blood vessels, is located within the hypodermis.
- The lower portions of hair follicles, blood vessels, nerves, and sweat glands extend into this layer.

The diagram illustrates how the epidermis forms the protective outer covering, while the dermis and hypodermis contain the follicles, glands, nerves, blood vessels, and adipose tissue that support skin function.

Figure 5.1.2: Histology Slides of Skin

This image contains two side-by-side histology images, labeled (a) and (b). Both images show a tissue surface layer above underlying connective tissue. The purpose of the figure is to compare the thickness and contour of the upper tissue layer in the two samples.

In image (a), the upper tissue layer is thicker and darker than in the second image. It forms a continuous surface with several downward projections extending into the lighter tissue below. Beneath this upper layer is a broader region of lighter, fibrous-looking connective tissue.

In image (b), the upper tissue layer is thinner and less prominent. The boundary between the surface layer and the underlying connective tissue appears flatter and more irregular. The connective tissue below remains visible and occupies most of the image.

Figure 5.1.3: Histology of thick skin

This image illustrates histological microscopy image stained pink and purple, showing a cross-section of skin and underlying tissue. At the top is the epidermis, appearing as a thin, dark pink, continuous layer. Beneath it lies the dermis, which is much thicker and lighter in color, containing irregular connective tissue with visible collagen fibers and small blood vessel spaces. The lower portion of the image shows a dense, darker pink band of skeletal muscle fibers arranged in parallel lines. In the bottom left corner, there is a smaller inset image that shows the same tissue section at a lower magnification, highlighting the relationship between the skin layers and the underlying muscle.

Figure 5.1.4: Layers of the Epidermis

This image is a microscopic diagram of thick skin showing the layers of the epidermis and selected cell types and structures.

Epidermis (from superficial to deep):

- Stratum corneum: The outermost layer, composed of dead cells filled with keratin that form a protective barrier.
- Stratum lucidum: A thin, translucent layer found only in thick skin.
- Stratum granulosum: Contains cells with lamellar granules, which contribute to the skin's waterproof barrier.
- Stratum spinosum: Contains numerous keratinocytes, the cells responsible for producing keratin.
- Stratum basale: The deepest layer of the epidermis. This layer contains melanocytes, which produce melanin pigment, and Merkel cells, which are associated with touch sensation. A sensory neuron extends upward from the dermis and makes contact with a Merkel cell.

Dermis:

- Located beneath the epidermis and shown as the pink connective tissue layer at the bottom of the figure.
- The cell bodies of the sensory neurons are not shown, but sensory nerve fibers extend from the dermis to the Merkel cells in the stratum basale.

The diagram emphasizes that the melanocyte and Merkel cell are located within the **stratum basale of the epidermis**, while the sensory neuron extends upward from the dermis to contact the Merkel cell.

Figure 5.1.5: Cells of the Epidermis

This image shows a high-magnification electron micrograph of the epidermis and underlying dermis, with labeled layers of the skin and associated structures.

The image is organized as a vertical cross-section of skin. The epidermis is located at the top, and the dermis is located below. The labels in the image include epidermis, dermis, stratum corneum, stratum granulosum, stratum spinosum, stratum basale (germinativum), capillary, and remnants of a cross-sectioned shed hair and its follicle.

In the epidermis, the outermost labeled layer is the stratum corneum. It is composed of flattened, tightly packed cells arranged in layers and appears as a dense surface layer. Its function is to provide a protective barrier, prevent water loss, and protect against environmental damage.

Below the stratum corneum is the stratum granulosum. This layer contains cells with visible internal structures associated with keratin production. Its function is to support keratin formation and waterproofing, and its cells begin to transition into the flattened protective cells of the outer layer.

Below the stratum granulosum is the stratum spinosum. This is a thicker layer composed of multiple rows of cells. The cells are more irregular in shape and closely connected. Its function is to provide strength and flexibility to the epidermis, and its cells are actively involved in producing structural proteins.

The deepest labeled epidermal layer is the stratum basale (germinativum). It is composed of a single layer of cells attached to the underlying tissue. Its function is cell division and regeneration of the epidermis. New cells are produced here and move upward as they mature.

In the dermis, the labeled structures include a capillary and remnants of a cross-sectioned shed hair and its follicle. The dermis is located beneath the epidermis and contains connective tissue with embedded structures. Its functions are to provide nutritional support to the epidermis through blood supply, contain structures that support skin function such as hair follicles, and contribute to strength, elasticity, and repair.

The keratinocytes in the stratum spinosum begin the synthesis of keratin and release a water-repelling glycolipid that helps prevent water loss from the body, making the skin relatively waterproof. As new keratinocytes are produced atop the stratum basale, the keratinocytes of the stratum spinosum are pushed into the stratum granulosum.

Figure 5.1.6: Layers of the Dermis

This image shows a histological section of human skin, focusing on the dermis, which is divided into two layers:

Papillary Layer

- Located just beneath the epidermis.
- Composed of loose connective tissue with fine collagen fibers and capillaries.
- Supports the epidermis and aids in nutrient exchange and sensory function.

Reticular Layer

- Found below the papillary layer.
- Made of dense connective tissue with thicker collagen fibers.
- Provides structural strength and elasticity.
- Contains sweat glands, hair follicles, and other deep dermal structures.

Figure 5.1.7: Skin Pigmentation

This image shows a side-by-side cellular comparison of dark and light skin, divided into two labeled sections:

- Left: "Dark"
- Right: "Light"

Skin Layers (Top to Bottom):

- Surface – Outermost skin layer
- Upper Keratinocytes – Contain melanin
- Melanosomes – Pigment organelles within keratinocytes
- Basal Keratinocytes – Base layer skin cells
- Melanocytes – Pigment-producing cells

Key Differences:

- Dark Skin has more melanin in keratinocytes and melanosomes. Melanocytes are more active.
- Light Skin has less melanin and fewer melanosomes. Melanocytes produce less pigment.

Figure 5.1.8: Moles

This image contains five close-up photographs of skin lesions displayed together for comparison. Each photo shows a small area of human skin with a distinct raised or pigmented spot.

- The top row shows three lesions that are generally flat to slightly raised and dark brown in color. Their shapes vary from round to slightly irregular, and their borders range from smooth to uneven. The surrounding skin appears normal in texture and color.
- The bottom left image shows a larger, dark lesion that is clearly raised above the skin surface. It appears dome-shaped with

a rough, uneven texture and a shiny surface.

- The bottom right image shows a raised lesion that is lighter in color, pink to flesh-toned, with a smooth, glossy appearance. Fine hairs are visible growing from the surrounding skin.

Figure 5.2.1: Hair Follicle

This image shows a cross-sectional diagram of a hair follicle embedded in the skin, including the structure of the hair and associated glands and tissues.

The diagram is organized as a vertical section of skin with the skin surface at the top and deeper layers extending downward. A hair follicle runs from the surface into the deeper tissue. The labels in the image include the hair shaft, cuticle, cortex, medulla, hair follicle, inner root sheath, outer root sheath, hair bulb, hair matrix, hair papilla, sebaceous gland, and arrector pili muscle.

At the top of the image, the hair shaft projects outward from the skin surface. An inset identifies three internal layers of the hair shaft. The labels for these layers are cuticle, cortex, and medulla. The cuticle is the outermost layer, the cortex is the middle layer, and the medulla is the innermost region. The hair shaft provides protection and insulation, and this layered structure contributes to the strength and flexibility of the hair.

Below the skin surface, the hair extends downward into the hair follicle, which is a tubular structure that surrounds and supports the hair root. The follicle anchors the hair in the skin and supports its growth.

Surrounding the hair within the follicle are two labeled sheath layers: the inner root sheath and the outer root sheath. These sheaths stabilize the growing hair and guide its upward movement toward the surface.

At the base of the follicle is an enlarged region labeled the hair bulb. Within the bulb is the hair matrix, which is composed of actively dividing cells. The hair matrix produces new cells that form the hair, and it is the primary site of hair growth.

Also at the base of the bulb is the hair papilla, which contains small blood vessels. The hair papilla supplies nutrients and oxygen to the growing hair cells and helps regulate hair growth activity.

Attached to the side of the hair follicle is the sebaceous gland. A short duct connects this gland to the follicle. The sebaceous gland produces sebum, an oily substance that lubricates and protects the hair and surrounding skin.

A band of muscle labeled the arrector pili muscle attaches to the hair follicle and extends toward the surrounding tissue. When this muscle contracts, it pulls the hair upright. This action contributes to goosebumps and helps move sebum along the hair shaft.

Figure 5.2.2: Histological Image of Skin

This image is a color-stained histological image of skin viewed under a microscope. The image is predominantly pink and purple, indicating a standard tissue stain used to highlight cells and connective tissue. At the center of the image is a hair follicle, visible as an elongated, tube-like structure running diagonally through the dermis. The follicle is surrounded by layers of cells that are darker purple, indicating densely packed epithelial tissue involved in hair growth. Around the hair follicle are sebaceous glands, which appear as clusters of pale, rounded cells attached to the follicle. These glands produce oil that lubricates the hair and skin. The surrounding area contains connective tissue with wavy collagen fibers, providing structural support. Toward the edges of the image, lighter circular spaces indicate adipose (fat) tissue, typical of the deeper dermal or subcutaneous layers. Overall, the image demonstrates the organization of skin structures beneath the surface, highlighting the relationship between the hair follicle, glands, connective tissue, and fat.

Figure 5.2.3: Structure of a Fingernail

This image is a structure of a fingernail, shown in external and cross-sectional views. The left panel shows the nail from the surface. The nail plate covers most of the top of the fingertip. The free edge is the white distal portion that extends beyond the fingertip. The lateral nail folds are the skin ridges along the sides of the nail plate. At the base of the nail is the proximal nail fold, which overlaps and protects the emerging nail. Just beneath it is the eponychium, or cuticle, a thin band of epidermal tissue

that extends onto the nail plate and forms a protective seal. The lunula is the pale, crescent-shaped region near the base of the nail. The nail plate protects the fingertip, while the lateral and proximal nail folds guide and stabilize nail growth. The eponychium helps prevent the entry of microorganisms, and the lunula marks the visible portion of the active nail-growth region.

The right panel shows a cross section of the nail and fingertip. The nail body is the visible portion of the nail plate extending across the top of the fingertip. Beneath the proximal nail fold is the nail root, the embedded portion where nail growth begins. The proximal nail fold covers the root, and the eponychium extends onto the surface of the nail to form a seal at the base. The lunula appears near the base of the nail body and corresponds to the visible portion of the nail matrix. At the distal end of the finger, the hyponychium lies beneath the free edge of the nail and forms a protective barrier. Beneath the nail are the epidermis and dermis, which support and nourish the overlying structures. Deep to these tissues is the phalanx, the bone of the fingertip, which provides structural support. The nail root produces the nail, the nail body protects the fingertip and assists with fine manipulation, the hyponychium seals the area beneath the nail, and the phalanx forms the rigid framework of the finger.

Figure 5.2.4: Human Skin

This image is a cross-sectional anatomical diagram of human skin, showing multiple layers and internal structures.

Labeled Components:

- Skin Surface – Outermost visible layer
- Pores – Openings for sweat and oil release
- Eccrine Sweat Gland – Deep coiled gland that regulates body temperature

Additional Visible Structures (Unlabeled):

- Hair Follicles – Tubes housing hair roots
- Blood Vessels – Arteries and veins supplying nutrients
- Nerves – Sensory pathways for touch, temperature, and pain
- Other Glands – Likely sebaceous glands secreting oil near hair follicles

Figure 5.3.1: Meissner corpuscle

Microscopic image of skin tissue showing a thick, dark-stained epidermis overlying a lighter pink dermis. The epidermis has a wavy appearance with downward projections extending into the connective tissue below. Within a dermal papilla near the junction of the epidermis and dermis, a large black arrow points to an oval, lightly stained structure composed of layered cells. This structure is a Meissner corpuscle, a touch receptor located in the papillary layer of the dermis. The surrounding dermis consists of fibrous connective tissue with scattered cell nuclei. The image highlights the location of a Meissner corpuscle just beneath the epidermis.

Figure 5.3.2: Thermoregulation

This image is divided into three labeled panels that explain Thermoregulation, or how the body conserves or releases heat.

- Left panel (a): A person is outdoors in a cold, snowy environment while engaging in a winter sport. This panel represents cold conditions where the body works to conserve heat.
- Middle panel (b): This figure explains how blood flow near the skin surface affects body temperature regulation. The left side of the diagram shows a condition in which heat is retained by the body. In this condition, blood circulation avoids the surface of the skin to retain heat. The deeper position of blood flow reduces heat transfer at the skin surface. The right side of the diagram shows a condition in which heat is lost through radiation and convection. In this condition, blood circulates to the surface of the skin to dispel heat. Arrows rising above the skin surface indicate heat loss to the surrounding environment.
- Right panel (c): A person is exercising outdoors in a warm, green environment. This panel represents warm conditions where the body needs to release excess heat. Above the skin in the diagram are arrows rising upward, representing heat leaving the body through radiation and convection. In this case, blood vessels near the skin surface widen, allowing more blood to flow close to the skin to release heat. Labels indicate heat loss at the skin surface and increased circulation to help cool the body.

Figure 5.4.3: Melanoma

This image contains two side-by-side close-up images of pigmented skin lesions. In the left image, the lesion is dark brown with an irregular, uneven outline and multiple rounded projections extending from the main area. The pigmentation varies across the lesion, with darker and lighter brown regions. In the right image, the lesion is darker overall and appears nearly black. It also has an irregular outline with asymmetry and an uneven border. The surrounding skin in both images is lighter in color, which makes the lesions stand out clearly.

Doctors often give their patients the following ABCDE mnemonic to help with the diagnosis of early-stage melanoma. If you observe a mole on your body displaying these signs, consult a doctor.

- Asymmetry – the two sides are not symmetrical
- Borders – the edges are irregular in shape
- Color – the color is varied shades of brown or black
- Diameter – it is larger than 6 mm (0.24 in)
- Evolving – its shape has changed

Some specialists cite the following additional signs for the most serious form, nodular melanoma:

- Elevated – it is raised on the skin surface
- Firm – it feels hard to the touch
- Growing – it is getting larger

Figure 5.4.4: Eczema

This image contains two side-by-side clinical images for comparison. The left image shows both forearms with a widespread pink to red rash. The affected skin appears diffuse and patchy, extending over a broad area rather than appearing as isolated spots. The right image shows part of a leg with multiple small, separate raised red bumps clustered in several groups. These lesions are more discrete and localized than the rash in the left image. Some appear darker or more inflamed than others.

Figure 5.4.5: Acne

This image is a three-panel medical diagram illustrating changes within the skin around a hair follicle as inflammation increases.

- Left panel: The skin is shown in cross-section with labeled layers. The epidermis forms the outer surface. A hair follicle extends downward into the skin and is labeled as plugged. At the base of the follicle, there is an accumulation of shed keratin and sebum, shown as material filling the follicle opening. The surrounding tissue appears relatively normal, with no visible inflammation.
- Middle panel: This panel shows mild inflammation. The sebaceous gland, which produces oil, is labeled next to the hair follicle. The follicle remains blocked, and bacteria are shown proliferating within the plugged area. The surrounding skin appears slightly irritated, indicating an early inflammatory response.
- Right panel:This panel illustrates marked inflammation. The area around the hair follicle is enlarged and filled with inflammatory material. The surrounding tissue is shown as more intensely affected, indicating a stronger immune response. The follicle remains blocked, and the inflammation extends into the nearby skin layers

Figure 5.4.6: Calculating the Size of a Burn

This image is a medical reference diagram used to illustrate the rule of nines, a method for estimating the percentage of total body surface area associated with different regions of the body. Two full-body outlines are shown side by side: a front view on the left and a back view on the right. Each major body region is labeled with a percentage:

- The head and neck together account for 9 percent of total body surface area.
- Each upper limb (arm) accounts for 9 percent, shown on both the front and back views.
- The trunk (chest, abdomen, and back combined) accounts for 36 percent, covering the largest central portion of the body.

- The genital area accounts for 1 percent, indicated at the lower central region of the body.
- Each lower limb (leg) accounts for 18 percent, shown extending from the hips to the feet on both views.

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6: BONE TISSUE AND SKELETAL SYSTEM INTRODUCTION

Chapter Overview

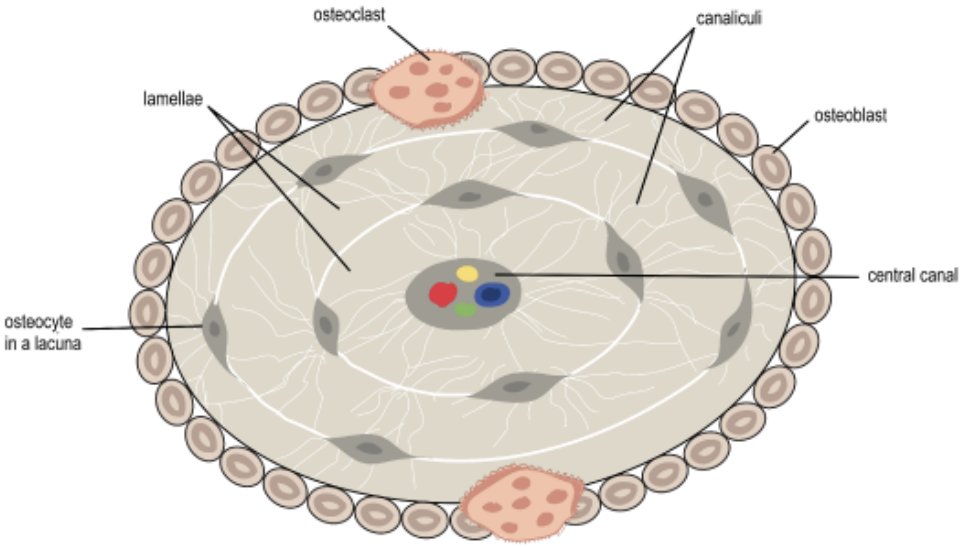


Figure 6.1: Cross-sectional diagram of an osteon (Haversian system) in compact bone, showing concentric lamellae surrounding a central canal, with osteocytes in lacunae connected by canaliculi and bone-forming osteoblasts and bone-resorbing osteoclasts on the surface. (CC BY 4.0; Danial Donnelly via Bone Structure). Alternative text description of the Figure 6.1.

Understanding the intricate structure and multifaceted functions of skeletal tissue provides a foundation for studying how the body maintains stability and mobility. This knowledge is essential for exploring how the skeletal system interacts with other systems to support overall health and function. As you delve into this chapter, consider how skeletal tissue not only shapes the body but also plays a dynamic role in our everyday life.

Major Functions of Bones and the Musculoskeletal System

The major functions of the bones are body support, facilitation of movement, protection of internal organs, storage of minerals and fat, and hematopoiesis. Together, the muscular system and skeletal system are known as the musculoskeletal system.

Classification of Bones by Shape

Bones can be classified according to their shapes. Long bones, such as the femur, are longer than they are wide. Short bones, such as the carpals, are approximately equal in length, width, and thickness. Flat bones are thin, but are often curved, such as the ribs. Irregular bones such as those of the face have no characteristic shape. Sesamoid bones, such as the patellae, are small and round, and are located in tendons.

Gross Structure of Long and Flat Bones

A hollow medullary cavity filled with yellow marrow runs the length of the diaphysis of a long bone. The walls of the diaphysis are compact bone. The epiphyses, which are wider sections at each end of a long bone, are filled with spongy bone and red marrow. The epiphyseal plate, a layer of hyaline cartilage, is replaced by osseous tissue as the organ grows in length. The medullary cavity has a delicate membranous lining called the endosteum. The outer surface of bone, except in regions covered with articular cartilage, is covered with a fibrous membrane called the periosteum. Flat bones consist of two layers of compact bone surrounding a layer of spongy bone.

Bone Markings: Articulations, Projections, and Holes

Bone markings depend on the function and location of bones. Articulations are places where two bones meet. Projections stick out from the surface of the bone and provide attachment points for tendons and ligaments. Holes are openings or depressions in the bones.

Bone Matrix and Bone Cells

Bone matrix consists of collagen fibers and organic ground substance, primarily hydroxyapatite formed from calcium salts. Osteogenic cells develop into osteoblasts. Osteoblasts are cells that make new bone. They become osteocytes, the cells of mature bone, when they get trapped in the matrix. Osteoclasts engage in bone resorption.

Compact Bone, Spongy Bone, and Bone Vascularization

Compact bone is dense and composed of osteons, while spongy bone is less dense and made up of trabeculae. Blood vessels and nerves enter the bone through the nutrient foramina to nourish and innervate bones.

Ossification: Intramembranous and Endochondral Bone Formation

All bone formation is a replacement process. Embryos develop a cartilaginous skeleton and various membranes. During development, these are replaced by bone during the ossification process. In intramembranous ossification, bone develops directly from sheets of mesenchymal connective tissue. In endochondral ossification, bone develops by replacing hyaline cartilage.

Bone Growth, Modeling, and Remodeling

Activity in the epiphyseal plate enables bones to grow in length. Modeling allows bones to grow in diameter. Remodeling occurs as bone is resorbed and replaced by new bone.

Osteogenesis Imperfecta: A Disorder of Bone Formation

Osteogenesis imperfecta is a genetic disease in which collagen production is altered, resulting in fragile, brittle bones.

Fracture Types and Methods of Bone Repair

Fractured bones may be repaired by closed reduction or open reduction. Fractures are classified by their complexity, location, and other features. Common types of fractures are transverse, oblique, spiral, comminuted, impacted, greenstick, open (or compound), and closed (or simple). Healing of fractures begins with the formation of a hematoma, followed by internal and external calli. Osteoclasts resorb dead bone, while osteoblasts create new bone that replaces the cartilage in the calli. The calli eventually unite, remodeling occurs, and healing is complete.

Nutritional and Hormonal Regulation of Bone Health

Mechanical stress stimulates the deposition of mineral salts and collagen fibers within bones. Calcium, the predominant mineral in bone, cannot be absorbed from the small intestine if vitamin D is lacking. Vitamin K supports bone mineralization and may have a synergistic role with vitamin D. Magnesium and fluoride, as structural elements, play a supporting role in bone health. Omega-3 fatty acids reduce inflammation and may promote production of new osseous tissue. Growth hormone increases the length of long bones, enhances mineralization, and improves bone density. Thyroxine stimulates bone growth and promotes the synthesis of bone matrix. The sex hormones (estrogen and testosterone) promote osteoblastic activity and the production of bone matrix, are responsible for the adolescent growth spurt, and promote closure of the epiphyseal plates. Osteoporosis is a disease characterized by decreased bone mass that is common in aging adults.

Calcium-Regulating Hormones and Their Effects on Bone

Calcitriol stimulates the digestive tract to absorb calcium and phosphate. Parathyroid hormone (PTH) stimulates osteoclast proliferation and resorption of bone by osteoclasts. Vitamin D plays a synergistic role with PTH in stimulating the osteoclasts. Additional functions of PTH include promoting reabsorption of calcium by kidney tubules and indirectly increasing calcium absorption from the small intestine. Calcitonin inhibits osteoclast activity and stimulates calcium uptake by bones.

Calcium Homeostasis and Its Systemic Effects

Calcium homeostasis, i.e., maintaining a blood calcium level of about 10 mg/dL, is critical for normal body functions. Hypocalcemia can result in problems with blood coagulation, muscle contraction, nerve functioning, and bone strength. Hypercalcemia can result in lethargy, sluggish reflexes, constipation and loss of appetite, confusion, and coma. Calcium homeostasis is controlled by PTH, vitamin D, and calcitonin and the interactions of the skeletal, endocrine, digestive, and urinary systems.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own.

By the end of this chapter, students should be able to:

- Describe the major functions of the skeletal system (support, protection, movement, mineral and triglyceride storage, blood cell formation, hormone production).
- Differentiate between the axial and appendicular skeleton and list major bones in each.
- Classify bones by shape and give examples; identify major structural features of a long bone and distinguish compact from spongy bone (including red vs. yellow marrow).
- Use correct anatomical terminology to name common bone markings and relate them to their functions.
- Compare and contrast bone cells (osteogenic cells, osteoblasts, osteocytes, osteoclasts) and describe the composition of bone matrix (organic vs. inorganic) and how it contributes to strength and flexibility.
- Explain the organization of compact bone into osteons and the structure of spongy bone with trabeculae and marrow spaces.
- Distinguish between intramembranous and endochondral ossification and describe how long bones grow in length and thickness, including the role of the epiphyseal plate.
- Describe bone remodeling (deposition and resorption), the stages of fracture repair, and the influence of mechanical stress and disuse on bone (Wolff's law).
- Discuss the roles of key hormones (PTH, calcitonin, sex hormones, growth hormone, vitamin D) in regulating blood calcium levels and bone metabolism.
- Define osteopenia, osteoporosis, and other common skeletal pathologies, and summarize major risk factors, prevention strategies, treatment approaches, and age-related changes in bone.

6.1: Understanding Bone- Composition, Cells, and Skeletal Organization

6.2: Bone Classification

6.3: Bone Anatomy

6.4: Bone Formation and Development

6.5: Fractures - Bone Repair

6.6: Bones and Calcium Homeostasis

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6.1: Understanding Bone- Composition, Cells, and Skeletal Organization

Functions of the Skeletal System

Support, Movement, and Protection

The most apparent functions of the skeletal system are the gross functions—those visible by observation. Simply by looking at a person, you can see how the bones support, facilitate movement, and protect the human body.

Just as the steel beams of a building provide a scaffold to support its weight, the bones and cartilage of your skeletal system compose the scaffold that supports the rest of your body. Without the skeletal system, you would be a limp mass of organs, muscle, and skin.

Bones also facilitate movement by serving as points of attachment for your muscles. While some bones only serve as a support for the muscles, others also transmit the forces produced when your muscles contract. From a mechanical point of view, bones act as levers and joints serve as fulcrums (Figure 6.1.1). Unless a muscle spans a joint and contracts, a bone is not going to move. For information on the interaction of the skeletal and muscular systems, that is, the musculoskeletal system, seek additional content.



Figure 6.1.1: Bones act as levers when muscles span a joint and contract. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 6.1.1.

Bones also protect internal organs from injury by covering or surrounding them. For example, your ribs protect your lungs and heart, the bones of your vertebral column (spine) protect your spinal cord, and the bones of your cranium (skull) protect your brain (Figure 6.1.2).

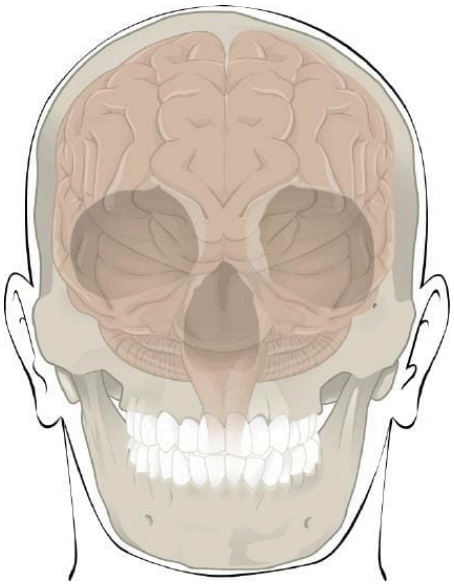


Figure 6.1.2: The cranium completely surrounds and protects the brain from non-traumatic injury. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 6.1.2

Career Connection

Orthopedist

An orthopedist is a doctor who specializes in diagnosing and treating disorders and injuries related to the musculoskeletal system. Some orthopedic problems can be treated with medications, exercises, braces, and other devices, but others may be best treated with surgery. Figure 6.1.3 shows a close-up view of a person's leg wearing a medical knee brace. The brace is black with adjustable straps and metallic hinges on both sides of the knee.

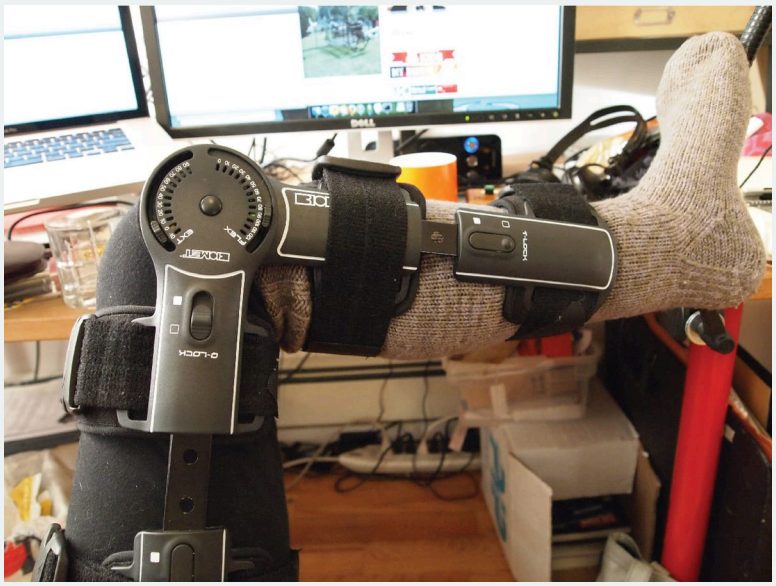


Figure 6.1.3: An orthopedist will sometimes prescribe the use of a brace that reinforces the underlying bone structure it is being used to support. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.1.3

While the origin of the word “orthopedics” (ortho- = “straight”; paed- = “child”), literally means “straightening of the child,” orthopedists can have patients who range from pediatric to geriatric. In recent years, orthopedists have even performed prenatal surgery to correct spina bifida, a congenital defect in which the neural canal in the spine of the fetus fails to close completely during embryologic development.

Orthopedists commonly treat bone and joint injuries but they also treat other bone conditions including curvature of the spine. Lateral curvatures (scoliosis) can be severe enough to slip under the shoulder blade (scapula) forcing it up as a hump. Spinal curvatures can also be excessive dorsoventrally (kyphosis) causing a hunch back and thoracic compression. These curvatures often appear in preteens as the result of poor posture, abnormal growth, or indeterminate causes. Mostly, they are readily treated by orthopedists. As people age, accumulated spinal column injuries and diseases like osteoporosis can also lead to curvatures of the spine, hence the stooping you sometimes see in the elderly.

Some orthopedists sub-specialize in sports medicine, which addresses both simple injuries, such as a sprained ankle, and complex injuries, such as a torn rotator cuff in the shoulder. Treatment can range from exercise to surgery.

Mineral Storage, Energy Storage, and Hematopoiesis

On a metabolic level, bone tissue performs several critical functions. For one, the bone matrix acts as a reservoir for a number of minerals important to the functioning of the body, especially calcium, and phosphorus. These minerals, incorporated into bone tissue, can be released back into the bloodstream to maintain levels needed to support physiological processes. Calcium ions, for example, are essential for muscle contractions and controlling the flow of other ions involved in the transmission of nerve impulses.

Bone also serves as a site for fat storage and blood cell production. The softer connective tissue that fills the interior of most bone is referred to as bone marrow (Figure 6.1.4). There are two types of bone marrow: yellow marrow and red marrow. Yellow marrow contains adipose tissue; the triglycerides stored in the adipocytes of the tissue can serve as a source of energy. Red marrow is where hematopoiesis—the production of blood cells—takes place. Red blood cells, white blood cells, and platelets are all produced in the red marrow.

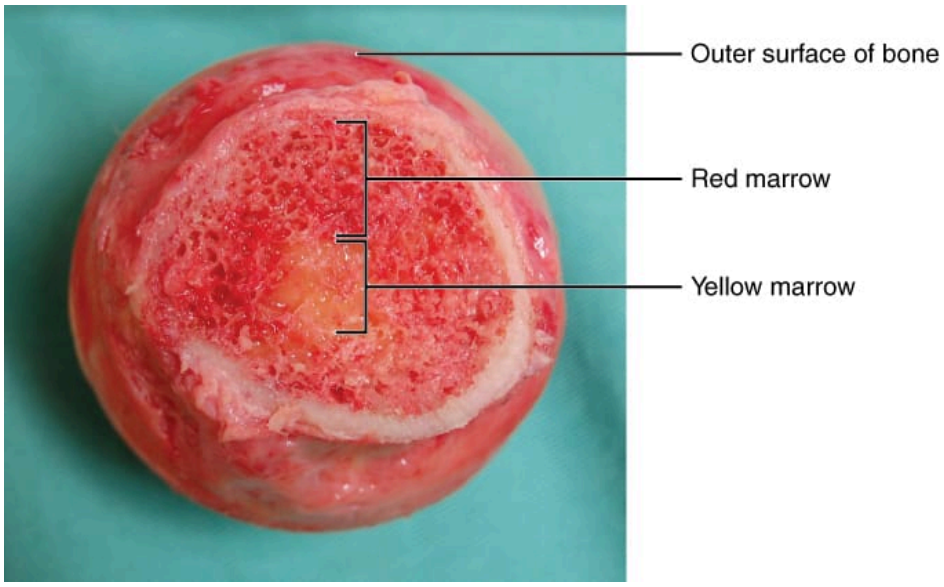


Figure 6.1.4: The head of the femur contains both yellow and red marrow. Yellow marrow stores fat. Red marrow is responsible for hematopoiesis. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.1.4.

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6.2: Bone Classification

Types of Bone by Shape

The 206 bones that compose the adult skeleton are divided into five categories based on their shapes (Figure 6.2.1). Their shapes and their functions are related such that each categorical shape of bone has a distinct function.

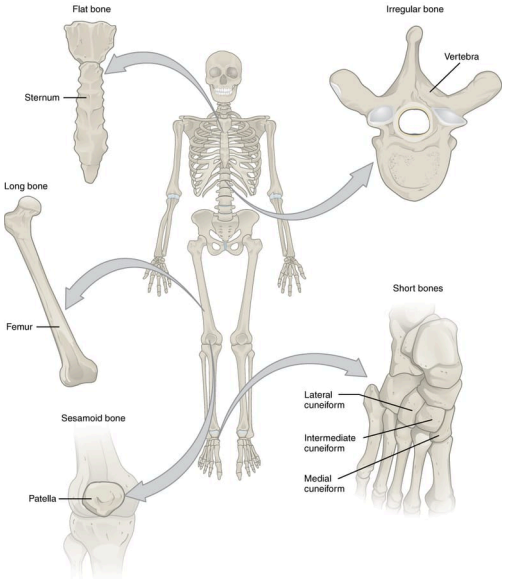


Figure 6.2.1: Classifications of bones by shape with examples from the skeleton: flat, long, irregular, short, and sesamoid bones. (CC BY 4.0; via Wikimedia Commons). Alternate text description of Figure 6.2.1.

Long Bones

A long bone is one that is cylindrical in shape, being longer than it is wide. Keep in mind, however, that the term describes the shape of a bone, not its size. Long bones are found in the arms (humerus, ulna, radius) and legs (femur, tibia, fibula), as well as in the fingers (metacarpals, phalanges) and toes (metatarsals, phalanges). Long bones function as levers; they move when muscles contract.

Short Bones

A short bone is one that is cube-like in shape, being approximately equal in length, width, and thickness. The only short bones in the human skeleton are in the carpals of the wrists and the tarsals of the ankles. Short bones provide stability and support as well as some limited motion.

Flat Bones

The term “flat bone” is somewhat of a misnomer because, although a flat bone is typically thin, it is also often curved. Examples include the cranial (skull) bones, the scapulae (shoulder blades), the sternum (breastbone), and the ribs. Flat bones serve as points of attachment for muscles and often protect internal organs.

Irregular Bones

An irregular bone is one that does not have any easily characterized shape and therefore does not fit any other classification. These bones tend to have more complex shapes, like the vertebrae that support the spinal cord and protect it from compressive

forces. Many facial bones, particularly the ones containing sinuses, are classified as irregular bones.

Sesamoid Bones

A sesamoid bone is a small, round bone that, as the name suggests, is shaped like a sesame seed. These bones form in tendons (the sheaths of tissue that connect bones to muscles) where a great deal of pressure is generated in a joint. The sesamoid bones protect tendons by helping them overcome compressive forces. Sesamoid bones vary in number and placement from person to person but are typically found in tendons associated with the feet, hands, and knees. The patellae (singular = patella) are the only sesamoid bones found in common with every person. Table 6.2.1 reviews bone classifications with their associated features, functions, and examples.

Table 6.2.1: Bone Classifications

Bone classification	Features	Function(s)	Examples
Long	Cylinder-like shape, longer than it is wide	Leverage	Femur, tibia, fibula, metatarsals, humerus, ulna, radius, metacarpals, phalanges
Short	Cube-like shape, approximately equal in length, width, and thickness	Provide stability, support, while allowing for some motion	Carpals, tarsals
Flat	Thin and curved	Points of attachment for muscles; protectors of internal organs	Sternum, ribs, scapulae, cranial bones
Irregular	Complex shape	Protect internal organs	Vertebrae, facial bones
Sesamoid	Small and round; embedded in tendons	Protect tendons from compressive forces	Patellae

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6.3: Bone Anatomy

Gross Anatomy of Bone

Bone tissue (osseous tissue) differs greatly from other tissues in the body. Bone is hard and many of its functions depend on that characteristic hardness. Later discussions in this chapter will show that bone is also dynamic in that its shape adjusts to accommodate stresses. This section will examine the gross anatomy of bone first and then move on to its histology.

The structure of a long bone allows for the best visualization of all of the parts of a bone (Figure 6.3.1). A long bone has two parts: the diaphysis and the epiphysis. The diaphysis is the tubular shaft that runs between the proximal and distal ends of the bone. The hollow region in the diaphysis is called the medullary cavity, which is filled with yellow marrow. The walls of the diaphysis are composed of dense and hard compact bone.

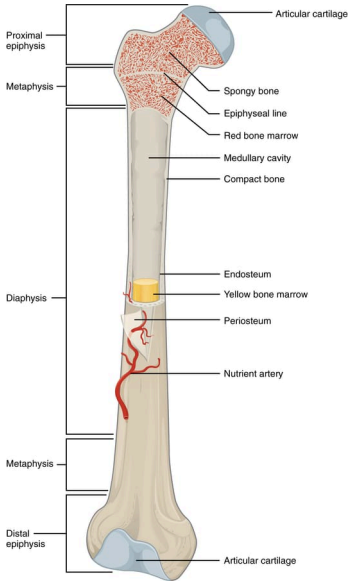
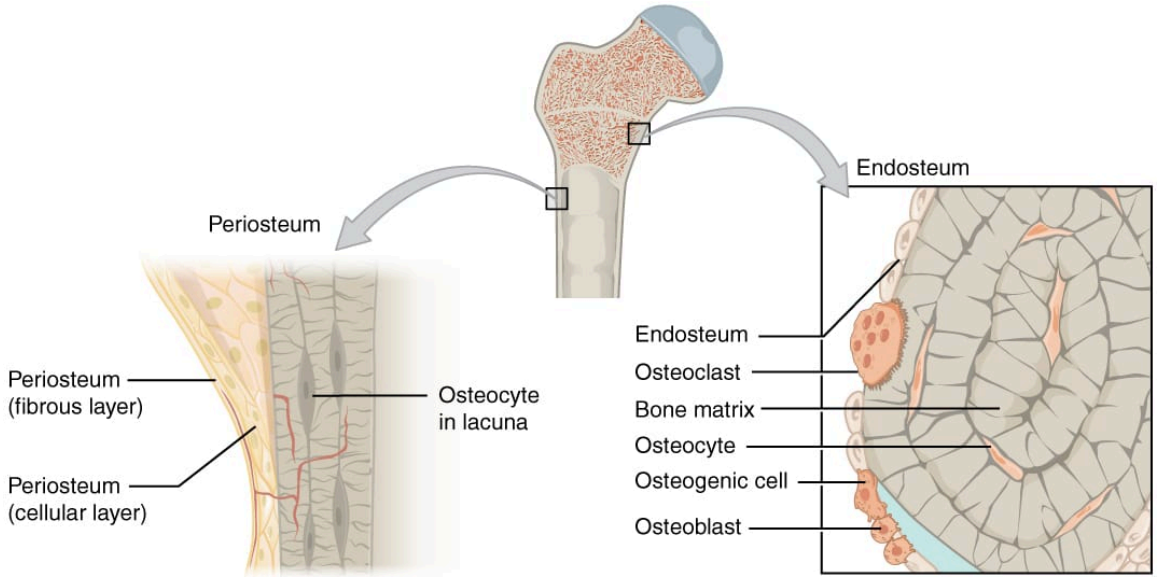


Figure 6.3.1: A typical long bone shows the gross anatomical characteristics of bone. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.1.

The medullary cavity has a delicate membranous lining called the endosteum (end- = “inside”; oste- = “bone”), where bone growth, repair, and remodeling occur. The outer surface of the bone is covered with a fibrous membrane called the periosteum (peri- = “around” or “surrounding”). The periosteum contains blood vessels, nerves, and lymphatic vessels that nourish compact bone. Tendons and ligaments also attach to bones at the periosteum. The periosteum covers the entire outer surface except where the epiphyses meet other bones to form joints (Figure 6.3.2). In this region, the epiphyses are covered with articular cartilage, a thin layer of cartilage that reduces friction and acts as a shock absorber.



Figure

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The periosteum forms the outer surface of bone, and the endosteum lines the medullary cavity. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.2

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Flat bones, like those of the cranium, consist of a layer of diploë (spongy bone), lined on either side by a layer of compact bone (Figure 6.3.3). The two layers of compact bone and the interior spongy bone work together to protect the internal organs. If the outer layer of a cranial bone fractures, the brain is still protected by the intact inner layer.

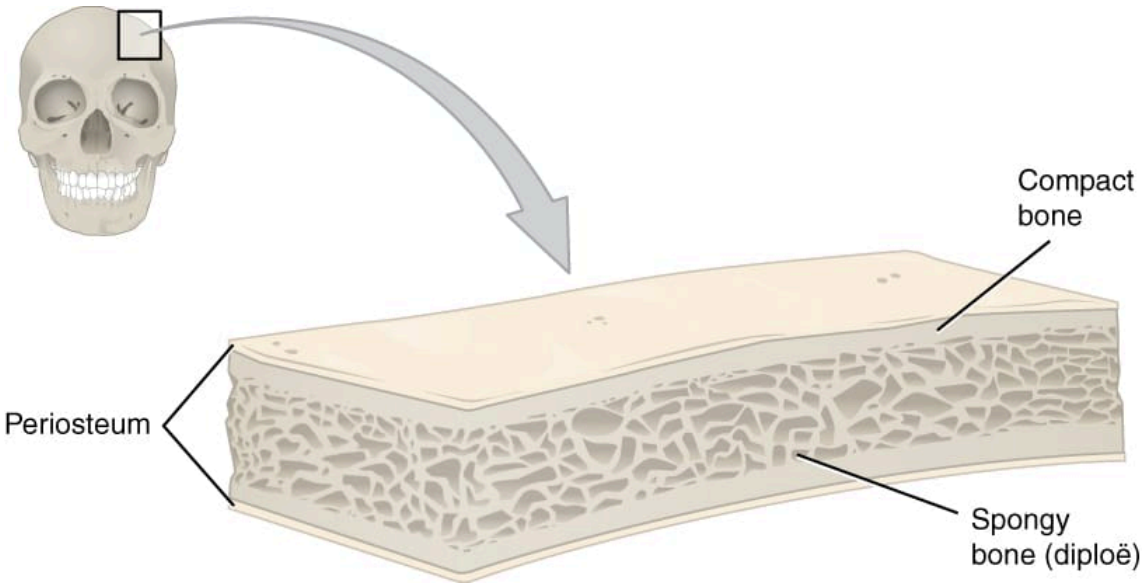


Figure 6.3.3: This cross-section of a flat bone shows the spongy bone (diploë) lined on either side by a layer of compact bone. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.3.

Bone Markings

The surface features of bones vary considerably, depending on the function and location in the body. Table Table 6.3.1 describes the bone markings, which are illustrated in (Figure 6.3.4). There are three general classes of bone markings: (1) articulations, (2) projections, and (3) holes. As the name implies, an articulation is where two bone surfaces come together (articulus = “joint”).

These surfaces tend to conform to one another, such as one being rounded and the other cupped, to facilitate the function of the articulation. A projection is an area of a bone that projects above the surface of the bone. These are the attachment points for tendons and ligaments. In general, their size and shape is an indication of the forces exerted through the attachment to the bone. A hole is an opening or groove in the bone that allows blood vessels and nerves to enter the bone. As with the other markings, their size and shape reflect the size of the vessels and nerves that penetrate the bone at these points.

Table 6.3.1: Common bone markings, their descriptions, and examples.

Marking	Description	Example
Articulations	Where two bones meet	Knee joint
Head	Prominent rounded surface	Head of femur
Facet	Flat surface	Vertebrae
Condyle	Rounded surface	Occipital condyles
Projections	Raised markings	Spinous process of the vertebrae
Protuberance	Protruding	Chin
Process	Prominence feature	Transverse process of vertebra
Spine	Sharp process	Ischial spine
Tubercle	Small, rounded process	Tubercle of humerus
Tuberosity	Rough surface	Deltoid tuberosity
Line	Slight, elongated ridge	Temporal lines of the parietal bones
Crest	Ridge	Iliac crest
Holes	Holes and depressions	Foramen (holes through which blood vessels can pass through)
Fossa	Elongated basin	Mandibular fossa
Fovea	Small pit	Fovea capitis on the head of the femur
Sulcus	Groove	Sigmoid sulcus of the temporal bones
Canal	Passage in bone	Auditory canal
Fissure	Slit through bone	Auricular fissure
Foramen	Hole through bone	Foramen magnum in the occipital bone
Meatus	Opening into canal	External auditory meatus
Sinus	Air-filled space in bone	Nasal sinus

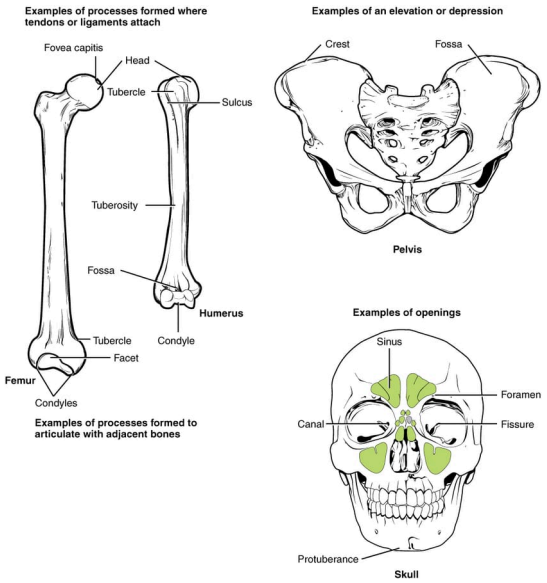


Figure 6.3.4: The surface features of bones depend on their function, location, attachment of ligaments and tendons, or the penetration of blood vessels and nerves. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.4.

Bone Cells and Tissue

Bone contains a relatively small number of cells entrenched in a matrix of collagen fibers that provide a surface for inorganic salt crystals to adhere. These salt crystals form when calcium phosphate and calcium carbonate combine to create hydroxyapatite, which incorporates other inorganic salts like magnesium hydroxide, fluoride, and sulfate as it crystallizes, or calcifies, on the collagen fibers. The hydroxyapatite crystals give bones their hardness and strength, while the collagen fibers give them flexibility so that they are not brittle.

Although bone cells compose a small amount of the bone volume, they are crucial to the function of bones. Four types of cells are found within bone tissue: osteoblasts, osteocytes, osteogenic cells, and osteoclasts (Figure 6.3.5).

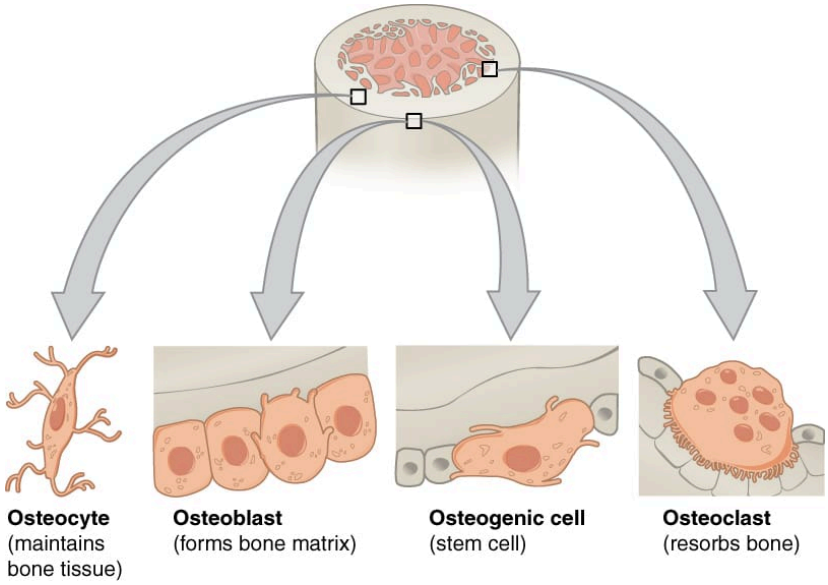


Figure 6.3.5: Four types of cells are found within bone tissue. Osteogenic cells are undifferentiated and develop into osteoblasts. When osteoblasts get trapped within the calcified matrix, their structure and function changes, and they become osteocytes. Osteoclasts develop from monocytes and macrophages and differ in appearance from other bone cells. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.5.

Table 6.3.2: Bone cell types with their structure, function, and location.

Cell type	Structure - Function	Location
Osteogenic cells	Undifferentiated with high mitotic activity and they are the only bone cells that divide; develop into osteoblasts	Immature osteogenic cells are found in the deep layers of the periosteum and the marrow
Osteoblasts	Do not divide, synthesize and secrete the collagen matrix and calcium salts; becomes an osteocyte, responsible for forming new bone	Growing portions of bone, including periosteum and endosteum
Osteocytes	Most abundant and longest-lived cells in adult bone, making up about 90–95% of all bone cells; maintain the mineral concentration of the matrix via the secretion of enzymes. During bone repair, osteocytes secrete growth factors that stimulate osteoblasts to produce new bone at the injury site. They also guide the alignment of new bone with existing tissue, ensuring proper healing	Entrapped in matrix, occupy small spaces called lacunae of lamella and extend long, slender cytoplasmic processes (dendrites) through tiny channels called canaliculi; these processes allow osteocytes to communicate with each other and with other bone cells, forming a vast network throughout the bone.
Osteoclasts	Large, multinucleated cells responsible for breaking down bone tissue—a process known as bone resorption, or breakdown; play a crucial role in bone remodeling, growth, repair, and maintaining calcium balance in the body.	Bone surfaces and at sites of old, injured, or unneeded bone.

Compact and Spongy Bone

The human skeletal system is ingeniously designed with two distinct types of bone tissue: compact and spongy bone, each serving unique and complementary functions. Most bones contain compact and spongy osseous tissue, but their distribution and concentration vary based on the bone's overall function. Compact bone is dense so that it can withstand compressive forces, while spongy (cancellous) bone has open spaces and supports shifts in weight distribution.

Compact Bone

Compact bone, or cortical bone, forms the dense outer layer of bones, providing the necessary strength and rigidity to withstand compressive forces and protect internal structures (Figure 6.3.6). It can be found under the periosteum and in the diaphyses of long bones, where it provides support and protection.

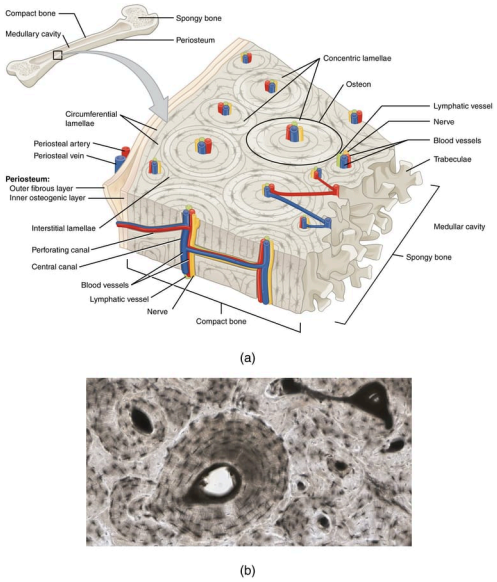


Figure 6.3.6: (a) This cross-sectional view of compact bone shows the basic structural unit, the osteon. (b) In this micrograph of the osteon, you can clearly see the concentric lamellae and central canals. LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012). (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.6.

The microscopic structural unit of compact bone is called an osteon, or Haversian system. Each osteon is composed of concentric rings of calcified matrix called lamellae (singular = lamella). Running down the center of each osteon is the central canal, or Haversian canal, which contains blood vessels, nerves, and lymphatic vessels. These vessels and nerves branch off at right angles through a perforating canal, also known as Volkmann's canals, to extend to the periosteum and endosteum.

The osteocytes are located inside spaces called lacunae (singular = lacuna), found at the borders of adjacent lamellae. As described earlier, canaliculi connect with the canaliculi of other lacunae and eventually with the central canal. This system allows nutrients to be transported to the osteocytes and wastes to be removed from them.

Spongy (Cancellous) Bone

Spongy bone, also known as cancellous or trabecular bone, resides predominantly at the ends of long bones and within the interior of vertebrae contributing to the reduction of overall skeletal weight. Spongy bone, contains osteocytes housed in lacunae, but they are not arranged in concentric circles. Instead, the lacunae and osteocytes are found in a lattice-like network of matrix spikes called trabeculae (singular = trabecula) (Figure 6.3.7). The trabeculae may appear to be a random network, but each trabecula forms along lines of stress to provide strength to the bone. The spaces of the trabeculated network provide balance to the dense and heavy compact bone by making bones lighter so that muscles can move them more easily. In addition, the spaces in some spongy bones contain red marrow, protected by the trabeculae, where hematopoiesis occurs.

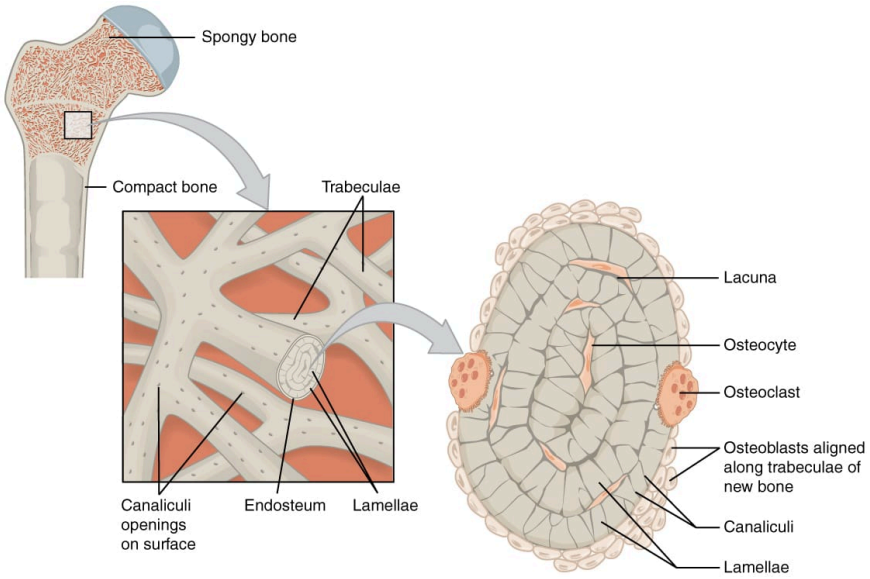


Figure 6.3.7: Spongy bone is composed of trabeculae that contain the osteocytes. Red marrow fills the spaces in some bones. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.7.

Aging and the...

Skeletal System: Paget's Disease

Paget's disease usually occurs in adults over age 40. It is a disorder of the bone remodeling process that begins with overactive osteoclasts. This means more bone is resorbed than is laid down. The osteoblasts try to compensate but the new bone they lay down is weak and brittle and therefore prone to fracture.

While some people with Paget's disease have no symptoms, others experience pain, bone fractures, and bone deformities (Figure 6.3.8). Bones of the pelvis, skull, spine, and legs are the most commonly affected. When occurring in the skull, Paget's disease can cause headaches and hearing loss.

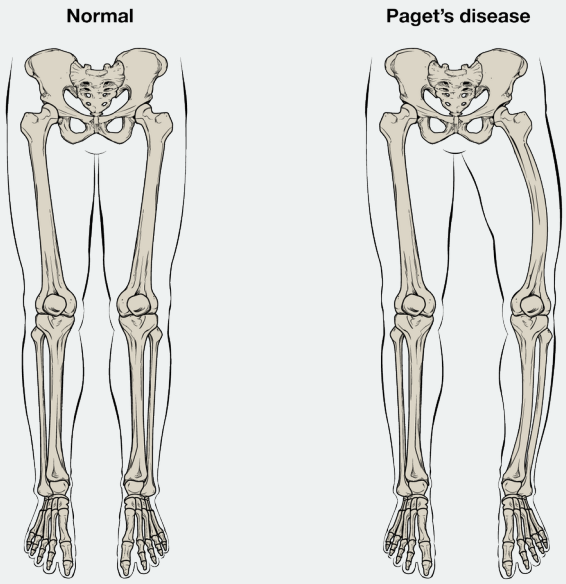


Figure 6.3.8: Normal leg bones are relatively straight, but those affected by Paget's disease are porous and curved. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.8.

What causes the osteoclasts to become overactive? The answer is still unknown, but hereditary factors seem to play a role. Some scientists believe Paget's disease is due to an as-yet-unidentified virus.

Paget's disease is diagnosed via imaging studies and lab tests. X-rays may show bone deformities or areas of bone resorption. Bone scans are also useful. In these studies, a dye containing a radioactive ion is injected into the body. Areas of bone resorption have an affinity for the ion, so they will light up on the scan if the ions are absorbed. In addition, blood levels of an enzyme called alkaline phosphatase are typically elevated in people with Paget's disease.

Bisphosphonates, drugs that decrease the activity of osteoclasts, are often used in the treatment of Paget's disease. However, in a small percentage of cases, Bisphosphonates themselves have been linked to an increased risk of fractures because the old bone that is left after Bisphosphonates are administered becomes worn out and brittle. Still, most doctors feel that the benefits of Bisphosphonates more than outweigh the risk; the medical professional has to weigh the benefits and risks on a case-by-case basis. Bisphosphonate treatment can reduce the overall risk of deformities or fractures, which in turn reduces the risk of surgical repair and its associated risks and complications.

Blood and Nerve Supply

The spongy bone and medullary cavity receive nourishment from arteries that pass through the compact bone. The arteries enter through the nutrient foramen (plural = foramina), small openings in the diaphysis (Figure 6.3.9). The osteocytes in spongy bone are nourished by blood vessels of the periosteum that penetrate spongy bone and blood that circulates in the marrow cavities. As the blood passes through the marrow cavities, it is collected by veins, which then pass out of the bone through the foramina.

In addition to the blood vessels, nerves follow the same paths into the bone where they tend to concentrate in the more metabolically active regions of the bone. The nerves sense pain, and it appears the nerves also play roles in regulating blood supplies and in bone growth, hence their concentrations in metabolically active sites of the bone.

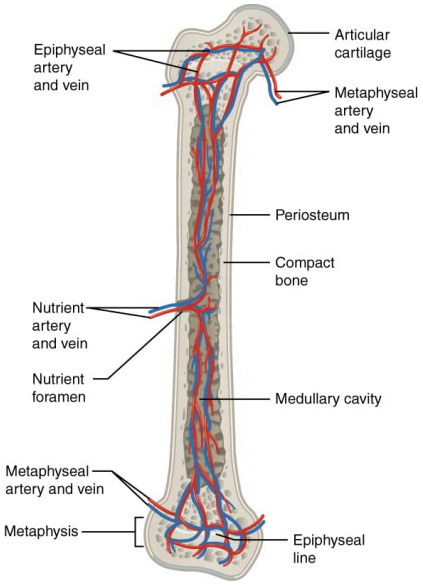


Figure 6.3.9: Blood vessels and nerves enter the bone through the nutrient foramen. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.3.9.

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6.4: Bone Formation and Development

Cartilage Templates

In the early stages of embryonic development, the embryo's skeleton consists of fibrous membranes and hyaline cartilage. By the sixth or seventh week of embryonic life, the actual process of bone development, ossification (osteogenesis), begins. There are two osteogenic pathways—intramembranous ossification and endochondral ossification—but bone is the same regardless of the pathway that produces it.

The process of bone formation, known as ossification, often begins with a cartilage template, a critical precursor in the development of many bones, particularly long bones. This cartilage model is composed primarily of hyaline cartilage, which provides a flexible yet sturdy framework for the initial stages of bone development. During fetal development, a framework is laid down that determines where bones will form. This framework is a flexible, semi-solid matrix produced by chondroblasts and consists of hyaluronic acid, chondroitin sulfate, collagen fibers, and water. As the matrix surrounds and isolates chondroblasts, they are called chondrocytes. Unlike most connective tissues, cartilage is avascular, meaning that it has no blood vessels supplying nutrients and removing metabolic wastes. All of these functions are carried on by diffusion through the matrix. This is why damaged cartilage does not repair itself as readily as most tissues do.

By the time a fetus is born, most of the cartilage has been replaced with bone. Some additional cartilage will be replaced throughout childhood, and some cartilage remains in the adult skeleton.

Intramembranous Ossification

Intramembranous ossification begins *in utero* during fetal development and continues on into adolescence. At birth, the skull and clavicles are not fully ossified nor are the sutures of the skull closed. This allows the skull and shoulders to deform during passage through the birth canal. The last bones to ossify via intramembranous ossification are the flat bones of the face, which reach their adult size at the end of the adolescent growth spurt.

During intramembranous ossification, compact and spongy bone develops directly from sheets of mesenchymal (undifferentiated) connective tissue. The flat bones of the face, most of the cranial bones, and the clavicles (collarbones) are formed via intramembranous ossification.

This process begins when mesenchymal cells in the embryonic skeleton gather together and begin to differentiate into specialized cells (Figure $6.4.1$) and occurs in four main steps to enable the direct formation of bone tissue from mesenchymal cells, producing the flat bones characteristic of the skull, face, and clavicles.

- Development of Ossification Centers - Mesenchymal cells cluster together and differentiate into osteoblasts, forming ossification centers where bone formation begins.
- Secretion and Calcification of Osteoid - Osteoblasts secrete osteoid (unmineralized bone matrix). The osteoid then calcifies (hardens) as mineral salts are deposited, trapping osteoblasts which become osteocytes.
- Formation of Trabeculae (Spongy Bone) - The osteoid accumulates around blood vessels, forming a network of trabeculae (thin columns of bone) that creates spongy bone. Blood vessels become enclosed, and the surrounding mesenchyme condenses to form the periosteum (outer bone covering).
- Development of Compact Bone and Red Marrow - Compact bone forms on the surface as osteoblasts in the periosteum lay down bone layers over the spongy bone. The spaces inside the spongy bone are eventually filled with red bone marrow.

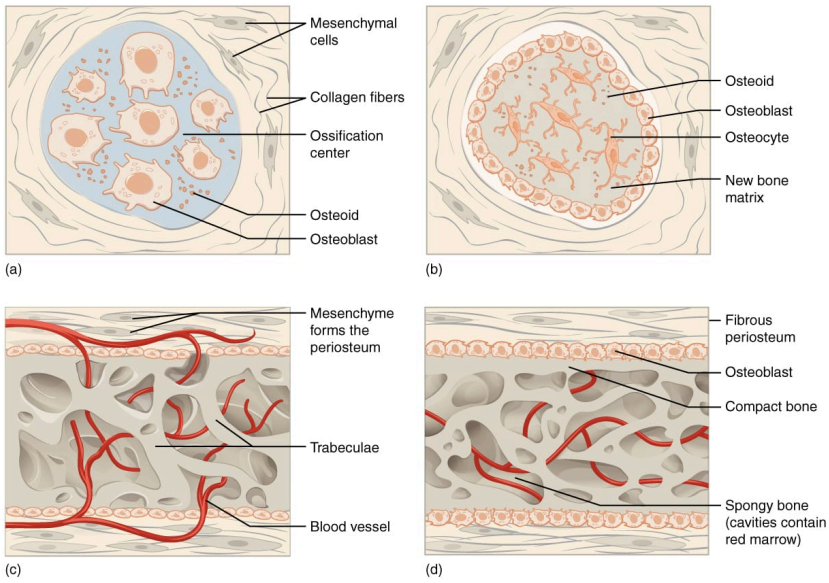


Figure 6.4.1: Intramembranous ossification follows four steps. (a) Mesenchymal cells group into clusters, and ossification centers form. (b) Secreted osteoid traps osteoblasts, which then become osteocytes. (c) Trabecular matrix and periosteum form. (d) Compact bone develops superficial to the trabecular bone, and crowded blood vessels condense into red marrow. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.4.1.

Endochondral Ossification

In endochondral ossification, bone develops by *replacing* hyaline cartilage. Cartilage does not become bone. Instead, cartilage serves as a template to be completely replaced by new bone. Endochondral ossification takes much longer than intramembranous ossification. Bones at the base of the skull and long bones form via endochondral ossification.

In a long bone, for example, at about 6 to 8 weeks after conception, some of the mesenchymal cells differentiate into chondrocytes (cartilage cells) that form the cartilaginous skeletal precursor of the bones (Figure 6.4.2*a*. Soon after, the perichondrium, a membrane that covers the cartilage, appears Figure 6.4.2*b*.

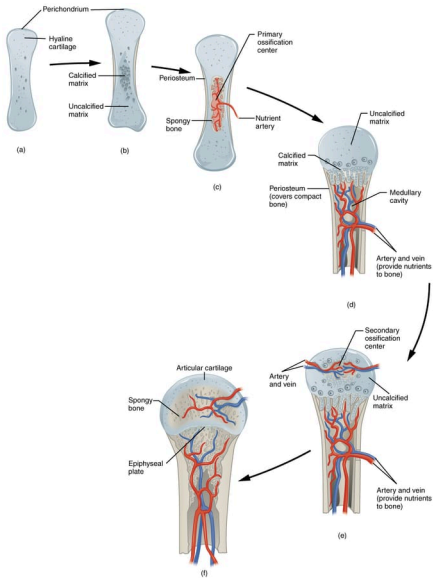


Figure 6.4.2: Endochondral ossification showing the transition from cartilage model to bone with a medullary cavity, spongy bone, and epiphyseal plate. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.4.2.

As more matrix is produced, the chondrocytes in the center of the cartilaginous model grow in size. As the matrix calcifies, nutrients can no longer reach the chondrocytes. This results in their death and the disintegration of the surrounding cartilage.

Blood vessels invade the resulting spaces, not only enlarging the cavities but also carrying osteogenic cells with them, many of which will become osteoblasts. These enlarging spaces eventually combine to become the medullary cavity.

As the cartilage grows, capillaries penetrate it. This penetration initiates the transformation of the perichondrium into the bone-producing periosteum. Here, the osteoblasts form a periosteal collar of compact bone around the cartilage of the diaphysis. By the second or third month of fetal life, bone cell development and ossification ramps up and creates the primary ossification center, a region deep in the periosteal collar where ossification begins (Figure $6.4.2c$).

While these deep changes are occurring, chondrocytes and cartilage continue to grow at the ends of the bone (the future epiphyses), which increases the bone's length at the same time bone is replacing cartilage in the diaphyses. By the time the fetal skeleton is fully formed, cartilage only remains at the joint surface as articular cartilage and between the diaphysis and epiphysis as the epiphyseal plate, the latter of which is responsible for the longitudinal growth of bones. After birth, this same sequence of events (matrix mineralization, death of chondrocytes, invasion of blood vessels from the periosteum, and seeding with osteogenic cells that become osteoblasts) occurs in the epiphyseal regions, and each of these centers of activity is referred to as a secondary ossification center (Figure $6.4.2e$).

Table $6.4.1$: Steps of endochondral ossification with descriptions.

Step	Description
Cartilage model formation	Mesenchymal cells → chondroblasts → hyaline cartilage model
Cartilage growth and maturation	Chondrocytes proliferate and hypertrophy, matrix changes, cartilage enlarges
Calcification and chondrocyte death	Matrix calcifies, chondrocytes die, cavities form
Primary ossification center forms	Blood vessels invade, osteoblasts replace cartilage with bone in diaphysis
Secondary ossification centers form	After birth, epiphyses ossify, articular cartilage and epiphyseal plate remain

How Bones Grow in Length

Bones grow in length through activity at the epiphyseal (growth) plate by a process similar to endochondral ossification. The epiphyseal plate is a layer of hyaline cartilage where ossification occurs in immature bones. On the epiphyseal side of the epiphyseal plate, cartilage is formed. On the diaphyseal side, cartilage is ossified, and the diaphysis grows in length. The longitudinal growth of bone is a result of cellular division in the proliferative zone and the maturation of cells in the zone of maturation and hypertrophy. The epiphyseal plate is composed of four zones of cells and activity (Figure $6.4.3$).The following is a description of activities in each zone.

1. Resting (reserve) zone - Small, inactive chondrocytes closest to the epiphysis serve as a reserve and anchor the plate to the epiphysis.
2. Proliferation zone - Chondrocytes divide rapidly, forming columns and producing new cartilage, which pushes the epiphysis away from the diaphysis and lengthens the bone.
3. Hypertrophic zone - Chondrocytes enlarge (hypertrophy) and the lacunae (spaces) around them expand.
4. Calcification zone - The matrix surrounding the hypertrophic chondrocytes calcifies, chondrocytes die, and the area is left with calcified cartilage. Capillaries and osteoblasts from the diaphysis penetrate this zone, and the osteoblasts secrete bone tissue on the remaining calcified cartilage. Thus, the zone of calcified matrix connects the epiphyseal plate to the diaphysis. A bone grows in length when osseous tissue is added to the diaphysis.

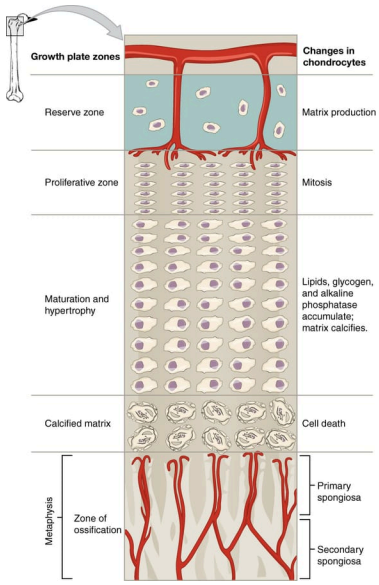


Figure 6.4.3: The epiphyseal plate is responsible for longitudinal bone growth. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.4.3.

Bones continue to grow in length until early adulthood. The rate of growth is controlled by hormones, which will be discussed later. When the chondrocytes in the epiphyseal plate cease their proliferation and bone replaces the cartilage, longitudinal growth stops. All that remains of the epiphyseal plate is the epiphyseal line (Figure 6.4.4).

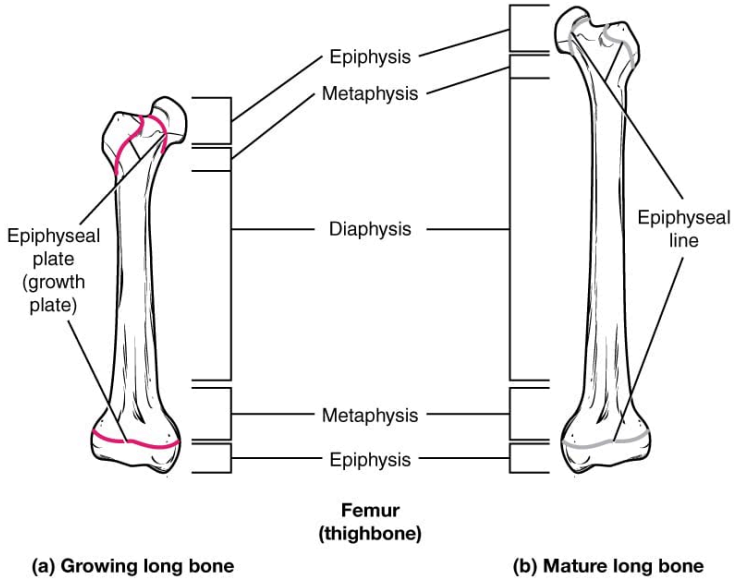


Figure 6.4.4: As a bone matures, the epiphyseal plate progresses to an epiphyseal line. (a) Epiphyseal plates are visible in a growing bone. (b) Epiphyseal lines are the remnants of epiphyseal plates in a mature bone. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.4.4.

How Bones Grow in Diameter

While bones are increasing in length, they are also increasing in diameter; growth in diameter can continue even after longitudinal growth ceases. Bones grow in diameter through a process called appositional growth, where new bone is added to the surface while old bone is removed from the inside. This involves osteoblasts in the outer layer building new bone, and osteoclasts on the inner surface breaking down old bone to create a larger medullary cavity. This balance increases the bone's overall thickness and width.

- Osteoblasts build new bone: Osteoblasts on the outer surface of the bone (under the periosteum) secrete new bone matrix, adding layers to the bone's exterior.
- Osteoclasts resorb old bone: Simultaneously, osteoclasts on the inner surface of the bone (lining the medullary cavity) break down and remove old bone tissue.

This dual process increases the diameter of the bone while also widening the internal marrow cavity, which helps keep the bone from becoming too heavy. This activity continues throughout life, allowing bones to remodel and thicken in response to mechanical stress.

Bone Remodeling

The process in which matrix is resorbed on one surface of a bone and deposited on another is known as bone modeling. Modeling primarily takes place during a bone's growth. However, in adult life, bone undergoes remodeling, in which resorption of old or damaged bone takes place on the same surface where osteoblasts lay new bone to replace that which is resorbed. Injury, exercise, and other activities lead to remodeling. Those influences are discussed later in the chapter, but even without injury or exercise, about 5 to 10 percent of the skeleton is remodeled annually just by destroying old bone and renewing it with fresh bone.

Use It or Lose It: Principles of Wolff's Law

Julius Wolff, a German surgeon and anatomist, articulated Wolff's law, which describes how bone adapts to the loads it experiences. Bone is living tissue that continually remodels in response to mechanical stress: regular loading reinforces its structure, while lack of use leads to weakening. This principle explains how activity, rehabilitation, and mechanical loading shape skeletal health and recovery.

Wolff's law refers to the reshaping of bone to meet functional demands. Mechanotransduction is the cellular process by which bone cells detect mechanical forces and convert them into biochemical signals that direct remodeling. It proceeds through four main stages:

- Mechanocoupling: Movement or exercise slightly deforms bone and drives fluid through its microscopic channels; bone cells sense these changes and are activated.
- Biochemical coupling: Mechanical cues trigger intracellular signaling pathways via specialized proteins.
- Signal transmission: Activated cells communicate with neighbors through gap junctions and by releasing factors such as IGF and prostaglandins.
- Effector response: Depending on the magnitude, rate, and frequency of loading, cells promote bone formation or limit resorption. Repeated, cyclic loading tends to strengthen bone.

In physiotherapy, this principle guides both rehabilitation and prevention. Appropriately dosed weight-bearing and resistance exercises provide controlled mechanical stress that stimulates remodeling and increases bone strength. Clinicians apply progressive loading programs for patients recovering from fractures or at risk of osteoporosis, carefully balancing protection with sufficient mechanical stimulus to rebuild bone and reduce future injury risk.

Nutrition provides the substrates and cofactors for this remodeling

Adequate calcium and vitamin D are foundational for mineralization, while protein supports collagen matrix synthesis. Magnesium, phosphorus, vitamin K, and overall energy availability further influence bone quality and turnover. Insufficient intake—or chronic low energy availability—impairs formation and increases injury risk.

Hormones orchestrate these processes

Estrogen and testosterone favor bone formation and suppress resorption; their decline (e.g., menopause or hypothalamic amenorrhea) accelerates bone loss. Parathyroid hormone and active vitamin D regulate calcium balance; thyroid hormone, growth hormone/IGF-1, insulin, and cortisol also affect remodeling rates and bone mass. The interplay is life-stage dependent: growth demands high nutrient supply and activity to build peak bone mass, while aging requires strategies to preserve it.

Together, appropriate exercise, sound nutrition, and balanced endocrine function act synergistically to optimize bone strength and reduce risks such as stress fractures and osteoporosis.

Diseases of the...

Skeletal System

Osteogenesis imperfecta (OI) is a genetic disease in which bones do not form properly and therefore are fragile and break easily. It is also called brittle bone disease. The disease is present from birth and affects a person throughout life.

The genetic mutation that causes OI affects the body's production of collagen, one of the critical components of bone matrix. The severity of the disease can range from mild to severe. Those with the most severe forms of the disease sustain many more fractures than those with a mild form. Frequent and multiple fractures typically lead to bone deformities and short stature. Bowing of the long bones and curvature of the spine are also common in people afflicted with OI. Curvature of the spine makes breathing difficult because the lungs are compressed.

Because collagen is such an important structural protein in many parts of the body, people with OI may also experience fragile skin, weak muscles, loose joints, easy bruising, frequent nosebleeds, brittle teeth, blue sclera, and hearing loss. There is no known cure for OI. Treatment focuses on helping the person retain as much independence as possible while minimizing fractures and maximizing mobility. Toward that end, safe exercises, like swimming, in which the body is less likely to experience collisions or compressive forces, are recommended. Braces to support legs, ankles, knees, and wrists are used as needed. Canes, walkers, or wheelchairs can also help compensate for weaknesses.

When bones do break, casts, splints, or wraps are used. In some cases, metal rods may be surgically implanted into the long bones of the arms and legs. Research is currently being conducted on using Bisphosphonates to treat OI. Smoking and being overweight are especially risky in people with OI, since smoking is known to weaken bones, and extra body weight puts additional stress on the bones.

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6.5: Fractures - Bone Repair

Overview

A fracture is a broken bone. It will heal whether or not a physician resets it in its anatomical position. If the bone is not reset correctly, the healing process will keep the bone in its deformed position. The most recent global data indicate that in 2021 there were approximately 172.8 million new fracture cases worldwide. In the same year, the number of people living with the acute or chronic effects of a fracture (prevalent cases) was about 453.3 million.

The underlying pathophysiology of fractures involves stress placed on a bone that results in a break in the bone's structure. Several different forces can result in bone fractures, including direct trauma, twisting movements, and crushing forces. Some of the most common causes of fractures include motor vehicle accidents, sports injuries, and falls. Usually when a bone fracture occurs, the soft tissue surrounding the bone is also affected. This can result in edema, hemorrhage, tendon damage, and severed nerves—all collectively referred to as soft tissue injuries.

When a broken bone is manipulated and set into its natural position without surgery, the procedure is called a closed reduction. Open reduction requires surgery to expose the fracture and reset the bone.

While some fractures can be minor, others are quite severe and result in grave complications. For example, a fractured diaphysis of the femur has the potential to release fat globules into the bloodstream. These can become lodged in the capillary beds of the lungs, leading to respiratory distress and if not treated quickly, death.

Types of Fractures

Fractures are classified based on several criteria, including whether the skin is broken (closed or open), if the bone fragments are aligned (non-displaced or displaced), and the completeness of the break (complete or incomplete). Different fracture patterns include transverse, oblique, spiral, comminuted, impacted, and greenstick (Figure 6.5.1). Table 6.5.1 outlines common types of fractures. Some fractures may be described using more than one term because it may have the features of more than one type (e.g., an open transverse fracture).

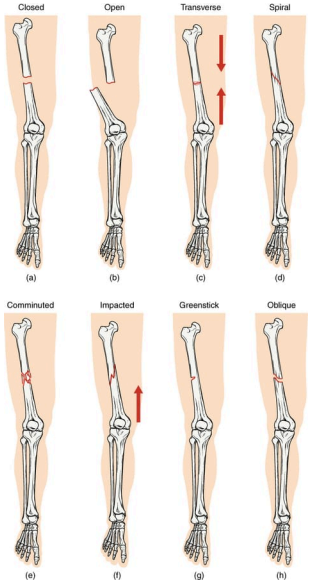


Figure 6.5.1: Common femur fracture patterns: closed, open, transverse, spiral, comminuted, impacted, greenstick, and oblique. (CC BY 4.0; via OpenStax). Check Table 6.5.1 for details.

Table 6.5.1: Common types of fractures

Type of fracture	Description
Closed (or simple) fracture	A fracture in which the skin remains intact
Open (or compound) fracture	A fracture in which at least one end of the broken bone tears through the skin; carries a high risk of infection
Transverse fracture	A straight break that runs horizontally across the long axis of the bone.
Spiral fracture	The break line curves around the bone, often the result of a twisting motion.
Comminuted fracture	Several breaks result in many small pieces between two large segments; the bone is shattered into multiple fragments.
Impacted fracture	One fragment of bone is driven into the other, typically due to compression.
Greenstick fracture	A partial fracture in which only one side of the bone is broken while the other side bends; most common in children due to more flexible bones.
Oblique fracture	A diagonal break across the bone, occurring at an angle that is not 90 degrees.
Stress (or Hairline) fracture	Tiny cracks in the bone surface that develop gradually from repeated strain.
Compression fracture	Occurs when bones are crushed, often in the vertebrae of the spine.

Bone Repair

When a bone breaks, blood flows from any vessel torn by the fracture. These vessels could be in the periosteum, osteons, and/or medullary cavity. The blood begins to clot, and about six to eight hours after the fracture, the clotting blood has formed a fracture hematoma (Figure 6.5.2*a*). The disruption of blood flow to the bone results in the death of bone cells around the fracture.

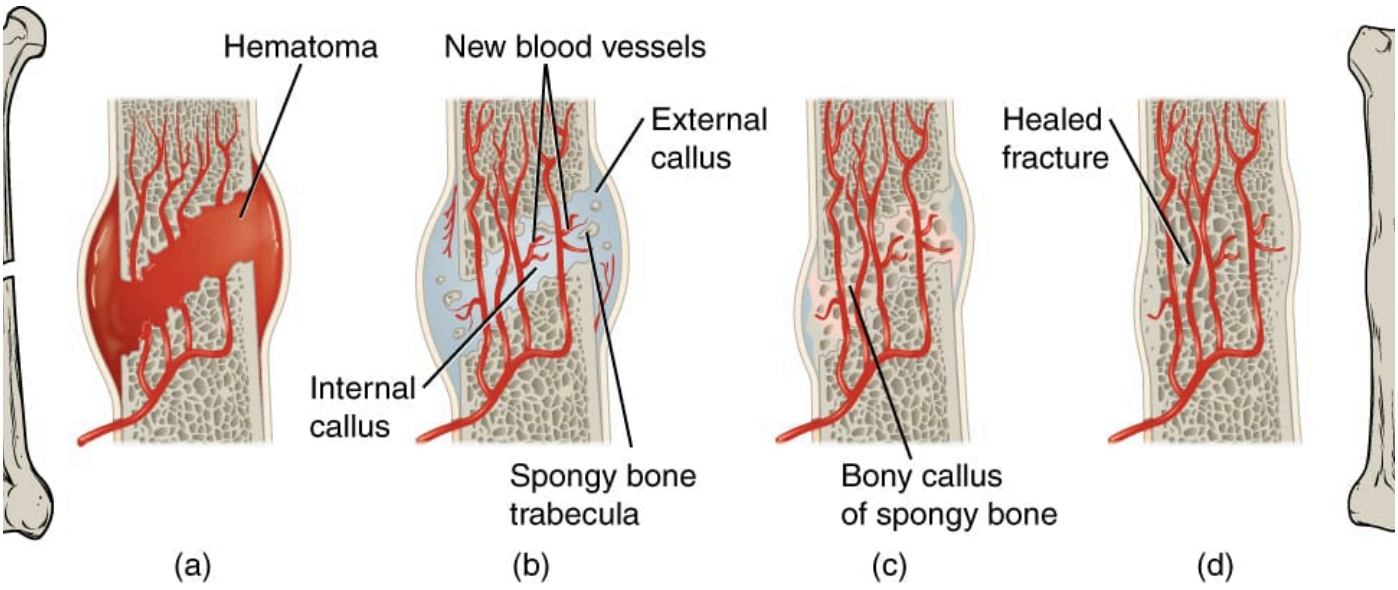


Figure 6.5.2: The healing of a bone fracture follows a series of progressive steps: (a) A fracture hematoma forms. (b) Internal and external calli form. (c) Cartilage of the calli is replaced by trabecular bone. (d) Remodeling occurs. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.5.2.

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6.6: Bones and Calcium Homeostasis

Maintaining Calcium in the Body

Calcium is not only the most abundant mineral in bone, it is also the most abundant mineral in the human body. Bone serves as both a structural organ and a dynamic reservoir that buffers blood calcium via continuous remodeling. About 99% of body calcium is stored in bone as hydroxyapatite; the remaining 1% in blood. Calcium ions are needed not only for bone mineralization but for tooth health, regulation of the heart rate and strength of contraction, blood coagulation, contraction of smooth and skeletal muscle cells, and regulation of nerve impulse conduction. The normal level of calcium in the blood is about 10 mg/dL. When the body cannot maintain this level, a person will experience hypo- or hypercalcemia.

Hypocalcemia, a condition characterized by abnormally low levels of calcium, can have an adverse effect on a number of different body systems including circulation, muscles, nerves, and bone. Without adequate calcium, blood has difficulty coagulating, the heart may skip beats or stop beating altogether, muscles may have difficulty contracting, nerves may have difficulty functioning, and bones may become brittle. The causes of hypocalcemia can range from hormonal imbalances to an improper diet. Treatments vary according to the cause, but prognoses are generally good.

Note

Clinical connections - Symptoms of Hypocalcemia

Neuromuscular irritability: perioral numbness, paresthesias (numbness, tingling, or burning sensation), muscle cramps, bronchospasm, tetany (painful, involuntary muscle spasms), seizures. Treated by restoring Ca and vitamin D and addressing the cause.

Conversely, in hypercalcemia, a condition characterized by abnormally high levels of calcium in blood. Causes of hypercalcemia include hyperparathyroidism, too much calcium intake, too much vitamin D intake, cancer of the kidney, lung, or ovary may secrete large amounts of a protein that, like parathyroid hormone, increases the calcium level in blood, if bone is broken down (resorbed) or destroyed, calcium is released into the blood, sometimes causing hypercalcemia.

Note

Clinical connections - Symptoms of Hypercalcemia

Fatigue, Bone pain, Muscle weakness, Nausea and vomiting, Confusion, Kidney stones, and Heart arrhythmias. Treatment may include fluids and medications to increase excretion of calcium

Obviously, calcium homeostasis is critical. The skeletal, endocrine, and digestive systems play a role in this, but the kidneys do, too. These body systems work together to maintain a normal calcium level in the blood (Figure 6.6.1).

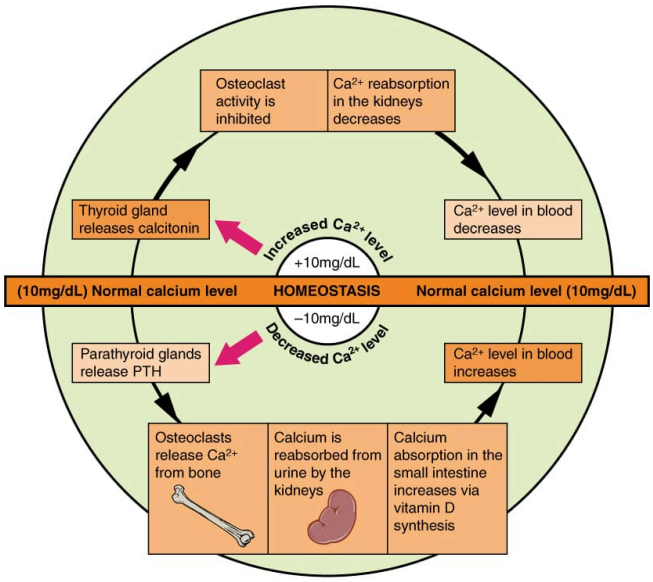


Figure 6.6.1: Hormonal regulation of blood calcium homeostasis by calcitonin and parathyroid hormone. (CC BY 4.0; via OpenStax). Alternate text description of Figure 6.6.1.

If blood calcium is low

- the parathyroid glands sense low blood calcium and release parathyroid hormone (PTH).
- PTH stimulates osteoclasts (bone-resorbing cells) to break down bone, releasing calcium into the blood.
- PTH causes the kidneys to reabsorb more calcium, reducing its excretion in urine, and also promotes the production of active vitamin D.
- active vitamin D, produced with the help of PTH, increases the absorption of calcium from food in the small intestine.

If blood calcium is high

- the thyroid gland releases hormone calcitonin.
- Calcitonin inhibits osteoclasts and promotes bone building, moving calcium from the blood into the bones.
- Calcitonin reduces calcium reabsorption in the kidneys, leading to more calcium being excreted in the urine.

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6.7: Terms and Definitions

Key Terms

Select to view definitions

Articular cartilage
thin layer of cartilage covering an epiphysis; reduces friction and acts as a shock absorber

Articulation
where two bone surfaces meet

Bone
hard, dense connective tissue that forms the structural elements of the skeleton

Canaliculi
(singular = canaliculus) channels within the bone matrix that house one of an osteocyte's many cytoplasmic extensions that it uses to communicate and receive nutrients

Cartilage
semi-rigid connective tissue found on the skeleton in areas where flexibility and smooth surfaces support movement

Central canal
longitudinal channel in the center of each osteon; contains blood vessels, nerves, and lymphatic vessels; also known as the Haversian canal

Closed reduction
manual manipulation of a broken bone to set it into its natural position without surgery

Compact bone
dense osseous tissue that can withstand compressive forces

Diaphysis
tubular shaft that runs between the proximal and distal ends of a long bone

Diploë
layer of spongy bone, that is sandwiched between two the layers of compact bone found in flat bones

Endochondral ossification
process in which bone forms by replacing hyaline cartilage

Endosteum
delicate membranous lining of a bone's medullary cavity

Epiphyseal line
completely ossified remnant of the epiphyseal plate

Epiphyseal plate
(also, growth plate) sheet of hyaline cartilage in the metaphysis of an immature bone; replaced by bone tissue as the organ grows in length

Epiphysis
wide section at each end of a long bone; filled with spongy bone and red marrow

External callus
collar of hyaline cartilage and bone that forms around the outside of a fracture

Flat bone
thin and curved bone; serves as a point of attachment for muscles and protects internal organs

Fracture
broken bone

Fracture hematoma
blood clot that forms at the site of a broken bone

Hematopoiesis
production of blood cells, which occurs in the red marrow of the bones

Hypercalcemia
condition characterized by abnormally high levels of calcium

Hypocalcemia
condition characterized by abnormally low levels of calcium

Internal callus
fibrocartilaginous matrix, in the endosteal region, between the two ends of a broken bone

Intramembranous ossification
process by which bone forms directly from mesenchymal tissue

Irregular bone
bone of complex shape; protects internal organs from compressive forces

Lacunae
(singular = lacuna) spaces in a bone that house an osteocyte

Long bone
cylinder-shaped bone that is longer than it is wide; functions as a lever

Medullary cavity
hollow region of the diaphysis; filled with yellow marrow

Modeling
process, during bone growth, by which bone is resorbed on one surface of a bone and deposited on another

Nutrient foramen
small opening in the middle of the external surface of the diaphysis, through which an artery enters the bone to provide nourishment

Open reduction
surgical exposure of a bone to reset a fracture

Orthopedist
doctor who specializes in diagnosing and treating musculoskeletal disorders and injuries

Osseous tissue
bone tissue; a hard, dense connective tissue that forms the structural elements of the skeleton

Ossification
(also, osteogenesis) bone formation

Ossification center
cluster of osteoblasts found in the early stages of intramembranous ossification

Osteoblast
cell responsible for forming new bone

Osteoclast
cell responsible for resorbing bone

Osteocyte
primary cell in mature bone; responsible for maintaining the matrix

Osteogenic cell
undifferentiated cell with high mitotic activity; the only bone cells that divide; they differentiate and develop into osteoblasts

Osteoid
uncalcified bone matrix secreted by osteoblasts

Osteon
(also, Haversian system) basic structural unit of compact bone; made of concentric layers of calcified matrix

Osteoporosis
disease characterized by a decrease in bone mass; occurs when the rate of bone resorption exceeds the rate of bone formation, a common occurrence as the body ages

Perforating canal
(also, Volkmann's canal) channel that branches off from the central canal and houses vessels and nerves that extend to the periosteum and endosteum

Perichondrium
membrane that covers cartilage

Periosteum
fibrous membrane covering the outer surface of bone and continuous with ligaments

Primary ossification center
region, deep in the periosteal collar, where bone development starts during endochondral ossification

Projection
bone markings where part of the surface sticks out above the rest of the surface, where tendons and ligaments attach

Proliferative zone
region of the epiphyseal plate that makes new chondrocytes to replace those that die at the diaphyseal end of the plate and contributes to longitudinal growth of the epiphyseal plate

Red marrow
connective tissue in the interior cavity of a bone where hematopoiesis takes place

Remodeling
process by which osteoclasts resorb old or damaged bone at the same time as and on the same surface where osteoblasts form new bone to replace that which is resorbed

Reserve zone
region of the epiphyseal plate that anchors the plate to the osseous tissue of the epiphysis

Secondary ossification center
region of bone development in the epiphyses

Sesamoid bone
small, round bone embedded in a tendon; protects the tendon from compressive forces

Short bone
cube-shaped bone that is approximately equal in length, width, and thickness; provides limited motion

Skeletal system
organ system composed of bones and cartilage that provides for movement, support, and protection

Spongy bone
(also, cancellous bone) trabeculated osseous tissue that supports shifts in weight distribution

Trabeculae
(singular = trabecula) spikes or sections of the lattice-like matrix in spongy bone

Yellow marrow
connective tissue in the interior cavity of a bone where fat is stored

Zone of calcified matrix
region of the epiphyseal plate closest to the diaphyseal end; functions to connect the epiphyseal plate to the diaphysis

Zone of maturation and hypertrophy
region of the epiphyseal plate where chondrocytes from the proliferative zone grow and mature and contribute to the longitudinal growth of the epiphyseal plate

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6.8: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. Which description best characterizes bone tissue?
   A. Dead calcified tissue
   B. Cartilage that has hardened
   C. The entire skeletal system
   D. Dense, hard connective tissue with living cells and mineralized matrix
2. If red bone marrow were destroyed or severely reduced, which function of the skeletal system would be most directly impaired?
   A. Storage of phosphate
   B. Storage of calcium
   C. Production of blood cells
   D. Lever action for movement
3. Yellow bone marrow is primarily associated with which function?
   A. Storage of fat
   B. Formation of new bone tissue
   C. Production of blood cells
   D. Production of synovial fluid
4. Which of the following is most commonly located at sites where bones move relative to one another?
   A. Hematopoietic tissue
   B. Articular cartilage
   C. Yellow marrow
   D. Red marrow
5. Most of the bones of the arms and hands are classified as long bones. However, the bones in the wrist are most accurately classified as which type of bone?
   A. Flat bones
   B. Short bones
   C. Sesamoid bones
   D. Irregular bones
6. Sesamoid bones are most commonly found embedded within which structures?
   A. Joints
   B. Skeletal muscles
   C. Ligaments
   D. Tendons
7. The vertebrae that encase and protect the spinal cord are classified as which type of bones?
   A. Irregular bones
   B. Sesamoid bones
   C. Flat bones
   D. Short bones
8. Long bones facilitate movement of body segments primarily by acting as which of the following?
   A. Counterweights

B. Resistive forces
C. Levers acted on by muscles
D. Fulcrums around which joints move

9. Which process occurs within the spongy bone of the epiphysis of a long bone in an adult?
A. Longitudinal growth of bone
B. Bone remodeling in response to stress
C. Hematopoiesis
D. Production of synovial fluid for shock absorption

10. The central region (shaft) of a long bone, the diaphysis, contains which of the following in an adult?
A. The metaphysis
B. A medullary cavity primarily filled with fat
C. Spongy bone only
D. Only compact bone, without any marrow

11. Which of the following cell types are not capable of undergoing mitosis?
A. Osteoblasts and osteoclasts
B. Osteocytes and osteoclasts
C. Osteoblasts and osteocytes
D. Osteogenic cells and osteoclasts

12. Which cell type involved in bone physiology does not arise from osteogenic (osteoprogenitor) cells?
A. Osteoblasts
B. Osteoclasts
C. Osteocytes
D. Osteoprogenitor cells

13. Which microscopic structures are present in both compact bone and spongy (cancellous) bone?
A. Osteons (Haversian systems)
B. Haversian canals
C. Lamellae
D. Volkmann's canals

14. Which of the following structural features is characteristic of spongy (cancellous) bone but not of compact bone?
A. Canaliculi
B. Volkmann's canals
C. Trabeculae
D. Calcium salts in the matrix

15. The passageway through which a nutrient artery enters a long bone is called a nutrient foramen. This opening represents which type of bone surface marking?
A. Hole
B. Facet
C. Canal
D. Fissure

16. Which statement best explains why cartilage heals more slowly than bone after injury?
A. Cartilage is gradually replaced by bone over time.
B. Cartilage is semi-solid and flexible, so it cannot be repaired.
C. Cartilage is avascular and relies on diffusion rather than a direct blood supply.
D. Endochondral ossification replaces all damaged cartilage with bone immediately.

17. During endochondral ossification, what ultimately happens to most of the chondrocytes in the cartilage model?
A. They transform directly into osteocytes.
B. They die within the calcified matrix, contributing to the formation of the medullary cavity.
C. They proliferate to form the periosteum.
D. They cluster to form the primary ossification center and remain there as mature chondrocytes.

18. Which bones are primarily formed by intramembranous ossification?
A. Metatarsals
B. Femur
C. Ribs
D. Flat bones of the cranial vault

19. Long bones grow both in length and in diameter. Which combination correctly identifies the primary site for increase in length and the primary site for increase in diameter?
A. Length: Epiphyseal plate; Diameter: On the endosteal surface of the medullary cavity
B. Length: Epiphyseal plate; Diameter: Beneath the periosteum on the outer surface

C. Length: Perichondrium; Diameter: Within the epiphyseal plate
D. Length: Periosteum; Diameter: Within the metaphysis only

20. In the epiphyseal plate of a growing long bone, which sequence of histological zones from the epiphysis toward the diaphysis is correct?
A. Zone of resting (reserve) cartilage → Zone of proliferation → Zone of hypertrophy (maturation) → Zone of calcification
B. Zone of proliferation → Zone of resting (reserve) cartilage → Zone of calcification → Zone of hypertrophy (maturation)
C. Zone of calcification → Zone of hypertrophy (maturation) → Zone of proliferation → Zone of resting (reserve) cartilage
D. Zone of hypertrophy (maturation) → Zone of calcification → Zone of resting (reserve) cartilage → Zone of proliferation

21. A fracture may be described as greenstick and comminuted, transverse and oblique, or open and closed. Which of the following describes a combination that can correctly occur in the same fracture?
A. Open and closed
B. Open and transverse
C. Transverse and greenstick
D. Greenstick and comminuted

22. A fracture of the shaft of a long bone can result in fat emboli entering the bloodstream. What is the most direct source of this fat?
A. Subcutaneous fat disrupted by the bone fragments
B. Yellow marrow within the diaphysis that is exposed and damaged
C. Fat released from intact bones elsewhere in response to injury
D. Red marrow in the fractured bone releasing fat to aid fracture repair

23. In a compound (open) fracture of a long bone, which of the following is true?
A. The break occurs at an angle across the bone.
B. The broken bone does not tear the skin.
C. One fragment of bone is driven into the other fragment.
D. The broken bone communicates with the external environment through a skin wound.

24. During fracture repair, which type of bone is formed first around the site of injury?
A. Mature compact bone
B. Lamellar bone with organized osteons
C. Spongy (woven) bone
D. Dense cortical bone with complete Haversian systems

25. Wolff's law describes how bone responds to mechanical stress. Which scenario best illustrates this principle?
A. A right-handed baseball pitcher has thicker, denser bones in the right upper limb than in the left.
B. A right-handed cyclist has substantially thicker bones in the right leg than in the left.
C. Every healed fracture results in a bone that is permanently thicker than before injury.
D. A patient who is bedridden for months will develop thicker bones than an active athlete.

26. Calcium absorption from the small intestine is significantly impaired when which substance is lacking?
A. Vitamin D
B. Vitamin K
C. Calcitonin
D. Fluoride

27. Which of the following foods provides nutrients that are especially important for bone health due to their vitamin K and calcium content?
A. Carrots
B. Liver
C. Leafy green vegetables
D. Oranges

28. Which pair of hormones is primarily responsible for the adolescent growth spurt and the eventual closure of the epiphyseal plates?
A. Estrogen and testosterone
B. Calcitonin and calcitriol
C. Growth hormone and parathyroid hormone
D. Thyroxine and progesterone

29. With respect to their direct effects on bone remodeling, which pair of hormones has opposite actions on blood calcium levels and bone resorption?
A. Estrogen and testosterone
B. Calcitonin and calcitriol
C. Estrogen and progesterone
D. Calcitonin and parathyroid hormone

30. When blood calcium levels deviate significantly from normal, which body system shows the most immediate and life-threatening functional changes?
    A. Skeletal system
    B. Endocrine system
    C. Digestive system
    D. Nervous system
31. All of the following are involved in maintaining calcium homeostasis except which one?
    A. Thyroxine
    B. Calcitonin
    C. Parathyroid hormone
    D. Vitamin D (calcitriol)
32. When blood calcium levels rise above the normal range, which hormone is most likely to be secreted in increased amounts to help restore homeostasis?
    A. Thyroxine
    B. Calcitonin
    C. Parathyroid hormone
    D. Vitamin D (calcitriol)

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6.9: Applied Thinking Self-Check

Challenge Yourself

- Critical thinking is essential in a time of endless information and AI. It helps you move from memorizing facts to making sense of what you learn.
- Use the short-essay, case-based prompts at the end of each chapter to check and deepen your understanding of skeletal organization by applying it to real-life situations.
- State your answer first Write 2 - 3 sentences that clearly give your main idea before any details. Explain your reasoning
  - Write 4 - 8 sentences that explain why or how.
  - Use correct terms (for example: osteon, trabecula, epiphysis, diaphysis, osteoblast, osteoclast, compact bone, spongy bone, load, torque).
  - Show clear cause → effect links (for example, “Because X changes in the bone, Y happens to its strength or function.”)
- Optional quick sketch: You may add a small labeled drawing (for example, an osteon, a trabecula, a long bone with diaphysis and epiphysis, or a lever system). Keep it simple and label only key parts.

1. The skeletal system is made of bone and cartilage and performs many functions (for example: support, protection, movement, mineral storage, blood cell production).
   - Choose three distinct functions of the skeletal system. For each function, describe one or two structural features of bone or cartilage that allow it to perform that function (for example: hard mineralized matrix for protection, joints and lever arms for movement, trabecular bone and marrow spaces for blood cell formation).
     - Explain clearly how each structure supports the function you chose.
     - Compare the micro-architecture of cortical (compact) and trabecular (spongy) bone (for example: osteons, density, porosity, orientation of bone tissue).
   - Explain how these differences allow each type of bone to meet specific mechanical demands (resisting bending/torsion vs absorbing and distributing loads) and help with calcium homeostasis.
   - Use this understanding to explain why vertebral compression fractures are common in osteoporosis and how this pattern of fracture differs from a typical mid-shaft humeral fracture.
2. An older adult comes to clinic with knee pain. Imaging shows degeneration of the hyaline cartilage on the articular surfaces of the femur and tibia, but the underlying bone is still intact. Based on the loss of smooth hyaline cartilage at this synovial joint, what symptoms and physical signs would you expect this patient to show during activity and at rest?
3. In what ways is the structural makeup of compact and spongy bone well suited to their respective functions? Explain how osteon organization, porosity, and orientation in compact bone versus trabecular struts (trabeculae) optimize resistance to different forces and support marrow/vascular functions. Apply this to why diaphyses resist bending/torsion while epiphyses adapt to multidirectional loads.
4. Compare the femur’s role as a weight-bearing long bone with the patella’s role as a sesamoid bone in the quadriceps tendon. Explain how shape, articulation, and lever arm modification affect knee extension torque and gait.
5. A runner develops midfoot pain after increasing mileage, while another patient sprains an ankle during inversion. Contrast the structural and functional roles of a tarsal (e.g., calcaneus or talus) and a metatarsal in load transfer and leverage. Use this to explain the different injury mechanisms, clinical signs, and expected imaging findings.
6. In what ways do intramembranous and endochondral ossification differ in starting tissue, mechanism, bones formed, and timing of bone development?
7. Considering how a long bone develops, what are the similarities and differences between a primary and a secondary ossification center?
8. What is the difference between closed reduction and open reduction? In what type of fracture would closed reduction most likely occur? In what type of fracture would open reduction most likely occur?
9. If you were a dietitian who had a young female patient with a family history of osteoporosis, what foods would you suggest she include in her diet? Why?
10. During the early years of space exploration our astronauts, who had been floating in space, would return to earth showing significant bone loss dependent on how long they were in space. Discuss how this might happen and what could be done to

alleviate this condition.

11. An individual with very low levels of vitamin D presents themselves to you complaining of seemingly fragile bones. Explain how these might be connected.
12. Describe the effects caused when the parathyroid gland fails to respond to calcium bound to its receptors.

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6.10: Alternate Text Descriptions

Figure 6.1: Osteon

Cross-sectional diagram of an osteon, the structural unit of compact bone. At the center is a circular central canal containing blood vessels. Surrounding the central canal are multiple concentric rings called lamellae. Dark oval-shaped osteocytes are located within small spaces called lacunae between the lamellae. Fine branching canaliculi extend from the lacunae, forming a network that connects osteocytes to one another and to the central canal. The outer edge of the osteon is lined with osteoblasts, shown as a ring of cells. Larger multinucleated osteoclasts are shown on the bone surface. Labels identify osteoclast, osteoblast, lamellae, osteocyte in a lacuna, canaliculi, and central canal.

Figure 6.1.1: Bones Support Movement

This image represents a person performing a leg press exercise on a weight machine with multiple weight plates loaded. The individual is lying on the bench with feet positioned on the footplate, wearing white athletic shoes, black shorts, and a light gray shirt. The machine is labeled 'Atlantis' and has a sturdy metal frame.

Figure 6.1.2: Bones Protect Brain

This image shows an anatomical illustration of the human head from a frontal perspective. The skull is drawn in light gray, and the brain is overlaid in a semi-transparent brownish color, allowing both structures to be visible. Key features include:

- The brain occupying the upper portion of the skull, with visible folds (gyri and sulci).
- The eye sockets (orbits) and nasal cavity clearly outlined.
- The teeth in the lower jaw are shown in white.

Figure 6.1.3: Complex Brace

This image shows a complex orthopedic brace designed to support and stabilize a limb. Such braces may be prescribed by an orthopedist to reinforce the underlying bone and joint structure, limit movement, and promote proper alignment during recovery.

Figure 6.1.4: The head of the femur

This image shows a cross-section of a bone, cut horizontally to reveal its internal structure. The bone appears circular, with clearly defined layers and labeled regions. The outer surface of the bone forms a firm, pale ring around the edge. This layer represents compact bone, which provides strength and protection. Inside the bone is a spongy, porous region. The red marrow is shown as darker red, sponge-like tissue closer to the inner surface of the compact bone. Red marrow is responsible for producing blood cells. Toward the center is the yellow marrow, which appears lighter and more fatty in texture. Yellow marrow primarily stores fat and can convert to red marrow when increased blood cell production is needed. Bracketed labels point to the red and yellow marrow regions, helping distinguish their locations within the bone. The image emphasizes the structural organization of bone and the functional differences between compact bone, red marrow, and yellow marrow.

Figure 6.2.1: Classification of Bone Types

This image shows a classification of bone types in the human body, using a central skeleton with arrows pointing to examples of each type of bone.

The overall organization shows a full human skeleton in the center, with enlarged examples of bone types placed around it. Arrows connect each example to its corresponding location in the skeleton. The category labels shown are flat bones, long bones,

irregular bones, short bones, and sesamoid bones. The example labels shown are sternum (breastbone) for flat bone, femur (thigh bone) for long bone, vertebra for irregular bone, cuneiform bones (medial, intermediate, lateral) for short bones, and patella (kneecap) for sesamoid bone.

The flat bone example is the sternum (breastbone). It is shown as a thin, flattened bone with a broad surface. Flat bones provide protection for internal organs and also offer large surfaces for muscle attachment.

The long bone example is the femur (thigh bone). It is shown as a bone that is longer than it is wide, with a shaft and enlarged ends. Long bones support body weight and act as levers for movement. They are essential for walking and other large movements.

The irregular bone example is the vertebra. It is shown as a bone with a complex shape that does not fit the other categories. Irregular bones provide specialized support and protection. Vertebrae protect the spinal cord and support body posture.

The short bones examples are the cuneiform bones, labeled medial, intermediate, and lateral, in the foot. These are shown as small, roughly cube-shaped bones. Short bones provide stability and support with limited movement. They help distribute forces during standing and walking.

The sesamoid bone example is the patella (kneecap). It is shown as a small, round bone embedded within a tendon. Sesamoid bones protect tendons from stress and improve the efficiency of muscle movement by changing the angle of force.

Figure 6.3.1: Anatomy of a Long Bone

This image shows the internal and external structure of a long bone, with labeled regions and components that contribute to bone growth, support, and function.

The bone is oriented vertically from top, or proximal end, to bottom, or distal end. The labels in the image include proximal epiphysis, distal epiphysis, metaphysis, diaphysis, spongy bone, red bone marrow, articular cartilage, epiphyseal line, compact bone, medullary cavity, yellow bone marrow, endosteum, periosteum, and nutrient artery. The major labeled regions are the epiphyses at the ends, the metaphyses as transition regions, and the diaphysis as the shaft.

At the top and bottom of the bone are the proximal epiphysis and distal epiphysis. These expanded end regions contain spongy bone with spaces filled by red bone marrow. Their outer surfaces are covered with articular cartilage. The epiphyses participate in joint formation, the articular cartilage provides a smooth surface that reduces friction during movement, and the red bone marrow functions in blood cell production.

Between each epiphysis and the shaft is the metaphysis. This region contains the epiphyseal line, which is the remnant of the growth plate. During growth, this region allows for lengthwise bone growth, and in adults the epiphyseal line marks where growth has occurred.

The long central shaft is the diaphysis. It is composed primarily of compact bone, which forms a strong outer layer. Inside is the medullary cavity, which contains yellow bone marrow. The compact bone provides strength and support for weight-bearing, the medullary cavity reduces bone weight while maintaining strength, and the yellow bone marrow stores energy in the form of fat.

The image also identifies two bone tissue types. Spongy bone is found mainly in the epiphyses and is composed of a network of trabeculae, or supporting structures. It provides lightweight structural support and houses red bone marrow for blood cell production. Compact bone forms the dense outer layer of the diaphysis. It provides rigidity and protection and resists bending and mechanical stress.

The internal lining labeled endosteum is a thin layer inside the medullary cavity. It is involved in bone growth and remodeling. The outer covering labeled periosteum is a membrane covering the outer surface of the bone. It provides protection and nourishment, anchors tendons and ligaments, and contains cells important for bone repair.

The labeled nutrient artery enters the diaphysis and branches inside the bone. Its function is to supply oxygen and nutrients to bone tissue and support bone maintenance and repair.

The wider section at each end of the bone is called the epiphysis (plural = epiphyses), which is filled with spongy bone. Red marrow fills the spaces in the spongy bone. Each epiphysis meets the diaphysis at the metaphysis, the narrow area that contains the epiphyseal plate (growth plate), a layer of hyaline (transparent) cartilage in a growing bone. When the bone stops growing in early adulthood (approximately 18–21 years), the cartilage is replaced by osseous tissue and the epiphyseal plate becomes an

epiphyseal line.

Figure 6.3.2: Periosteum and Endosteum

This image shows a long bone with two magnified views that explain the membranes and cells associated with bone tissue. The main image in the center identifies the bone as the source of two close-up sections. One close-up focuses on the periosteum, which covers the outer surface of the bone. The other close-up focuses on the endosteum, which lines the inner bone surface.

In the left magnified section of the image, the label Periosteum identifies the outer covering of the bone. The diagram further labels the periosteum (fibrous layer) and the periosteum (cellular layer), showing that the periosteum has two distinct layers. The fibrous layer is the outer protective layer, while the cellular layer is the inner layer involved in bone growth and repair. The label osteocyte in lacuna identifies a mature bone cell located within a small space in the bone tissue beneath these outer layers.

In the right magnified section of the image, the label Endosteum identifies the membrane lining the inner surface of the bone. Additional labels identify the major structures and cell types involved in bone remodeling. The osteoclast is shown along the bone surface and represents the cell responsible for breaking down bone tissue. The bone matrix is the hard structural material of the bone. The osteocyte is a mature bone cell embedded within the matrix. The osteogenic cell is a precursor cell that can develop into bone-forming cells. The osteoblast is the cell responsible for building new bone.

Overall, the image explains that the periosteum covers the outside of bone and contains fibrous and cellular layers, while the endosteum lines the inside of bone and contains cells involved in bone breakdown, formation, and maintenance. Together, these labels show how bone tissue is organized and how different bone cells support growth, repair, and remodeling.

Figure 6.3.3: Anatomy of a Flat Bone

This image shows a cross section of a cranial bone, constructed somewhat like a sandwich. The topmost and bottommost layers are the thin, translucent, periosteum. The upper and lower periosteum cover an upper and lower layer of compact bone, respectively. The compact bone is solid, with each layer occupying about one tenth of the thickness of the cranial bone. The majority of the cross section is occupied by the spongy bone, or diploe, sandwiched between the upper and lower compact bone. The spongy bone contains many crisscrossing threads of bone. Dark air spaces occur between the threads, giving the bone a porous appearance, much like that of a sponge or Swiss cheese.

Figure 6.3.4: Bone Features

This image contains three diagrams showing examples of common bone markings. The diagrams use the femur and humerus, the pelvis, and the skull to illustrate markings associated with attachment, articulation, elevation or depression, and openings in bone.

The left diagram in the image includes an anterior view of the femur and an anterior view of the humerus. It is organized under two headings. The first heading is examples of processes formed where tendons or ligaments attach. In this section, the labeled examples are fovea capitis, head, tubercle, tuberosity, and sulcus. On the proximal femur, the rounded articular knob is labeled head, and the small depression on that head is labeled fovea capitis. On the humerus, the proximal region includes labeled tubercles, and the groove between them is labeled sulcus. The shaft of the humerus includes a labeled tuberosity, identifying a roughened area used for attachment.

The same left diagram also includes the heading examples of processes formed to articulate with adjacent bones. In this section, the distal femur shows condyles, and the articular surface between or associated with these structures is labeled facet. On the distal humerus, a labeled condyle appears near the lower end, and a labeled fossa identifies a depression in the bone. Together, this section shows examples of markings involved in joint formation and articulation with nearby bones.

The middle diagram in the image is titled examples of an elevation or depression and shows the pelvis in anterior view. The upper border of the hip bone is labeled crest, showing an elevated ridge. A shallow depression on the internal surface is labeled fossa. This diagram contrasts a raised bony ridge with a depressed area.

The right diagram in the image is titled examples of openings and shows the skull in anterior view. The labels include sinus, canal, foramen, and fissure. The sinuses are shown as internal cavities within the skull bones. The canals identify passageways through

bone. The foramina identify openings through which structures such as nerves or blood vessels may pass. The fissures identify narrow slit-like openings. The skull also includes the label protuberance, identifying a projecting area of bone.

Overall, the image teaches that bone markings can be grouped by function and form. The labeled examples include head, fovea capitis, tubercle, tuberosity, sulcus, facet, condyle, condyles, fossa, crest, sinus, canal, foramen, fissure, and protuberance.

Figure 6.3.5: Bone Cells

This image shows a cross section of bone tissue with callouts to four major bone cell types. At the top is a generic cross section of bone. Three highlighted regions indicate different locations within the bone structure, and arrows lead from these regions to labeled examples of bone cells below. The diagram is designed to show both the location and function of osteoblasts, osteocytes, osteogenic cells, and osteoclasts.

A callout in the image from the periosteum leads to two labeled cell examples. One image shows osteoblasts, with the caption osteoblasts form the matrix of the bone. These cells are arranged in a row along the periosteal surface, showing their role in forming new bone matrix at the outer surface of the bone. A second image from the same periosteal region shows an osteogenic cell with the caption stem cell. This identifies the osteogenic cell as a precursor cell located near the periosteum that can develop into other bone cells.

A callout from within the compact bone points to an osteocyte. The caption identifies its function as maintains bone tissue. This shows that osteocytes are located within bone tissue and are responsible for maintaining the bone matrix.

A callout from the inner edge of the compact bone, where it transitions toward spongy bone, points to an osteoclast. The caption identifies its function as resorbs bone. This shows the osteoclast at a bone surface where bone breakdown or resorption occurs.

Overall, the image explains the relationship between bone cell type, location, and function. Osteoblasts form bone matrix, osteogenic cells act as stem cells, osteocytes maintain bone tissue, and osteoclasts resorb bone.

Figure 6.3.6: A generic long bone

A generic long bone is shown in the image. This figure contains two panels labeled (a) and (b). Together, the panels show the structure of compact bone and how it appears in a microscope view.

In panel (a), a long bone is shown in lengthwise section to reveal its internal anatomy. The outer covering is labeled periosteum. Beneath the outer surface is compact bone, which surrounds the medullary cavity. Spongy bone is shown in the expanded ends of the bone. A callout indicates that the enlarged main image is a zoomed-in view of the compact bone from the shaft region.

In the enlarged diagram of the image, the periosteum is peeled back to show two layers. The outer layer is labeled outer fibrous layer, and the inner layer is labeled inner osteogenic layer. A periosteal artery and periosteal vein are shown near the periosteum. Just deep to the periosteum are layers labeled circumferential lamellae, which run along the outer surface of the compact bone.

Most of the compact bone is organized into circular units called osteons. Each osteon contains concentric lamellae arranged around a central canal. The central canal contains blood vessels, a lymphatic vessel, and a nerve. The figure also shows a perforating canal, which runs across the compact bone and connects vessels from the periosteum with the vessels in the central canals. Between neighboring osteons are areas labeled interstitial lamellae.

At the inner edge of the enlarged block , the compact bone transitions to spongy bone. The spongy bone is made of branching structures labeled trabeculae. Open spaces among the trabeculae border the medullary cavity.

In the image, Panel (b) is a micrograph of compact bone. It shows an osteon in cross section, with ring-like layers corresponding to concentric lamellae surrounding a central open space that represents the central canal. Additional surrounding circular and partial circular patterns indicate adjacent bone structures in the compact bone.

Overall, the figure explains that compact bone is covered by the periosteum, organized into osteons with concentric lamellae and central canals, connected by perforating canals, and positioned next to spongy bone made of trabeculae near the medullary cavity.

Figure 6.3.7: Diagram of Spongy Bone

This image shows spongy bone in the proximal epiphysis of the femur using two successive magnified views. The image begins with a section of the femur that identifies spongy bone in the epiphysis and compact bone in the shaft. A highlighted region within the spongy bone is enlarged to show the structure of the trabeculae.

The lower-magnification enlarged view shows branching trabeculae within the spongy bone. The surface of the trabeculae is labeled with canaliculi openings on surface, indicating small openings that connect with the canaliculi within the bone matrix. One trabecula is shown in cross section to reveal its internal structure. Its outer covering is labeled endosteum, and beneath that covering are layers of bone matrix labeled lamellae.

The higher-magnification view shows the cross section of a trabecula in greater detail. The labels identify lamellae, canaliculi, lacuna, osteocyte, osteoclast, and osteoblasts aligned along trabeculae of new bone. The lamellae form layered rings of bone matrix. Small spaces within the matrix, labeled lacunae, contain osteocytes, which are mature bone cells. Fine channels labeled canaliculi extend through the matrix and connect the spaces within the bone tissue. On the outer surface of the trabecula, osteoblasts line areas of new bone formation, while osteoclasts appear on the surface where bone resorption occurs.

Overall, the diagram explains that spongy bone is made of branching trabeculae covered by endosteum and built from layered lamellae. It also shows that osteocytes occupy lacunae, canaliculi connect through the matrix, and osteoblasts and osteoclasts function on the trabecular surface during bone remodeling.

Figure 6.3.8: Paget's Disease

This image shows two anterior-view skeletal diagrams of the pelvis and lower limbs placed side by side for comparison. The figure on the left shows one alignment pattern, and the figure on the right shows a different alignment pattern. The purpose of the diagram is to compare how the femurs angle from the pelvis toward the knees and how this affects the position of the knees and lower legs.

In the left diagram of the image, the femurs angle inward from the pelvis toward the knees. The knees are positioned relatively close together, while the lower legs extend more vertically below them. This arrangement illustrates one pattern of lower-limb alignment in which the femurs converge toward the midline.

In the right diagram of the image, the femurs show a different alignment. The knees are positioned farther apart, and the lower limbs create a wider stance pattern. This arrangement illustrates a contrasting lower-limb alignment pattern compared with the figure on the left.

Overall, the image is designed to compare two different skeletal alignments of the lower limbs by showing how the angle of the femur affects knee position and the spacing of the legs.

Figure 6.3.9: Diagram of Blood and Nerve Supply

This image shows an anterior view of the right femur split lengthwise to reveal its internal anatomy and blood supply. The image labels the main vessels that enter the bone and shows how they relate to the periosteum, compact bone, medullary cavity, and the ends of the bone.

The outer covering of the femur is labeled periosteum. Deep to the periosteum is a layer of compact bone that surrounds the medullary cavity. At both epiphyses, the interior includes spongy bone, and the upper end is also labeled articular cartilage.

At the center of the diaphysis, a nutrient artery and vein enter the bone through the nutrient foramen. After entering, these vessels branch within the medullary cavity and extend upward and downward through the shaft. Some branches continue toward the spongy bone in the proximal and distal ends of the femur.

Additional vessels labeled in of the image are metaphyseal artery and vein enter the bone from outside at the metaphysis. The lower end of the figure also labels the metaphysis and the epiphyseal line, showing the relationship between the blood supply and the growth region of the bone. At the upper end, the diagram labels the epiphyseal artery and vein, which supply the epiphysis.

Overall, the image explains that the femur receives blood from several vessel systems. The nutrient artery and vein supply the

shaft and medullary cavity, while the metaphyseal and epiphyseal vessels supply the ends of the bone. The image also relates these vessels to surrounding structures including the periosteum, compact bone, medullary cavity, spongy bone, metaphysis, epiphyseal line, and articular cartilage.

Figure 6.4.1: Intramembranous Ossification

This image illustrates the process by which bone forms directly from connective tissue. The figure is organized as a sequence of four panels, labeled **(a)** through **(d)**, showing the progression from mesenchymal tissue to mature bone. Labels appearing in the figure include:

- Mesenchymal cells
- Collagen fibers
- Ossification center
- Osteoid
- Osteoblast
- Osteocyte
- New bone matrix
- Mesenchyme forms the periosteum
- Trabeculae
- Blood vessel
- Fibrous periosteum
- Compact bone
- Spongy bone (cavities contain red marrow)

a. Mesenchymal cells are scattered among surrounding collagen fibers. A cluster of mesenchymal cells forms an ossification center, where some cells differentiate into osteoblasts. The osteoblasts secrete osteoid, an unmineralized organic bone matrix that marks the beginning of bone formation.
b. Osteoblasts continue secreting osteoid around the developing center. As matrix accumulates and mineralizes, some osteoblasts become enclosed within it and differentiate into osteocytes. The mineralized tissue forms new bone matrix.
c. The developing bone is organized into trabeculae, creating a network of bony supports. Blood vessels grow through the spaces between the trabeculae. The surrounding mesenchyme forms the periosteum, establishing the outer membrane that will cover the bone.
d. The mature structure contains an outer layer of compact bone beneath the fibrous periosteum. Osteoblasts remain along the bone surface. The interior consists of spongy bone, whose cavities contain red marrow. This organization produces a bone that is strong on the outside while maintaining a lighter, marrow-filled interior.

Overall, the figure shows that intramembranous ossification begins when mesenchymal cells form an ossification center and differentiate into osteoblasts that secrete osteoid. The osteoid becomes new bone matrix containing osteocytes, trabeculae and blood vessels develop, mesenchyme forms the periosteum, and the process culminates in the formation of compact bone surrounding spongy bone with red marrow.

Figure 6.4.2: Endochondral ossification

This image explains the stages of endochondral ossification, the process by which a long bone develops from a hyaline cartilage model. The sequence is organized into six panels labeled (a) through (f), beginning with a cartilage template covered by perichondrium and ending with a developing long bone that contains articular cartilage, spongy bone, and an epiphyseal plate.

In panel (a), the structure consists of a hyaline cartilage model surrounded by perichondrium. This cartilage template represents the future bone before ossification begins.

In panel (b), the cartilage model has increased in size and the ends have become enlarged. A region of calcified matrix appears in the center of the shaft, while uncalcified matrix remains around the calcified area and throughout much of the cartilage toward the outer portions and ends of the model. This stage shows calcification beginning within the interior of the cartilage while surrounding cartilage remains unchanged.

In panel (c), a primary ossification center develops in the shaft region. The outer covering has become periosteum, and spongy bone is forming within the ossification center where cartilage is being replaced by bone. A nutrient artery enters the developing

bone, demonstrating vascular invasion of the ossifying tissue.

In panel (d), further ossification has occurred in the shaft, producing a central medullary cavity. The cavity is surrounded by developing compact bone, which is covered externally by the periosteum. Near the ends of the bone, areas of calcified matrix persist within the interior cartilage, while uncalcified matrix remains closer to the outer portions of the epiphyses. An artery and vein travel through the developing bone and provide circulation to the growing tissues.

In panel (e), a secondary ossification center forms within the epiphysis. Arteries and veins have entered the epiphyseal region and extend into the new ossification center. Surrounding the ossification center, uncalcified matrix remains within the epiphyseal cartilage, showing that bone formation is progressing within the center while cartilage is still present around it.

In panel (f), the developing long bone has a more mature structure. Spongy bone occupies much of the epiphysis, while articular cartilage remains on the joint surface. Between the epiphysis and the shaft is the epiphyseal plate, a region of cartilage that allows continued lengthwise growth of the bone. Bone has replaced most of the original cartilage model, but cartilage remains at the articular surface and growth plate.

Overall, the sequence shows that endochondral ossification begins with a hyaline cartilage model, progresses through calcification of cartilage and formation of a primary ossification center in the shaft, continues with invasion by blood vessels and development of a medullary cavity, and later forms secondary ossification centers in the epiphyses. As ossification advances, cartilage is gradually replaced by bone, remaining only at the articular surfaces and within the epiphyseal plates.

Figure 6.4.3: Longitudinal Bone Growth

This image shows the zones of the epiphyseal growth plate and the corresponding changes in chondrocytes during endochondral bone growth. The figure is organized from top to bottom. The left side lists the growth plate zones, the center shows the appearance and arrangement of cells and matrix within each zone, and the right side lists the main cellular changes occurring in each region. At the bottom, the image transitions into the metaphysis, where ossification occurs.

The top region is labeled the reserve zone. The corresponding change in chondrocytes is matrix production. In this region, the chondrocytes are scattered within the cartilage matrix and are relatively inactive compared with the zones below.

Below the reserve zone is the proliferative zone. The corresponding change is mitosis. In this zone, the chondrocytes divide and become arranged in vertical columns. This organization reflects active cell proliferation that contributes to bone lengthening.

Below the proliferative zone is the maturation and hypertrophy zone. The corresponding description states that lipids, glycogen, and alkaline phosphatase accumulate; matrix calcifies. In this region, the chondrocytes enlarge, and the surrounding matrix begins to change in preparation for calcification.

Below that is the calcified matrix zone. The corresponding change is cell death. In this region, the matrix has calcified, and the chondrocytes die as the cartilage is prepared for replacement by bone.

At the bottom of the image is the zone of ossification, which is located in the metaphysis. Blood vessels extend upward into this region. The right side of the image labels primary spongiosa and secondary spongiosa, indicating newly formed and more developed spongy bone in the metaphyseal region. This is where calcified cartilage is replaced by bone tissue.

Overall, the image explains the sequence of events in the growth plate during endochondral bone growth. Chondrocytes first produce matrix in the reserve zone, then divide in the proliferative zone, enlarge and alter the matrix in the maturation and hypertrophy zone, die in the calcified matrix zone, and are replaced by bone in the metaphyseal zone of ossification.

Figure 6.4.4: Long Bone Growth and Maturation

This image compares a growing long bone with a mature long bone using the femur as an example. The diagram is divided into two parts. On the left is panel (a), labeled growing long bone. On the right is panel (b), labeled mature long bone. Both images label the main regions of a long bone: epiphysis, metaphysis, and diaphysis.

In panel (a), the growing femur shows an epiphyseal plate, also called a growth plate, near both ends of the bone. One growth plate is shown near the proximal end and another near the distal end. The labeled regions show that the epiphysis is located at each end of the bone, the metaphysis lies between each epiphysis and the shaft, and the diaphysis forms the long central shaft.

The presence of epiphyseal plates indicates that the bone is still growing in length.

In panel (b), the mature femur shows the same overall regions: epiphysis, metaphysis, and diaphysis. However, instead of epiphyseal plates, the bone contains epiphyseal lines. These lines indicate the former location of the growth plates after growth has ended. The mature bone no longer has active growth plates.

Overall, the image explains that a growing long bone contains epiphyseal plates at the metaphysis near each epiphysis, while a mature long bone contains epiphyseal lines in those same locations. The diagram also reinforces the organization of the long bone into epiphysis, metaphysis, and diaphysis.

Figure 6.5.2: Stages in Fracture Repair

This image illustrates a left-to-right progression of bone repair following a fracture in the shaft of the femur. The sequence begins with the broken bone and then shows four magnified stages of healing labeled (a) through (d).

In panel (a), the fracture site is enlarged and labeled hematoma. Blood fills the gap between the broken ends of the bone and also spreads around the outer sides of the fracture. This pooled blood creates a swollen region at the break site.

In panel (b), the hematoma has been replaced by an internal callus and an external callus. The image also labels new blood vessels and spongy bone trabeculae. In this stage, vascular tissue reconnects across the fracture and early spongy bone begins to form between the broken ends.

In panel (c), the fracture gap is bridged by a bony callus of spongy bone. This indicates that spongy bone has regenerated across the break and now connects the two ends of the bone. The outer repair tissue remains larger than the original shaft because remodeling is not yet complete.

In panel (d), the fracture is labeled healed fracture. The bone has been repaired and the outer shape is closer to its final form, although a slight bulge remains at the repair site. The final image at the far right shows the healed femur in a zoomed-out view.

Overall, the image shows that fracture repair begins with a hematoma, progresses through formation of internal and external callus, develops into a bony callus of spongy bone, and ends with a healed fracture.

Figure 6.6.1: Calcium Level Homeostasis

This image shows calcium homeostasis as a feedback system that maintains the normal calcium level in the blood at about 10 milligrams per deciliter. The center of the figure is labeled homeostasis and normal calcium level (10 mg/dL). Two feedback pathways surround the center: one for increased calcium levels and one for decreased calcium levels.

When the calcium level in the blood increases, the diagram shows that the thyroid gland releases calcitonin. Calcitonin then leads to two responses: osteoclast activity is inhibited and calcium reabsorption in the kidneys decreases. These responses cause the calcium level in the blood to decrease, returning it toward the normal level.

When the calcium level in the blood decreases, the diagram shows that the parathyroid glands release parathyroid hormone, or PTH. PTH leads to three responses: osteoclasts release calcium from bone, calcium is reabsorbed from urine by the kidneys, and calcium absorption in the small intestine increases through vitamin D synthesis. These responses cause the calcium level in the blood to increase, returning it toward the normal level.

Overall, the figure explains that calcium balance is maintained by two opposing hormonal pathways. Calcitonin lowers elevated blood calcium levels, while parathyroid hormone raises low blood calcium levels.

Blood calcium homeostasis is the body's process of maintaining stable blood calcium levels through a feedback system involving parathyroid hormone (PTH), vitamin D, and calcitonin.

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7: THE AXIAL SKELETON

Chapter Overview

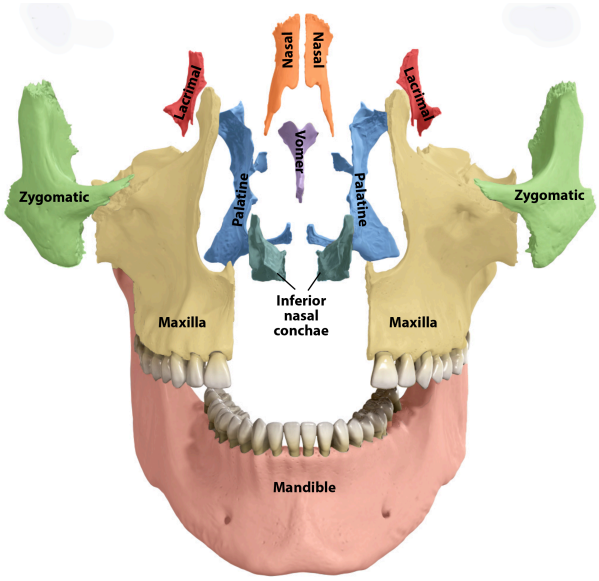


Figure 7.1: Exploded anterior view of facial skull bones with color-coded labels identifying the maxillae, mandible, zygomatic bones, nasal bones, lacrimal bones, palatine bones, vomer, and inferior nasal conchae. (CC BY-NC-SA 4.0; via The Skull). Alternative text description of the Figure 7.1.

Functions and Divisions of the Skeletal System

The skeletal system includes all of the bones, cartilages, and ligaments of the body. It serves to support the body, protect the brain and other internal organs, and provides a rigid structure upon which muscles can pull to generate body movements. It also stores fat and the tissue responsible for the production of blood cells. The skeleton is subdivided into two parts. The axial skeleton forms a vertical axis that includes the head, neck, back, and chest. It has 80 bones and consists of the skull, vertebral column, and thoracic cage. The adult vertebral column consists of 24 vertebrae plus the sacrum and coccyx. The thoracic cage is formed by 12 pairs of ribs and the sternum. The appendicular skeleton consists of 126 bones in the adult and includes all of the bones of the upper and lower limbs plus the bones that anchor each limb to the axial skeleton.

Brain Case (Cranial Bones) and Sutures of the Skull

The skull consists of the brain case and the facial bones. The brain case surrounds and protects the brain, which occupies the cranial cavity inside the skull. It consists of the rounded calvaria and a complex base. The brain case is formed by eight bones, the paired parietal and temporal bones plus the unpaired frontal, occipital, sphenoid, and ethmoid bones. The narrow gap between the bones is filled with dense, fibrous connective tissue that unites the bones. The sagittal suture joins the right and left parietal bones. The coronal suture joins the parietal bones to the frontal bone, the lambdoid suture joins them to the occipital bone, and the squamous suture joins them to the temporal bone.

Facial Bones and the Hard Palate

The facial bones support the facial structures and form the upper and lower jaws. These consist of 14 bones, with the paired maxillary, palatine, zygomatic, nasal, lacrimal, and inferior conchae bones and the unpaired vomer and mandible bones. The ethmoid bone also contributes to the formation of facial structures. The maxilla forms the upper jaw and the mandible forms the lower jaw. The maxilla also forms the larger anterior portion of the hard palate, which is completed by the smaller palatine bones that form the posterior portion of the hard palate.

Cranial Fossae and Major Foramina of the Skull Base

The floor of the cranial cavity increases in depth from front to back and is divided into three cranial fossae. The anterior cranial fossa is located between the frontal bone and lesser wing of the sphenoid bone. A small area of the ethmoid bone, consisting of the crista galli and cribriform plates, is located at the midline of this fossa. The middle cranial fossa extends from the lesser wing of the sphenoid bone to the petrous ridge (petrous portion of temporal bone). The right and left sides are separated at the midline by the sella turcica, which surrounds the shallow hypophyseal fossa. Openings through the skull in the floor of the middle fossa include the optic canal and superior orbital fissure, which open into the posterior orbit, the foramen rotundum, foramen ovale, and foramen spinosum, and the exit of the carotid canal with its underlying foramen lacerum. The deep posterior cranial fossa extends from the petrous ridge to the occipital bone. Openings here include the large foramen magnum, plus the internal acoustic meatus, jugular foramina, and hypoglossal canals. Additional openings located on the external base of the skull include the stylomastoid foramen and the entrance to the carotid canal.

Anterior Skull: Orbits, Nasal Cavity, and Paranasal Sinuses

The anterior skull has the orbits that house the eyeballs and associated muscles. The walls of the orbit are formed by contributions from seven bones: the frontal, zygomatic, maxillary, palatine, ethmoid, lacrimal, and sphenoid. Located at the superior margin of the orbit is the supraorbital foramen, and below the orbit is the infraorbital foramen. The mandible has two openings, the mandibular foramen on its inner surface and the mental foramen on its external surface near the chin. The nasal conchae are bony projections from the lateral walls of the nasal cavity. The large inferior nasal concha is an independent bone, while the middle and superior conchae are parts of the ethmoid bone. The nasal septum is formed by the perpendicular plate of the ethmoid bone, the vomer bone, and the septal cartilage. The paranasal sinuses are air-filled spaces located within the frontal, maxillary, sphenoid, and ethmoid bones.

Lateral Skull, Temporal and Infratemporal Fossae, and Zygomatic Arch

On the lateral skull, the zygomatic arch consists of two parts, the temporal process of the zygomatic bone anteriorly and the zygomatic process of the temporal bone posteriorly. The temporal fossa is the shallow space located on the lateral skull above the level of the zygomatic arch. The infratemporal fossa is located below the zygomatic arch and deep to the ramus of the mandible.

Hyoid Bone and Its Functions

The hyoid bone is located in the upper neck and does not join with any other bone. It is held in position by muscles and serves to support the tongue above, the larynx below, and the pharynx posteriorly.

Regions and Curvatures of the Vertebral Column

The vertebral column forms the neck and back. The vertebral column originally develops as 33 vertebrae, but is eventually reduced to 24 vertebrae, plus the sacrum and coccyx. The vertebrae are divided into the cervical region (C1–C7 vertebrae), the thoracic region (T1–T12 vertebrae), and the lumbar region (L1–L5 vertebrae). The sacrum arises from the fusion of five sacral vertebrae and the coccyx from the fusion of four small coccygeal vertebrae. The vertebral column has four curvatures, the cervical, thoracic, lumbar, and sacrococcygeal curves. The thoracic and sacrococcygeal curves are primary curves retained from the original fetal curvature. The cervical and lumbar curves develop after birth and thus are secondary curves. The cervical curve develops as the infant begins to hold up the head, and the lumbar curve appears with standing and walking.

General Structure of a Typical Vertebra

A typical vertebra consists of an enlarged anterior portion called the body, which provides weight-bearing support. Attached posteriorly to the body is a vertebral arch, which surrounds and defines the vertebral foramen for passage of the spinal cord. The vertebral arch consists of the pedicles, which attach to the vertebral body, and the laminae, which come together to form the roof of the arch. Arising from the vertebral arch are the laterally projecting transverse processes and the posteriorly oriented spinous process. The superior articular processes project upward, where they articulate with the downward projecting inferior articular processes of the next higher vertebrae.

Distinctive Features of Cervical, Thoracic, Lumbar Vertebrae, Sacrum, and Coccyx

A typical cervical vertebra has a small body, a bifid (Y-shaped) spinous process, and U-shaped transverse processes with a transverse foramen. In addition to these characteristics, the axis (C2 vertebra) also has the dens projecting upward from the vertebral body. The atlas (C1 vertebra) differs from the other cervical vertebrae in that it does not have a body, but instead consists of bony ring formed by the anterior and posterior arches. The atlas articulates with the dens from the axis. A typical thoracic vertebra is distinguished by its long, downward projecting spinous process. Thoracic vertebrae also have articulation facets on the body and transverse processes for attachment of the ribs. Lumbar vertebrae support the greatest amount of body weight and thus have a large, thick body. They also have a short, blunt spinous process. The sacrum is triangular in shape. The median sacral crest is formed by the fused vertebral spinous processes and the lateral sacral crest is derived from the fused transverse processes. Anterior (ventral) and posterior (dorsal) sacral foramina allow branches of the sacral spinal nerves to exit the sacrum. The auricular surfaces are articulation sites on the lateral sacrum that anchor the sacrum to the hipbones to form the pelvis. The coccyx is small and derived from the fusion of four small vertebrae.

Intervertebral Discs and Vertebral Ligaments

The intervertebral discs fill in the gaps between the bodies of adjacent vertebrae. They provide strong attachments and padding between the vertebrae. The outer, fibrous layer of a disc is called the anulus fibrosus. The gel-like interior is called the nucleus pulposus. The disc can change shape to allow for movement between vertebrae. If the anulus fibrosus is weakened or damaged, the nucleus pulposus can protrude outward, resulting in a herniated disc.

Major Longitudinal and Connecting Ligaments of the Vertebral Column

The anterior longitudinal ligament runs along the full length of the anterior vertebral column, uniting the vertebral bodies. The supraspinous ligament is located posteriorly and interconnects the spinous processes of the thoracic and lumbar vertebrae. In the neck, this ligament expands to become the nuchal ligament. The nuchal ligament is attached to the cervical spinous processes and superiorly to the base of the skull, out to the external occipital protuberance. The posterior longitudinal ligament runs within the vertebral canal and unites the posterior sides of the vertebral bodies. The ligamentum flavum unites the lamina of adjacent vertebrae.

Thoracic Cage and Sternum

The thoracic cage protects the heart and lungs. It is composed of 12 pairs of ribs with their costal cartilages and the sternum. The ribs are anchored posteriorly to the 12 thoracic vertebrae. The sternum consists of the manubrium, body, and xiphoid process. The manubrium and body are joined at the sternal angle, which is also the site for attachment of the second ribs.

Rib Structure and Classification: True, False, and Floating Ribs

Ribs are flattened, curved bones and are numbered 1–12. Posteriorly, the head of the rib articulates with the costal facets located on the bodies of thoracic vertebrae and the rib tubercle articulates with the facet located on the vertebral transverse process. The angle of the ribs forms the most posterior portion of the thoracic cage. The costal groove in the inferior margin of each rib carries blood vessels and a nerve. Anteriorly, each rib ends in a costal cartilage. True ribs (1–7) attach directly to the sternum via their costal cartilage. The false ribs (8–12) either attach to the sternum indirectly or not at all. Ribs 8–10 have their costal cartilages attached to the cartilage of the next higher rib. The floating ribs (11–12) are short and do not attach to the sternum or to another rib.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own. By the end of this chapter, students should be able to:

- Classify the skeleton into axial vs appendicular, list the axial components, and link each to core functions (support, protection, movement, hematopoiesis, mineral homeostasis).
- Identify on models, diagrams, and basic imaging the major skull bones (cranial vs facial) and key landmarks (processes, sinuses, ridges). Delineate cranial sutures and fontanelles, describe the anterior/middle/posterior cranial fossae, and match major foramina/canals to the neurovascular structures that traverse them.
- Distinguish typical vs atypical vertebrae by region (cervical including C1/C2, thoracic, lumbar, sacral, coccygeal) using hallmark features, and explain how form supports function.
- Describe intervertebral joints (discs and zygapophyseal facets) and relate facet orientation and disc properties to permitted motions across regions.
- Explain normal spinal curvatures (primary vs secondary), their developmental basis, and predict biomechanical consequences of deviations (kyphosis, lordosis, scoliosis).
- Identify the components of the thoracic cage (sternum, true/false/floating ribs, costal cartilages) and describe costovertebral and costosternal articulations.
- Relate thoracic cage structure to ventilation mechanics (pump-handle and bucket-handle movements) and to protection of thoracic organs.
- Correlate external surface landmarks (e.g., mastoid process, sternal angle, spinous processes, costal margin, iliac crest) with underlying axial anatomy and common procedures (e.g., lumbar puncture level, chest tube insertion site).
- Predict the functional impact of selected injuries or conditions (e.g., herniated disc level and affected spinal nerve, whiplash/C1–C2 instability, rib fracture patterns) using anatomical reasoning.
- Summarize embryonic development of the axial skeleton: intramembranous vs endochondral ossification; fontanelle closure; and relate to congenital anomalies (spina bifida, craniosynostosis).
- Describe age-related and hormonal influences on the axial skeleton (disc degeneration, osteoporosis-related vertebral compression, facet arthropathy) and their clinical implications.

7.1: Divisions of the Skeletal System

7.2: The Skull

7.3: The Vertebral Column

7.4: The Thoracic Cage

7.5: Terms and Definitions

7.6: Chapter Review Questions

7.7: Critical Thinking Self-Check

7.8: Alternate Text Descriptions

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7.1: Divisions of the Skeletal System

The Axial Skeleton

The skeletal system includes all of the bones, cartilages, and ligaments of the body that support and give shape to the body and body structures. The skeleton consists of the bones of the body. For adults, there are 206 bones in the skeleton. Younger individuals have higher numbers of bones because some bones fuse together during childhood and adolescence to form an adult bone. The primary functions of the skeleton are to provide a rigid, internal structure that can support the weight of the body against the force of gravity, and to provide a structure upon which muscles can act to produce movements of the body. The lower portion of the skeleton is specialized for stability during walking or running. In contrast, the upper skeleton has greater mobility and ranges of motion, features that allow you to lift and carry objects or turn your head and trunk.

In addition to providing for support and movements of the body, the skeleton has protective and storage functions. It protects the internal organs, including the brain, spinal cord, heart, lungs, and pelvic organs. The bones of the skeleton serve as the primary storage site for important minerals such as calcium and phosphate. The bone marrow found within bones stores fat and houses the blood-cell producing tissue of the body. The skeleton is subdivided into two major divisions—the axial and appendicular.

The skeleton is subdivided into two major divisions—the axial and appendicular. The axial skeleton forms the vertical, central axis of the body and includes all bones of the head, neck, chest, and back (Figure 7.1.1). It serves to protect the brain, spinal cord, heart, and lungs. It also serves as the attachment site for muscles that move the head, neck, and back, and for muscles that act across the shoulder and hip joints to move their corresponding limbs.

The axial skeleton of the adult consists of 80 bones, including the skull, the vertebral column, and the thoracic cage. The skull is formed by 22 bones. Also associated with the head are an additional seven bones, including the hyoid bone and the ear ossicles (three small bones found in each middle ear). The vertebral column consists of 24 bones, each called a vertebra, plus the sacrum and coccyx. The thoracic cage includes the 12 pairs of ribs, and the sternum, the flattened bone of the anterior chest.

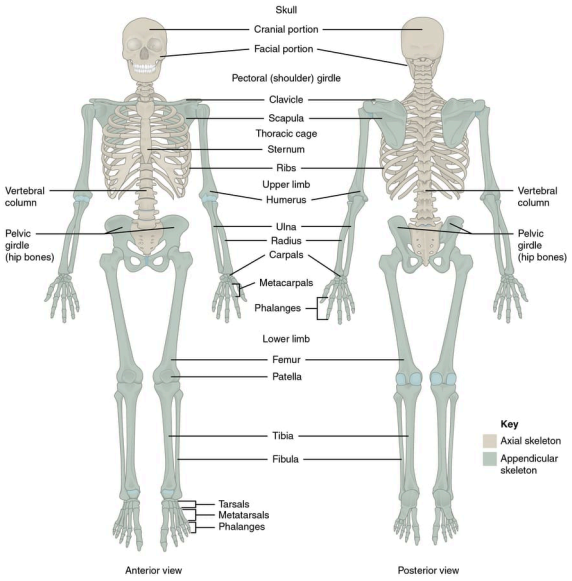


Figure 7.1.1: Axial and Appendicular Skeleton. The axial skeleton supports the head, neck, back, and chest and thus forms the vertical axis of the body. It consists of the skull, vertebral column (including the sacrum and coccyx), and the thoracic cage, formed by the ribs and sternum. The appendicular skeleton is made up of all bones of the upper and lower limbs. (CC BY 4.0 ; via Wikimedia Commons). Alternative text description of Figure 7.1.1.

The appendicular skeleton includes all bones of the upper and lower limbs, plus the bones that attach each limb to the axial skeleton. There are 126 bones in the appendicular skeleton of an adult. The bones of the appendicular skeleton are covered in chapter 8.

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7.2: The Skull

Cranial Bones

The cranium (skull) is the skeletal structure of the head that supports the musculature and structures of the face and forms a protective cavity for the brain (Figure 7.2.1. The adult human skull is comprised of twenty-two bones which are divided into two parts of differing embryological origin: the neurocranium and the viscerocranium. The neurocranium forms the cranial cavity that surrounds and protects the brain and brainstem. With the exception of the mandible, all 22 two bones are joined together by sutures—synarthrodial (immovable) joints.

The neurocranium is formed from eight bones, the occipital bone, two temporal bones, two parietal bones, the sphenoid, ethmoid and frontal bones; they are all joined together with sutures (Figure 7.2.1).

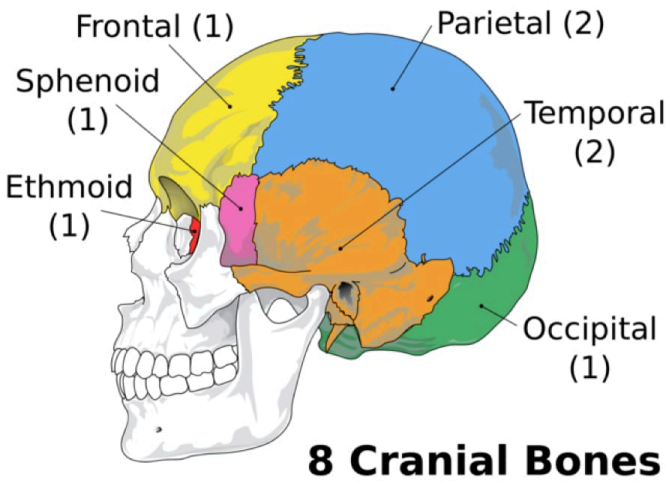


Figure 7.2.1: Lateral skull diagram highlighting the eight cranial bones. (CC BY 4.0; Boundless Anatomy and Physiology). Alternative text description of the Figure 7.2.1.

Anterior View of Skull

The anterior view of the skull prominently features the frontal bone , which forms the forehead and the upper edge of the eye sockets, or orbits. Also seen are the upper and lower jaws, with their respective teeth (Figure 7.2.2). The orbits themselves appear as large, rounded openings housing the eyes, and muscles that move the eyeball or open the upper eyelid, bordered by the superior orbital margins.

- The frontal bone forms the superior part of the orbits (eye sockets) and extends upward to meet the parietal bones at the coronal suture.
- Nasal Bones are small, rectangular bones that are situated in the midline of the face, forming the bridge of the nose.
- While primarily visible from the lateral and superior views, the parietal bones are located posteriorly to the frontal bone and contribute to the cranial vault. They play a crucial role in the overall shape and protection of the brain.
- Temporal bones, also more prominent in the lateral view, are located on the sides of the skull and contribute to the structure behind the orbits.
- Sphenoid bone is partially visible in the anterior view at the lateral walls of the orbits. It spans the skull laterally, contributing to the cranial base.
- Lacrimal Bones found at the medial wall of each orbit, these small, thin bones are situated near the tear ducts.
- Zygomatic bones, commonly known as the cheekbones, are located on each side of the face, forming the prominence of the cheeks and part of the lateral wall and floor of the orbits.

- Ethmoid bone forms part of the medial wall of the orbits and the superior part of the nasal cavity. It is located posterior to the nasal bones and is partially visible in the anterior view.
- Vomer, located within the nasal cavity, forms the inferior portion of the nasal septum, dividing the nasal cavity into two.
- Maxilla, the paired bones form the upper jaw and the central part of the facial skeleton, including the lower portion of the orbits and the alveolar processes that hold the upper teeth.
- Mandible, the lower jawbone is the largest and strongest bone of the face, featuring the body (horizontal part) and the rami (vertical parts). It holds the lower teeth and forms the chin.
- Supraorbital foramen is located on the frontal bone, just above each orbit, this small opening allows the passage of nerves and blood vessels to the forehead.
- Infraorbital foramen is situated on the maxilla below each orbit, these openings allow the infraorbital nerves and vessels to pass to the face.
- Mental foramen found on the anterior surface of the mandible, near the chin, allow the passage of the mental nerve and vessels.

Together, these bones and features create a complex, intricate structure that supports and protects the brain, sensory organs, and the entrance to the digestive and respiratory systems.

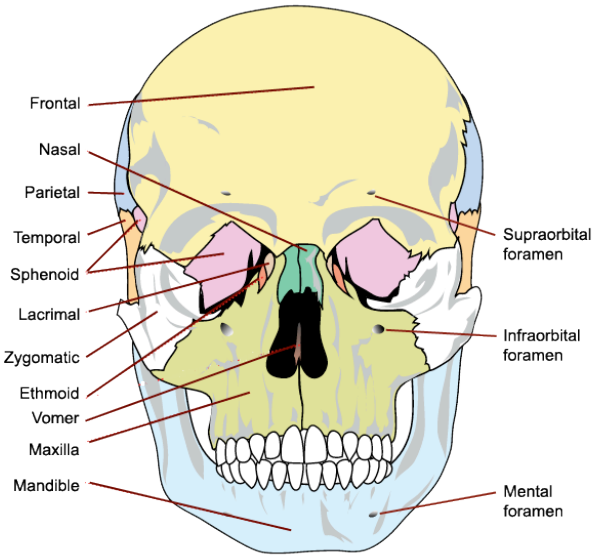


Figure 7.2.2: An anterior view of the skull shows the bones that form the forehead, orbits (eye sockets), nasal cavity, nasal septum, and upper and lower jaws. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.2.

Lateral View of Skull

A view of the lateral skull is dominated by the large, rounded brain case above and the upper and lower jaws with their teeth below (Figure 7.2.3). Separating these areas is the bridge of bone called the zygomatic arch. The zygomatic arch is the bony arch on the side of skull that spans from the area of the cheek to just above the ear canal. It is formed by the junction of two bony processes: a short anterior component, the temporal process of the zygomatic bone (the cheekbone) and a longer posterior portion, the zygomatic process of the temporal bone, extending forward from the temporal bone. Thus the temporal process (anteriorly) and the zygomatic process (posteriorly) join together, like the two ends of a drawbridge, to form the zygomatic arch. One of the major muscles that pulls the mandible upward during biting and chewing arises from the zygomatic arch.

On the lateral side of the brain case, above the level of the zygomatic arch, is a shallow space called the temporal fossa. Below the level of the zygomatic arch and deep to the vertical portion of the mandible is another space called the infratemporal fossa. Both the temporal fossa and infratemporal fossa contain muscles that act on the mandible during chewing.

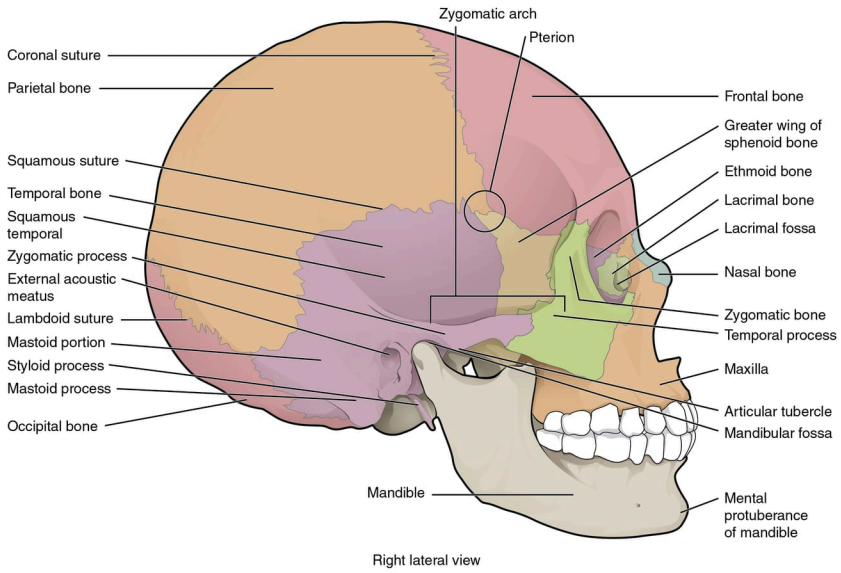


Figure 7.2.3: Skull diagram identifying major bones, foramina, and internal anatomical landmarks of the head. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.3.

Floor of the Brain Case

The floor of the brain case is referred to as the base of the skull. This is a complex area that varies in depth and has numerous openings for the passage of cranial nerves, blood vessels, and the spinal cord. Inside the skull, the base is subdivided into three large spaces, called the anterior cranial fossa, middle cranial fossa, and posterior cranial fossa (fossa = “trench or ditch”) (Figure 7.2.4). From anterior to posterior, the fossae increase in depth. The shape and depth of each fossa corresponds to the shape and size of the brain region that each houses. The boundaries and openings of the cranial fossae (singular = fossa) will be described in a later section.

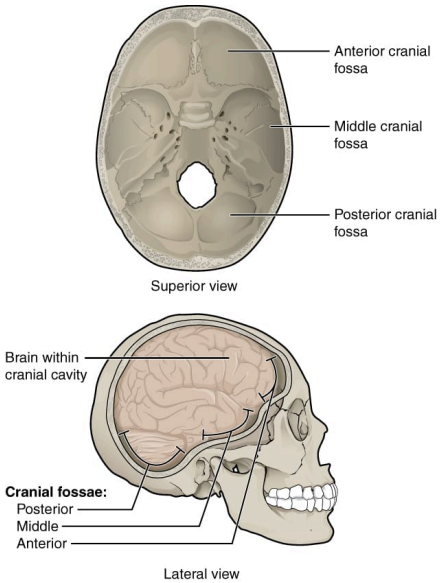


Figure 7.2.4: Illustration of cranial fossae from superior and lateral perspectives, indicating where the brain rests within the skull. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.4.

Parietal Bone

The parietal bone forms most of the upper lateral side of the skull as illustrated in Figure 7.2.3. These are paired bones, with the right and left parietal bones joining together at the top of the skull. Each parietal bone is also bounded anteriorly by the frontal

bone, inferiorly by the temporal bone, and posteriorly by the occipital bone.

Temporal Bone

The temporal bone forms the lower lateral side of the skull, refer to Figure 7.2.5. Common wisdom has it that the temporal bone (temporal = “time”) is so named because this area of the head (the temple) is where hair typically first turns gray, indicating the passage of time.

The temporal bone is subdivided into several regions as illustrated in Figure 7.2.5. The flattened, upper portion is the squamous portion of the temporal bone. Below this area and projecting anteriorly is the zygomatic process of the temporal bone, which forms the posterior portion of the zygomatic arch. Posteriorly is the mastoid portion of the temporal bone. Projecting inferiorly from this region is a large prominence, the mastoid process, which serves as a muscle attachment site. The mastoid process can easily be felt on the side of the head just behind your earlobe. On the interior of the skull, the petrous portion of each temporal bone forms the prominent, diagonally oriented petrous ridge in the floor of the cranial cavity. Located inside each petrous ridge are small cavities that house the structures of the middle and inner ears.

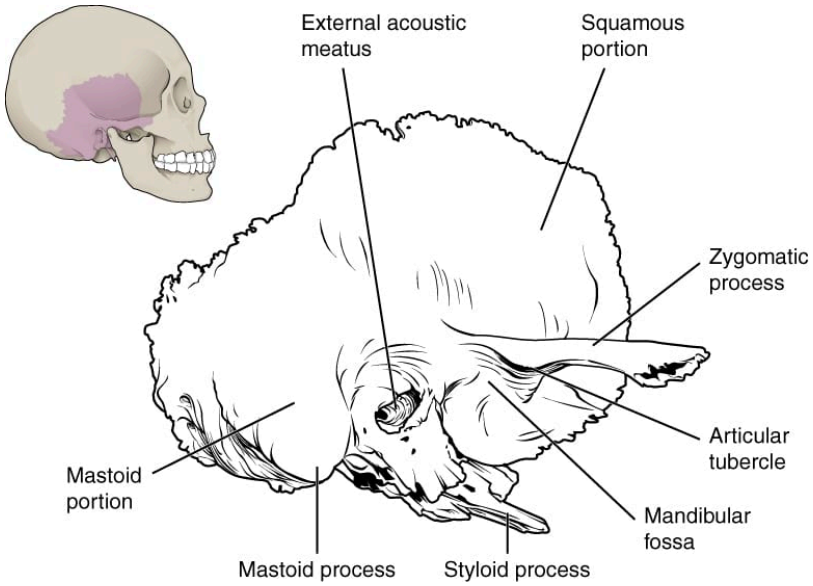


Figure 7.2.5: A lateral view of the isolated temporal bone shows the squamous, mastoid, and zygomatic portions of the temporal bone. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.5.

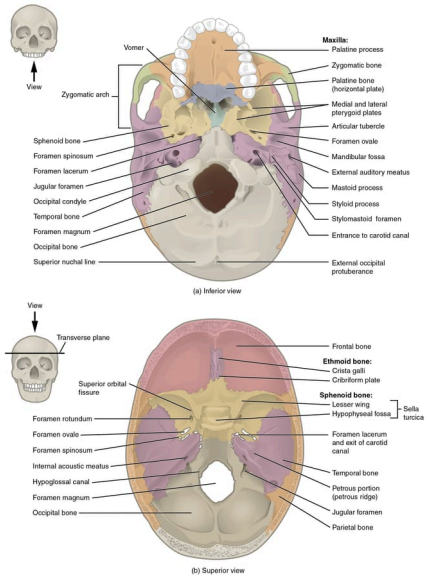


Figure 7.2.6: Inferior (a) and superior (b) views of the skull base illustrating cranial bones, openings, and anatomical landmarks. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.6.

Frontal Bone

The frontal bone is the single bone that forms the forehead. At its anterior midline, between the eyebrows, there is a slight depression called the glabella. The frontal bone also forms the supraorbital margin of the orbit. Near the middle of this margin, is the supraorbital foramen, the opening that provides passage for a sensory nerve to the forehead. The frontal bone is thickened just above each supraorbital margin, forming rounded brow ridges. These are located just behind your eyebrows and vary in size among individuals, although they are generally larger in males. Inside the cranial cavity, the frontal bone extends posteriorly. This flattened region forms both the roof of the orbit below and the floor of the anterior cranial cavity above.

Occipital Bone

The occipital bone is the single bone that forms the posterior skull and posterior base of the cranial cavity (Figure 7.2.7); also refer to Figure 7.2.6. On its outside surface, at the posterior midline, is a small protrusion called the external occipital protuberance, which serves as an attachment site for a ligament of the posterior neck. Lateral to either side of this bump is a superior nuchal line (nuchal = "nape" or "posterior neck"). The nuchal lines represent the most superior point at which muscles of the neck attach to the skull, with only the scalp covering the skull above these lines. On the base of the skull, the occipital bone contains the large opening of the foramen magnum, which allows for passage of the spinal cord as it exits the skull. On either side of the foramen magnum is an oval-shaped occipital condyle. These condyles form joints with the first cervical vertebra and thus support the skull on top of the vertebral column.

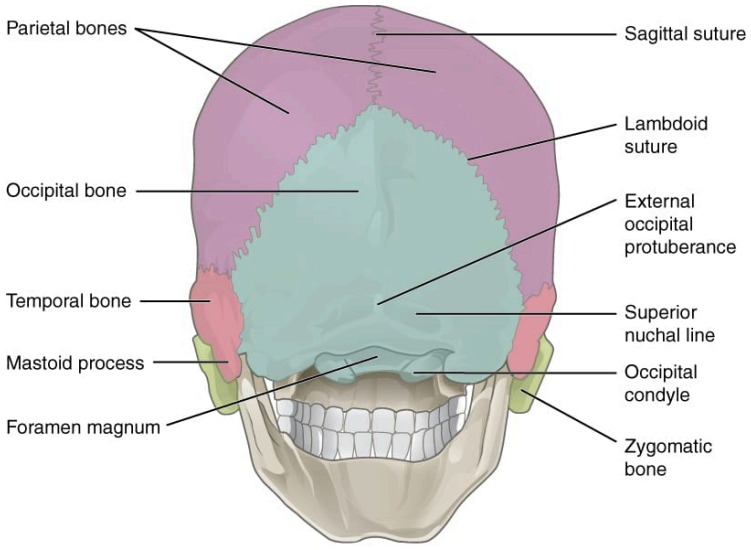


Figure 7.2.7: Posterior skull anatomy highlighting cranial bones, sutures, and surface features visible from the back of the head. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.7.

Sphenoid Bone

The sphenoid bone is a single, complex bone of the central skull (Figure 7.2.8). It serves as a "keystone" bone, because it joins with almost every other bone of the skull. The sphenoid forms much of the base of the central skull as referenced in Figure 7.2.6 and also extends laterally to contribute to the sides of the skull, refer to Figure 7.2.3. Inside the cranial cavity, the right and left lesser wings of the sphenoid bone, which resemble the wings of a flying bird, form the lip of a prominent ridge that marks the boundary between the anterior and middle cranial fossae. The sella turcica ("Turkish saddle") is located at the midline of the middle cranial fossa. This bony region of the sphenoid bone is named for its resemblance to the horse saddles used by the Ottoman Turks, with a high back and a tall front. The rounded depression in the floor of the sella turcica is the hypophyseal (pituitary) fossa, which houses the pea-sized pituitary (hypophyseal) gland. The greater wings of the sphenoid bone extend laterally to either side away from the sella turcica, where they form the anterior floor of the middle cranial fossa. The greater wing is best seen on the outside of the lateral skull, where it forms a rectangular area immediately anterior to the squamous portion of the temporal bone.

On the inferior aspect of the skull, each half of the sphenoid bone forms two thin, vertically oriented bony plates. These are the medial pterygoid plate and lateral pterygoid plate (pterygoid = "wing-shaped"). The right and left medial pterygoid plates form

the posterior, lateral walls of the nasal cavity. The somewhat larger lateral pterygoid plates serve as attachment sites for chewing muscles that fill the infratemporal space and act on the mandible.

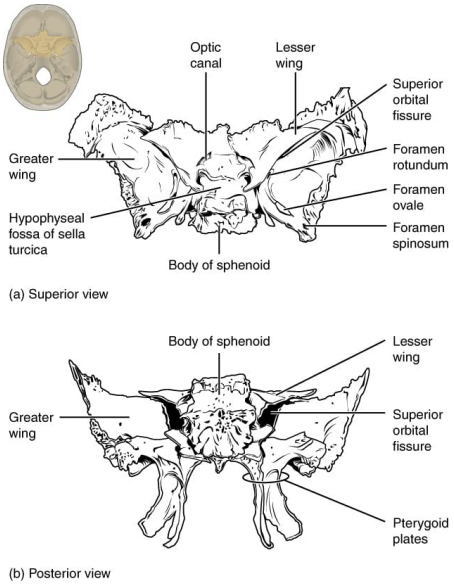


Figure 7.2.8: Superior and posterior views of the sphenoid bone identifying major openings, wings, and central structures. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.8.

Ethmoid Bone

The ethmoid bone is a single, midline bone that forms the roof and lateral walls of the upper nasal cavity, the upper portion of the nasal septum, and contributes to the medial wall of the orbit (Figure 7.2.9 and Figure 7.2.10). On the interior of the skull, the ethmoid also forms a portion of the floor of the anterior cranial cavity**.**

Within the nasal cavity, the perpendicular plate of the ethmoid bone forms the upper portion of the nasal septum. The ethmoid bone also forms the lateral walls of the upper nasal cavity. Extending from each lateral wall are the superior nasal concha and middle nasal concha, which are thin, curved projections that extend into the nasal cavity (Figure 7.2.11).

In the cranial cavity, the ethmoid bone forms a small area at the midline in the floor of the anterior cranial fossa. This region also forms the narrow roof of the underlying nasal cavity. This portion of the ethmoid bone consists of two parts, the crista galli and cribriform plates. The crista galli (“rooster’s comb or crest”) is a small upward bony projection located at the midline. It functions as an anterior attachment point for one of the covering layers of the brain. To either side of the crista galli is the cribriform plate (cribrum = “sieve”), a small, flattened area with numerous small openings termed olfactory foramina. Small nerve branches from the olfactory areas of the nasal cavity pass through these openings to enter the brain.

The lateral portions of the ethmoid bone are located between the orbit and upper nasal cavity, and thus form the lateral nasal cavity wall and a portion of the medial orbit wall. Located inside this portion of the ethmoid bone are several small, air-filled spaces that are part of the paranasal sinus system of the skull.

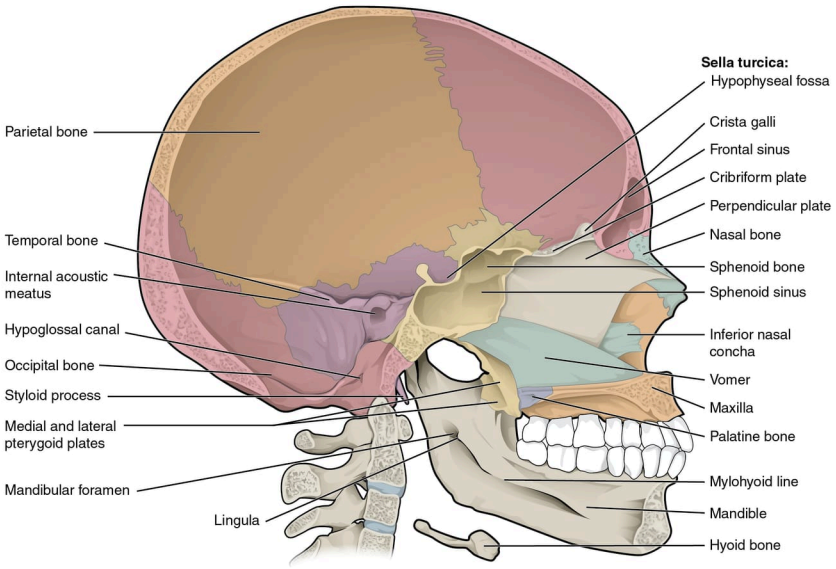


Figure 7.2.9: This midline view of the sagittally sectioned skull shows the nasal septum. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.9.

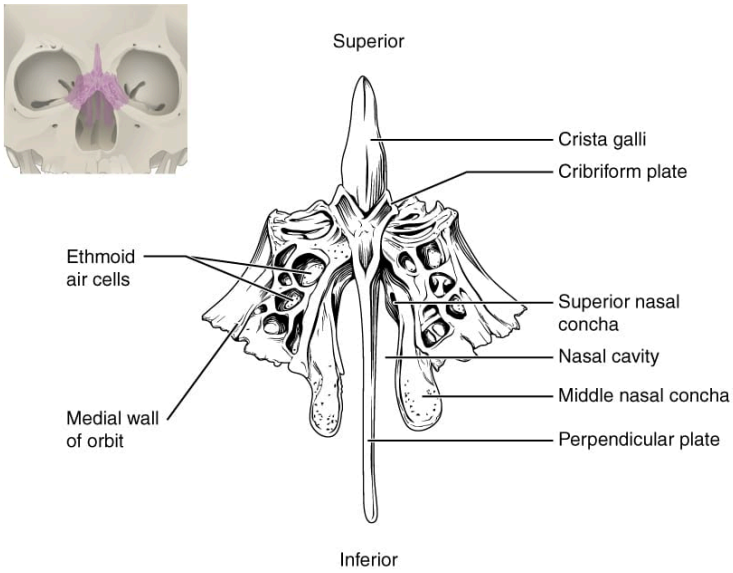


Figure 7.2.10: Anatomy of the ethmoid bone in superior–inferior orientation, highlighting orbital, nasal, and cranial features. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.10.

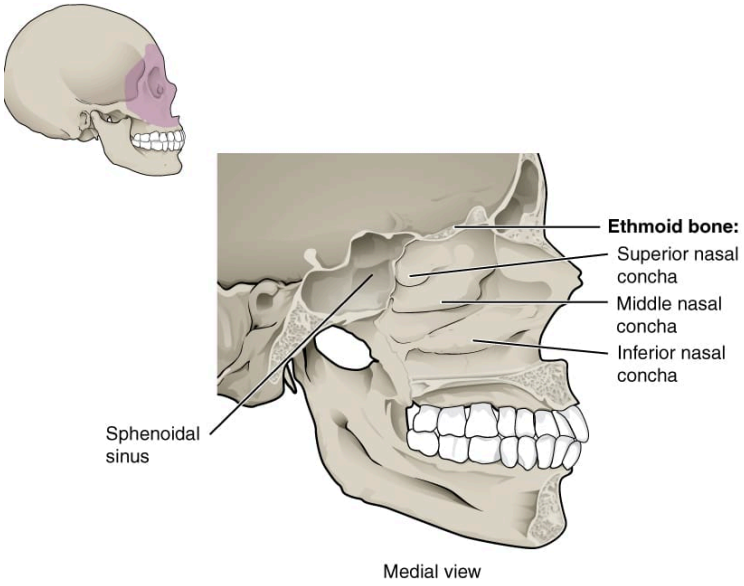


Figure 7.2.11: Medial view of the skull emphasizing the ethmoid bone's role in forming the nasal cavity and sinus region. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.11.

Sutures of the Skull

A suture is an immobile joint between adjacent bones of the skull. The narrow gap between the bones is filled with dense, fibrous connective tissue that unites the bones. The long sutures located between the bones of the brain case are not straight, but instead follow irregular, tightly twisting paths. These twisting lines serve to tightly interlock the adjacent bones, thus adding strength to the skull for brain protection.

The two suture lines seen on the top of the skull are the coronal and sagittal sutures. The coronal suture runs from side to side across the skull, within the coronal plane of section . It joins the frontal bone to the right and left parietal bones. The sagittal suture extends posteriorly from the coronal suture, running along the midline at the top of the skull in the sagittal plane of section. It unites the right and left parietal bones. On the posterior skull, the sagittal suture terminates by joining the lambdoid suture. The lambdoid suture extends downward and laterally to either side away from its junction with the sagittal suture. The lambdoid suture joins the occipital bone to the right and left parietal and temporal bones. This suture is named for its upside-down "V" shape, which resembles the capital letter version of the Greek letter lambda (Λ). The squamous suture is located on the lateral skull. It unites the squamous portion of the temporal bone with the parietal bone (Figure 7.2.11). At the intersection of four bones is the pterion, a small, capital-H-shaped suture line region that unites the frontal bone, parietal bone, squamous portion of the temporal bone, and greater wing of the sphenoid bone. It is the weakest part of the skull. The pterion is located approximately two finger widths above the zygomatic arch and a thumb's width posterior to the upward portion of the zygomatic bone.

Disorders of the...

Skeletal System

Head and traumatic brain injuries are major causes of immediate death and disability, with bleeding and infections as possible additional complications. According to the Centers for Disease Control and Prevention (2010), approximately 30 percent of all injury-related deaths in the United States are caused by head injuries. The majority of head injuries involve falls. They are most common among young children (ages 0–4 years), adolescents (15–19 years), and the elderly (over 65 years). Additional causes vary, but prominent among these are automobile and motorcycle accidents.

Strong blows to the brain-case portion of the skull can produce fractures. These may result in bleeding inside the skull with subsequent injury to the brain. The most common is a linear skull fracture, in which fracture lines radiate from the point of impact. Other fracture types include a comminuted fracture, in which the bone is broken into several pieces at the point of impact, or a depressed fracture, in which the fractured bone is pushed inward. In a contrecoup (counterblow) fracture, the

bone at the point of impact is not broken, but instead a fracture occurs on the opposite side of the skull. Fractures of the occipital bone at the base of the skull can occur in this manner, producing a basilar fracture that can damage the artery that passes through the carotid canal.

A blow to the lateral side of the head may fracture the bones of the pterion. The pterion is an important clinical landmark because located immediately deep to it on the inside of the skull is a major branch of an artery that supplies the skull and covering layers of the brain. A strong blow to this region can fracture the bones around the pterion. If the underlying artery is damaged, bleeding can cause the formation of a hematoma (collection of blood) between the brain and interior of the skull. As blood accumulates, it will put pressure on the brain. Symptoms associated with a hematoma may not be apparent immediately following the injury, but if untreated, blood accumulation will exert increasing pressure on the brain and can result in death within a few hours.

Facial Bones of the Skull

The facial bones of the skull form the upper and lower jaws, the nose, nasal cavity and nasal septum, and the orbit. The facial bones include 14 bones, with six paired bones and two unpaired bones. The paired bones are the maxilla, palatine, zygomatic, nasal, lacrimal, and inferior nasal conchae bones. The unpaired bones are the vomer and mandible bones. Although classified with the brain-case bones, the ethmoid bone also contributes to the nasal septum and the walls of the nasal cavity and orbit.

Maxillary Bone

The maxillary bone, often referred to simply as the maxilla (plural = maxillae), is one of a pair that together form the upper jaw, much of the hard palate, the medial floor of the orbit, and the lateral base of the nose. The curved, inferior margin of the maxillary bone that forms the upper jaw and contains the upper teeth is the alveolar process of the maxilla (Figure 7.2.12). Each tooth is anchored into a deep socket called an alveolus. On the anterior maxilla, just below the orbit, is the infraorbital foramen. This is the point of exit for a sensory nerve that supplies the nose, upper lip, and anterior cheek. On the inferior skull, the palatine process from each maxillary bone can be seen joining together at the midline to form the anterior three-quarters of the hard palate, as shown in Figure 7.2.6*a*. The hard palate is the bony plate that forms the roof of the mouth and floor of the nasal cavity, separating the oral and nasal cavities.

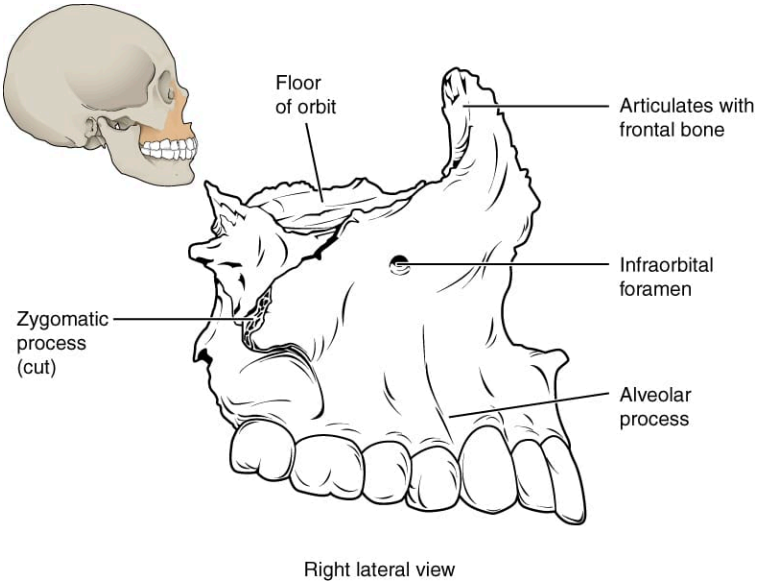


Figure 7.2.12 Isolated maxilla highlighting the infraorbital foramen, orbital surface, and alveolar process. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.12.

Palatine Bone

The palatine bone is one of a pair of irregularly shaped bones that contribute small areas to the lateral walls of the nasal cavity and the medial wall of each orbit. The largest region of each of the palatine bone is the horizontal plate. The plates from the

right and left palatine bones join together at the midline to form the posterior quarter of the hard palate (Figure 7.2.6). Thus, the palatine bones are best seen in an inferior view of the skull and hard palate.

Homeostatic Imbalances

Cleft Lip and Cleft Palate

During embryonic development, the right and left maxilla bones come together at the midline to form the upper jaw. At the same time, the muscle and skin overlying these bones join together to form the upper lip. Inside the mouth, the palatine processes of the maxilla bones, along with the horizontal plates of the right and left palatine bones, join together to form the hard palate. If an error occurs in these developmental processes, a birth defect of cleft lip or cleft palate may result.

Cleft lip is a common development defect that affects approximately 1:1000 births, most of which are male. This defect involves a partial or complete failure of the right and left portions of the upper lip to fuse together, leaving a cleft (gap).

A more severe developmental defect is cleft palate, which affects the hard palate. The hard palate is the bony structure that separates the nasal cavity from the oral cavity. It is formed during embryonic development by the midline fusion of the horizontal plates from the right and left palatine bones and the palatine processes of the maxilla bones. Cleft palate affects approximately 1:2500 births and is more common in females. It results from a failure of the two halves of the hard palate to completely come together and fuse at the midline, thus leaving a gap between them. This gap allows for communication between the nasal and oral cavities. In severe cases, the bony gap continues into the anterior upper jaw where the alveolar processes of the maxilla bones also do not properly join together above the front teeth. If this occurs, a cleft lip will also be seen. Because of the communication between the oral and nasal cavities, a cleft palate makes it very difficult for an infant to generate the suckling needed for nursing, thus leaving the infant at risk for malnutrition. Surgical repair is required to correct cleft palate defects.

Zygomatic Bone

The zygomatic bone is also known as the cheekbone. Each of the paired zygomatic bones forms much of the lateral wall of the orbit and the lateral-inferior margins of the anterior orbital opening. The short temporal process of the zygomatic bone projects posteriorly, where it forms the anterior portion of the zygomatic arch Figure 7.2.3.

Nasal Bone

The nasal bone is one of two small bones that articulate (join) with each other to form the bony base (bridge) of the nose. They also support the cartilages that form the lateral walls of the nose (Figure 7.2.2, Figure 7.2.3, Figure 7.2.9). These are the bones that are damaged when the nose is broken.

Lacrimal Bone

Each lacrimal bone is a small, rectangular bone that forms the anterior, medial wall of the orbit (see Figure 7.4 and Figure 7.5). The anterior portion of the lacrimal bone forms a shallow depression called the lacrimal fossa, and extending inferiorly from this is the nasolacrimal canal. The lacrimal fluid (tears of the eye), which serves to maintain the moist surface of the eye, drains at the medial corner of the eye into the nasolacrimal canal. This duct then extends downward to open into the nasal cavity, behind the inferior nasal concha. In the nasal cavity, the lacrimal fluid normally drains posteriorly, but with an increased flow of tears due to crying or eye irritation, some fluid will also drain anteriorly, thus causing a runny nose.

Inferior Nasal Conchae

The right and left inferior nasal conchae form a curved bony plate that projects into the nasal cavity space from the lower lateral wall Figure 7.2.11. The inferior concha is the largest of the nasal conchae and can easily be seen when looking into the anterior opening of the nasal cavity.

Vomer Bone

The unpaired vomer bone, often referred to simply as the vomer, is triangular-shaped and forms the posterior-inferior part of the nasal septum Figure $7.2.6a$. The vomer is best seen when looking from behind into the posterior openings of the nasal cavity. In this view, the vomer is seen to form the entire height of the nasal septum. A much smaller portion of the vomer can also be seen when looking into the anterior opening of the nasal cavity.

Mandible

The mandible forms the lower jaw and is the only moveable bone of the skull. At the time of birth, the mandible consists of paired right and left bones, but these fuse together during the first year to form the single U-shaped mandible of the adult skull. Each side of the mandible consists of a horizontal body and posteriorly, a vertically oriented ramus of the mandible (ramus = "branch"). The outside margin of the mandible, where the body and ramus come together is called the angle of the mandible (Figure $7.2.13$).

The ramus on each side of the mandible has two upward-going bony projections. The more anterior projection is the flattened coronoid process of the mandible, which provides attachment for one of the biting muscles. The posterior projection is the condylar process of the mandible, which is topped by the oval-shaped condyle. The condyle of the mandible articulates (joins) with the mandibular fossa and articular tubercle of the temporal bone. Together these articulations form the temporomandibular joint, which allows for opening and closing of the mouth. The broad U-shaped curve located between the coronoid and condylar processes is the mandibular notch.

Important landmarks for the mandible include the following:

- Alveolar process of the mandible—This is the upper border of the mandibular body and serves to anchor the lower teeth.
- Mental protuberance—The forward projection from the inferior margin of the anterior mandible that forms the chin (mental = "chin").
- Mental foramen—The opening located on each side of the anterior-lateral mandible, which is the exit site for a sensory nerve that supplies the chin.
- Mylohyoid line—This bony ridge extends along the inner aspect of the mandibular body (Figure $7.2.9$). The muscle that forms the floor of the oral cavity attaches to the mylohyoid lines on both sides of the mandible.
- Mandibular foramen—This opening is located on the medial side of the ramus of the mandible. The opening leads into a tunnel that runs down the length of the mandibular body. The sensory nerve and blood vessels that supply the lower teeth enter the mandibular foramen and then follow this tunnel. Thus, to numb the lower teeth prior to dental work, the dentist must inject anesthesia into the lateral wall of the oral cavity at a point prior to where this sensory nerve enters the mandibular foramen.
- Lingula—This small flap of bone is named for its shape (lingula = "little tongue"). It is located immediately next to the mandibular foramen, on the medial side of the ramus. A ligament that anchors the mandible during opening and closing of the mouth extends down from the base of the skull and attaches to the lingula.

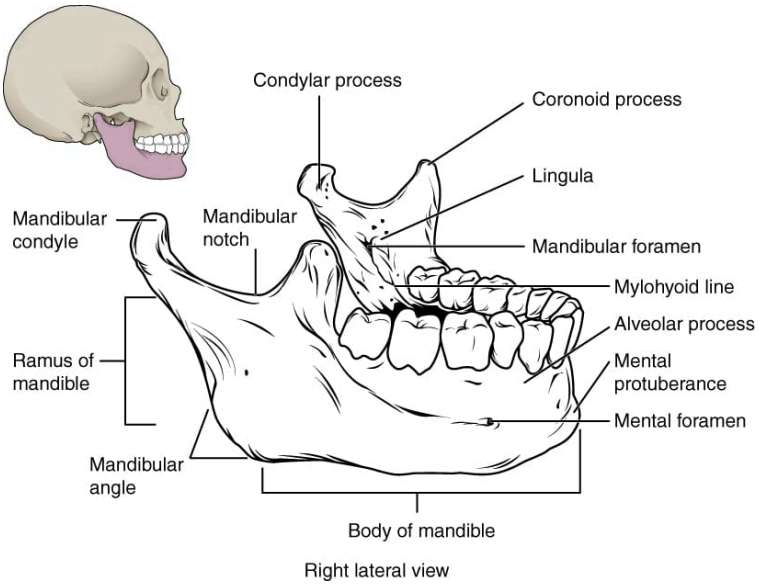


Figure 7.2.13: A right lateral view of the human jaw, identifying the ramus of mandible, mandibular condyle, and mental protuberance. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.13.

The Orbit

The orbit is the bony socket that houses the eyeball and contains the muscles that move the eyeball or open the upper eyelid. Each orbit is cone-shaped, with a narrow posterior region that widens toward the large anterior opening. To help protect the eye, the bony margins of the anterior opening are thickened and somewhat constricted. The medial walls of the two orbits are parallel to each other but each lateral wall diverges away from the midline at a 45° angle. This divergence provides greater lateral peripheral vision.

The walls of each orbit include contributions from seven skull bones (Figure 7.2.14). The frontal bone forms the roof and the zygomatic bone forms the lateral wall and lateral floor. The medial floor is primarily formed by the maxilla, with a small contribution from the palatine bone. The ethmoid bone and lacrimal bone make up much of the medial wall and the sphenoid bone forms the posterior orbit.

At the posterior apex of the orbit is the opening of the optic canal, which allows for passage of the optic nerve from the retina to the brain. Lateral to this is the elongated and irregularly shaped superior orbital fissure, which provides passage for the artery that supplies the eyeball, sensory nerves, and the nerves that supply the muscles involved in eye movements.

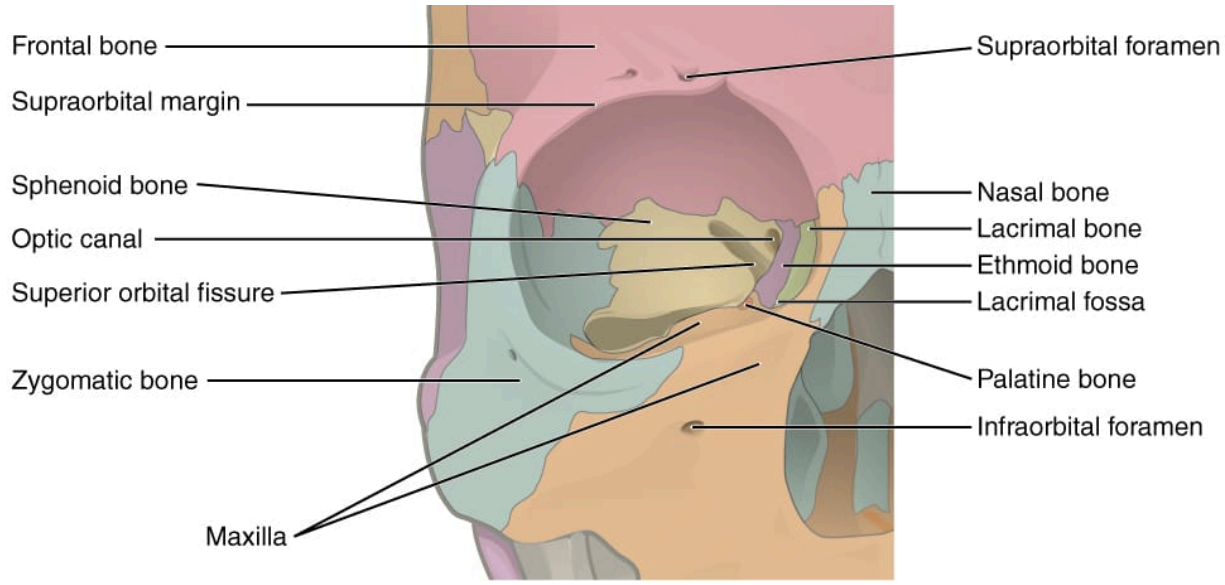


Figure 7.2.14: Seven skull bones contribute to the walls of the orbit. Opening into the posterior orbit from the cranial cavity are the optic canal and superior orbital fissure. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.14.

The Nasal Septum and Nasal Conchae

The nasal septum consists of both bone and cartilage components (Figure 7.2.15). The upper portion of the septum is formed by the perpendicular plate of the ethmoid bone. The lower and posterior parts of the septum are formed by the triangular-shaped vomer bone. In an anterior view of the skull, the perpendicular plate of the ethmoid bone is easily seen inside the nasal opening as the upper nasal septum, but only a small portion of the vomer is seen as the inferior septum. A better view of the vomer bone is seen when looking into the posterior nasal cavity with an inferior view of the skull, where the vomer forms the full height of the nasal septum. The anterior nasal septum is formed by the septal cartilage, a flexible plate that fills in the gap between the perpendicular plate of the ethmoid and vomer bones. This cartilage also extends outward into the nose where it separates the right and left nostrils. The septal cartilage is not found in the dry skull.

Attached to the lateral wall on each side of the nasal cavity are the superior, middle, and inferior nasal conchae (singular = concha), which are named for their positions (Figure 7.2.11). These are bony plates that curve downward as they project into the space of the nasal cavity. They serve to swirl the incoming air, which helps to warm and moisturize it before the air moves into the delicate air sacs of the lungs. This also allows mucus, secreted by the tissue lining the nasal cavity, to trap incoming dust, pollen, bacteria, and viruses. The largest of the conchae is the inferior nasal concha, which is an independent bone of the skull. The middle concha and the superior conchae, which is the smallest, are both formed by the ethmoid bone. When looking into the anterior nasal opening of the skull, only the inferior and middle conchae can be seen. The small superior nasal concha is well hidden above and behind the middle concha.

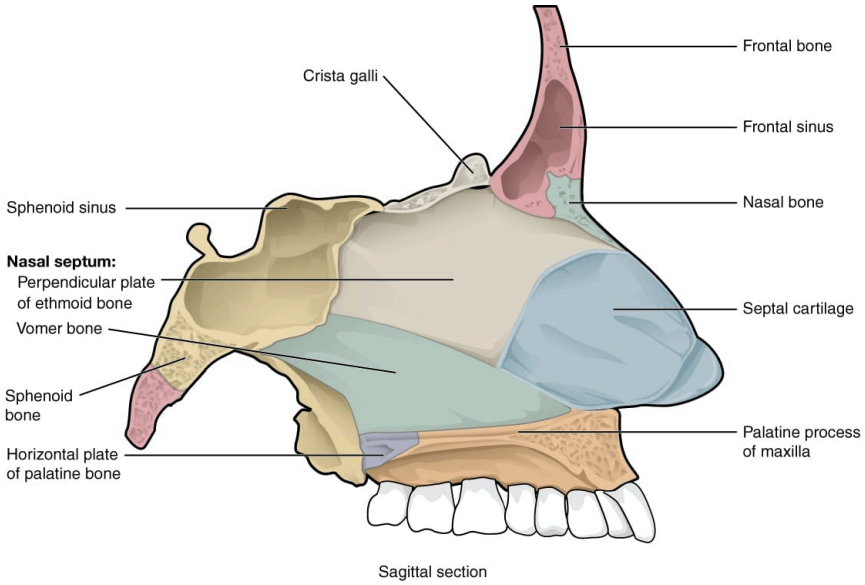


Figure 7.2.15: The nasal septum is formed by the perpendicular plate of the ethmoid bone and the vomer bone. The septal cartilage fills the gap between these bones and extends into the nose. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.15.

Cranial Fossae

Inside the skull, the floor of the cranial cavity is subdivided into three cranial fossae (spaces), which increase in depth from anterior to posterior (Figure 7.2.4). Since the brain occupies these areas, the shape of each conforms to the shape of the brain regions that it contains. Each cranial fossa has anterior and posterior boundaries and is divided at the midline into right and left areas by a significant bony structure or opening.

Anterior Cranial Fossa

The anterior cranial fossa is the most anterior and the shallowest of the three cranial fossae. It overlies the orbits and contains the frontal lobes of the brain. Anteriorly, the anterior fossa is bounded by the frontal bone, which also forms the majority of the floor for this space. The lesser wings of the sphenoid bone form the prominent ledge that marks the boundary between the anterior and middle cranial fossae. Located in the floor of the anterior cranial fossa at the midline is a portion of the ethmoid bone, consisting of the upward projecting crista galli and to either side of this, the cribriform plates.

Middle Cranial Fossa

The middle cranial fossa is deeper and situated posterior to the anterior fossa. It extends from the lesser wings of the sphenoid bone anteriorly, to the petrous ridges (petrous portion of the temporal bones) posteriorly. The large, diagonally positioned petrous ridges give the middle cranial fossa a butterfly shape, making it narrow at the midline and broad laterally. The temporal lobes of the brain occupy this fossa. The middle cranial fossa is divided at the midline by the upward bony prominence of the sella turcica, a part of the sphenoid bone. The middle cranial fossa has several openings for the passage of blood vessels and cranial nerves.

Openings in the middle cranial fossa are as follows:

- Optic canal—This opening is located at the anterior lateral corner of the sella turcica. It provides for passage of the optic nerve into the orbit.
- Superior orbital fissure—This large, irregular opening into the posterior orbit is located on the anterior wall of the middle cranial fossa, lateral to the optic canal and under the projecting margin of the lesser wing of the sphenoid bone. Nerves to the eyeball and associated muscles, and sensory nerves to the forehead pass through this opening.
- Foramen rotundum—This rounded opening (rotundum = “round”) is located in the floor of the middle cranial fossa, just inferior to the superior orbital fissure. It is the exit point for a major sensory nerve that supplies the cheek, nose, and upper teeth.
- Foramen ovale of the middle cranial fossa—This large, oval-shaped opening in the floor of the middle cranial fossa provides passage for a major sensory nerve to the lateral head, cheek, chin, and lower teeth.

- Foramen spinosum—This small opening, located posterior-lateral to the foramen ovale, is the entry point for an important artery that supplies the covering layers surrounding the brain. The branching pattern of this artery forms readily visible grooves on the internal surface of the skull and these grooves can be traced back to their origin at the foramen spinosum.
- Carotid canal—This is the zig-zag passageway through which a major artery to the brain enters the skull. The entrance to the carotid canal is located on the inferior aspect of the skull, anteromedial to the styloid process (Figure 7.2.6. From here, the canal runs anteromedially within the bony base of the skull. Just above the foramen lacerum, the carotid canal opens into the middle cranial cavity, near the posterior-lateral base of the sella turcica.
- Foramen lacerum—This irregular opening is located in the base of the skull, immediately inferior to the exit of the carotid canal. This opening is an artifact of the dry skull, because in life it is completely filled with cartilage. All the openings of the skull that provide for passage of nerves or blood vessels have smooth margins; the word lacerum ("ragged" or "torn") tells us that this opening has ragged edges and thus nothing passes through it.

Posterior Cranial Fossa

The posterior cranial fossa is the most posterior and deepest portion of the cranial cavity. It contains the cerebellum of the brain. The posterior fossa is bounded anteriorly by the petrous ridges, while the occipital bone forms the floor and posterior wall. It is divided at the midline by the large foramen magnum ("great aperture"), the opening that provides for passage of the spinal cord.

Located on the medial wall of the petrous ridge in the posterior cranial fossa is the internal acoustic meatus (Figure 7.2.6*b*). This opening provides for passage of the nerve from the hearing and equilibrium organs of the inner ear, and the nerve that supplies the muscles of the face. Located at the anterior-lateral margin of the foramen magnum is the hypoglossal canal. These emerge on the inferior aspect of the skull at the base of the occipital condyle and provide passage for an important nerve to the tongue.

Immediately inferior to the internal acoustic meatus is the large, irregularly shaped jugular foramen (Figure 7.2.6*b*). Several cranial nerves from the brain exit the skull via this opening. It is also the exit point through the base of the skull for all the venous return blood leaving the brain. The venous structures that carry blood inside the skull form large, curved grooves on the inner walls of the posterior cranial fossa, which terminate at each jugular foramen.

Paranasal Sinuses

The paranasal sinuses are hollow, air-filled spaces located within certain bones of the skull (Figure 7.2.16). All of the sinuses communicate with the nasal cavity (paranasal = "next to nasal cavity") and are lined with nasal mucosa. They serve to reduce bone mass and thus lighten the skull, and they also add resonance to the voice. This second feature is most obvious when you have a cold or sinus congestion. These produce swelling of the mucosa and excess mucus production, which can obstruct the narrow passageways between the sinuses and the nasal cavity, causing your voice to sound different to yourself and others. This blockage can also allow the sinuses to fill with fluid, with the resulting pressure producing pain and discomfort.

The paranasal sinuses are named for the skull bone that each occupies. The frontal sinus is located just above the eyebrows, within the frontal bone. This irregular space may be divided at the midline into bilateral spaces, or these may be fused into a single sinus space. The frontal sinus is the most anterior of the paranasal sinuses. The largest sinus is the maxillary sinus. These are paired and located within the right and left maxillary bones, where they occupy the area just below the orbits. The maxillary sinuses are most commonly involved during sinus infections. Because their connection to the nasal cavity is located high on their medial wall, they are difficult to drain. The sphenoid sinus is a single, midline sinus. It is located within the body of the sphenoid bone, just anterior and inferior to the sella turcica, thus making it the most posterior of the paranasal sinuses. The lateral aspects of the ethmoid bone contain multiple small spaces separated by very thin bony walls. Each of these spaces is called an ethmoid air cell. These are located on both sides of the ethmoid bone, between the upper nasal cavity and medial orbit, just behind the superior nasal conchae.

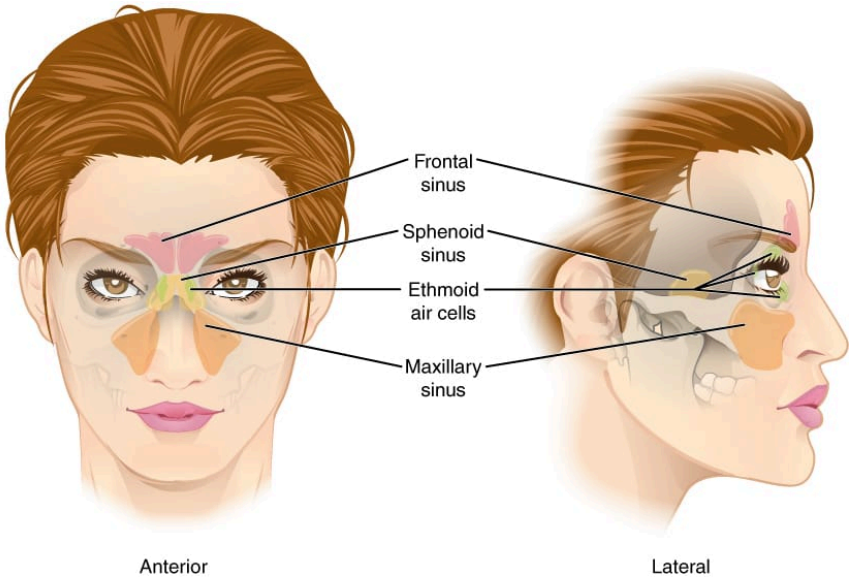


Figure 7.2.16: Anterior and lateral illustrations identifying the frontal, sphenoid, ethmoid, and maxillary sinuses within the skull. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.16.

Hyoid Bone

The hyoid bone is an independent bone that does not contact any other bone and thus is not part of the skull (Figure 7.2.17). It is a small U-shaped bone located in the upper neck near the level of the inferior mandible, with the tips of the "U" pointing posteriorly. The hyoid serves as the base for the tongue above, and is attached to the larynx below and the pharynx posteriorly. The hyoid is held in position by a series of small muscles that attach to it either from above or below. These muscles act to move the hyoid up/down or forward/back. Movements of the hyoid are coordinated with movements of the tongue, larynx, and pharynx during swallowing and speaking.

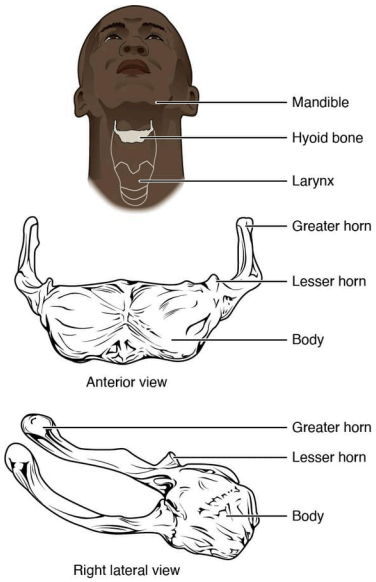


Figure 7.2.17: The hyoid bone is located in the upper neck and does not join with any other bone. It provides attachments for muscles that act on the tongue, larynx, and pharynx. (CC BY 4.0; via The Skull). Alternative text description of the Figure 7.2.17.

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7.3: The Vertebral Column

Anatomy of the Vertebral Column

The vertebral column is also known as the spinal column or spine (Figure 7.3.1). It consists of a sequence of vertebrae (singular = vertebra), each of which is separated and united by an intervertebral disc. Together, the vertebrae and intervertebral discs form the vertebral column. It is a flexible column that supports the head, neck, and body and allows for their movements. It also protects the spinal cord, which passes down the back through openings in the vertebrae.

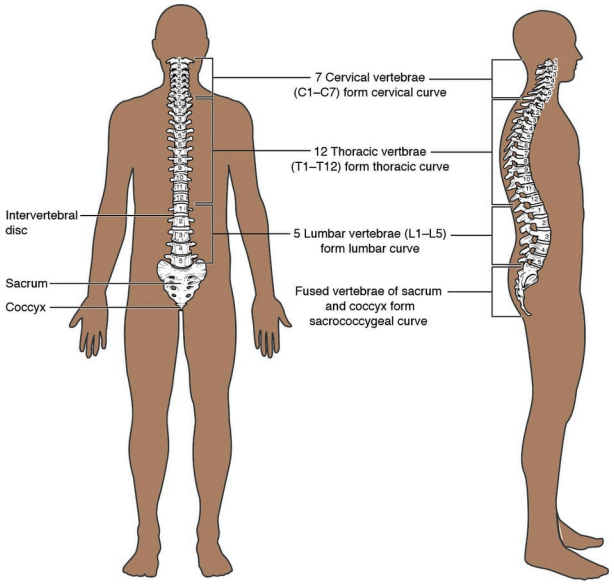


Figure 7.3.1: The adult vertebral column consists of 24 vertebrae, plus the sacrum and coccyx. The vertebrae are divided into three regions: cervical C1–C7 vertebrae, thoracic T1–T12 vertebrae, and lumbar L1–L5 vertebrae. The vertebral column is curved, with two primary curvatures (thoracic and sacrococcygeal curves) and two secondary curvatures. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.1.

Regions of the Vertebral Column

The vertebral column originally develops as a series of 33 vertebrae, but this number is eventually reduced to 24 vertebrae, plus the sacrum and coccyx. The vertebral column is subdivided into five regions, with the vertebrae in each area named for that region and numbered in descending order. In the neck, there are seven cervical vertebrae, each designated with the letter “C” followed by its number. Superiorly, the C1 vertebra articulates (forms a joint) with the occipital condyles of the skull. Inferiorly, C1 articulates with the C2 vertebra, and so on. Below these are the 12 thoracic vertebrae, designated T1–T12. The lower back contains the L1–L5 lumbar vertebrae. The single sacrum, which is also part of the pelvis, is formed by the fusion of five sacral vertebrae. Similarly, the coccyx, or tailbone, results from the fusion of four small coccygeal vertebrae. However, the sacral and coccygeal fusions do not start until age 20 and are not completed until middle age.

An interesting anatomical fact is that almost all mammals have seven cervical vertebrae, regardless of body size. This means that there are large variations in the size of cervical vertebrae, ranging from the very small cervical vertebrae of a shrew to the greatly elongated vertebrae in the neck of a giraffe. In a full-grown giraffe, each cervical vertebra is 11 inches tall.

Curvatures of the Vertebral Column

The adult vertebral column does not form a straight line, but instead has four curvatures along its length, as in Figure 7.3.1). These curves increase the vertebral column’s strength, flexibility, and ability to absorb shock. When the load on the spine is increased, by carrying a heavy backpack for example, the curvatures increase in depth (become more curved) to accommodate the extra weight. They then spring back when the weight is removed. The four adult curvatures are classified as either primary or secondary

curvatures. Primary curves are retained from the original fetal curvature, while secondary curvatures develop after birth.

During fetal development, the body is flexed anteriorly into the fetal position, giving the entire vertebral column a single curvature that is concave anteriorly. In the adult, this fetal curvature is retained in two regions of the vertebral column as the thoracic curve, which involves the thoracic vertebrae, and the sacrococcygeal curve, formed by the sacrum and coccyx. Each of these is thus called a primary curve because they are retained from the original fetal curvature of the vertebral column.

A secondary curve develops gradually after birth as the child learns to sit upright, stand, and walk. Secondary curves are concave posteriorly, opposite in direction to the original fetal curvature. The cervical curve of the neck region develops as the infant begins to hold their head upright when sitting. Later, as the child begins to stand and then to walk, the lumbar curve of the lower back develops. In adults, the lumbar curve is generally deeper in females.

Disorders associated with the curvature of the spine include kyphosis (an excessive posterior curvature of the thoracic region), lordosis (an excessive anterior curvature of the lumbar region), and scoliosis (an abnormal, lateral curvature, accompanied by twisting of the vertebral column).

Disorders of the...

Vertebral Column

Developmental anomalies, pathological changes, or obesity can enhance the normal vertebral column curves, resulting in the development of abnormal or excessive curvatures (Figure 7.3.2). Kyphosis, also referred to as humpback or hunchback, is an excessive posterior curvature of the thoracic region. This can develop when osteoporosis causes weakening and erosion of the anterior portions of the upper thoracic vertebrae, resulting in their gradual collapse (Figure 7.3.3). Lordosis, or swayback, is an excessive anterior curvature of the lumbar region and is most commonly associated with obesity or late pregnancy. The accumulation of body weight in the abdominal region results an anterior shift in the line of gravity that carries the weight of the body. This causes in an anterior tilt of the pelvis and a pronounced enhancement of the lumbar curve.

Scoliosis is an abnormal, lateral curvature, accompanied by twisting of the vertebral column. Compensatory curves may also develop in other areas of the vertebral column to help maintain the head positioned over the feet. Scoliosis is the most common vertebral abnormality among girls. The cause is usually unknown, but it may result from weakness of the back muscles, defects such as differential growth rates in the right and left sides of the vertebral column, or differences in the length of the lower limbs. When present, scoliosis tends to get worse during adolescent growth spurts. Although most individuals do not require treatment, a back brace may be recommended for growing children. In extreme cases, surgery may be required.

Excessive vertebral curves can be identified while an individual stands in the anatomical position. Observe the vertebral profile from the side and then from behind to check for kyphosis or lordosis. Then have the person bend forward. If scoliosis is present, an individual will have difficulty in bending directly forward, and the right and left sides of the back will not be level with each other in the bent position.

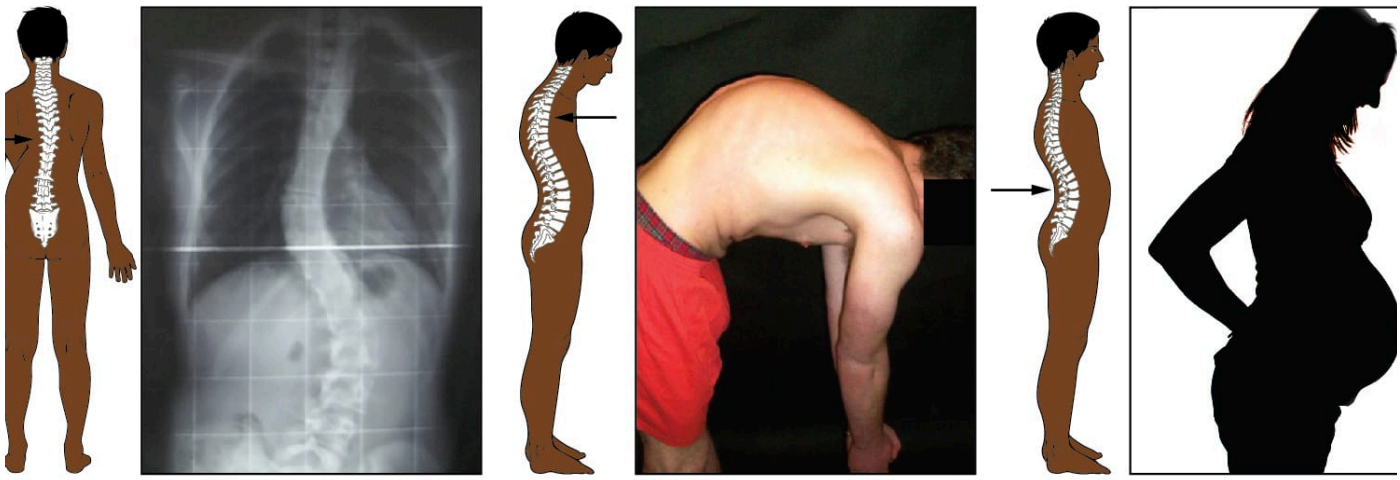


Figure 7.3.2: The changes to the abnormal curves of the vertebral columns in different diseases. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.2.

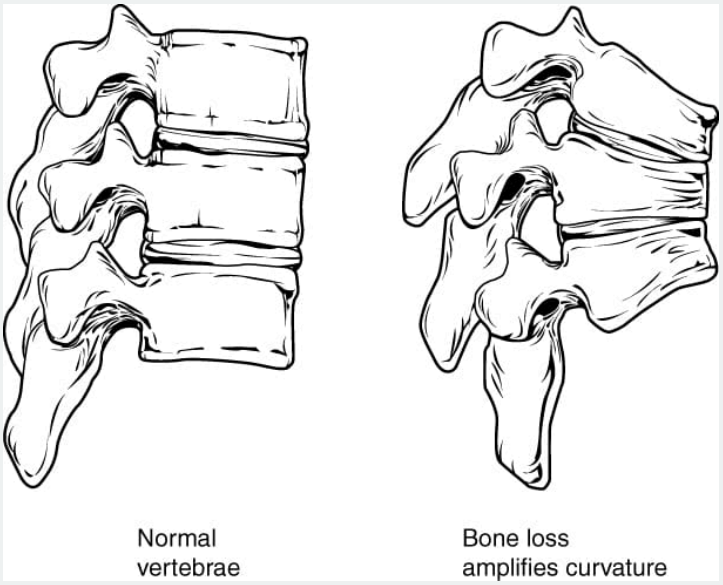


Figure 7.3.3: Osteoporosis is an age-related disorder that causes the gradual loss of bone density and strength. When the thoracic vertebrae are affected, there can be a gradual collapse of the vertebrae. This results in kyphosis, an excessive curvature of the thoracic region. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.3.

General Structure of a Vertebra

Within the different regions of the vertebral column, vertebrae vary in size and shape, but they all follow a similar structural pattern. A typical vertebra will consist of a body, a vertebral arch, and seven processes (Figure 7.3.4).

The body is the anterior portion of each vertebra and is the part that supports the body weight. Because of this, the vertebral bodies progressively increase in size and thickness going down the vertebral column. The bodies of adjacent vertebrae are separated and strongly united by an intervertebral disc.

The vertebral arch forms the posterior portion of each vertebra. It consists of four parts, the right and left pedicles and the right and left laminae. Each pedicle forms one of the lateral sides of the vertebral arch. The pedicles are anchored to the posterior side of the vertebral body. Each lamina forms part of the posterior roof of the vertebral arch. The large opening between the vertebral arch and body is the vertebral foramen, which contains the spinal cord. In the intact vertebral column, the vertebral foramina of

all of the vertebrae align to form the vertebral (spinal) canal, which serves as the bony protection and passageway for the spinal cord down the back. When the vertebrae are aligned together in the vertebral column, notches in the margins of the pedicles of adjacent vertebrae together form an intervertebral foramen, the opening through which a spinal nerve exits from the vertebral column (Figure 7.3.5).

Seven processes arise from the vertebral arch. Each paired transverse process projects laterally and arises from the junction point between the pedicle and lamina. The single spinous process (vertebral spine) projects posteriorly at the midline of the back. The vertebral spines can easily be felt as a series of bumps just under the skin down the middle of the back. The transverse and spinous processes serve as important muscle attachment sites. A superior articular process extends or faces upward, and an inferior articular process faces or projects downward on each side of a vertebrae. The paired superior articular processes of one vertebra join with the corresponding paired inferior articular processes from the next higher vertebra. These junctions form slightly moveable joints between the adjacent vertebrae. The shape and orientation of the articular processes vary in different regions of the vertebral column and play a major role in determining the type and range of motion available in each region.

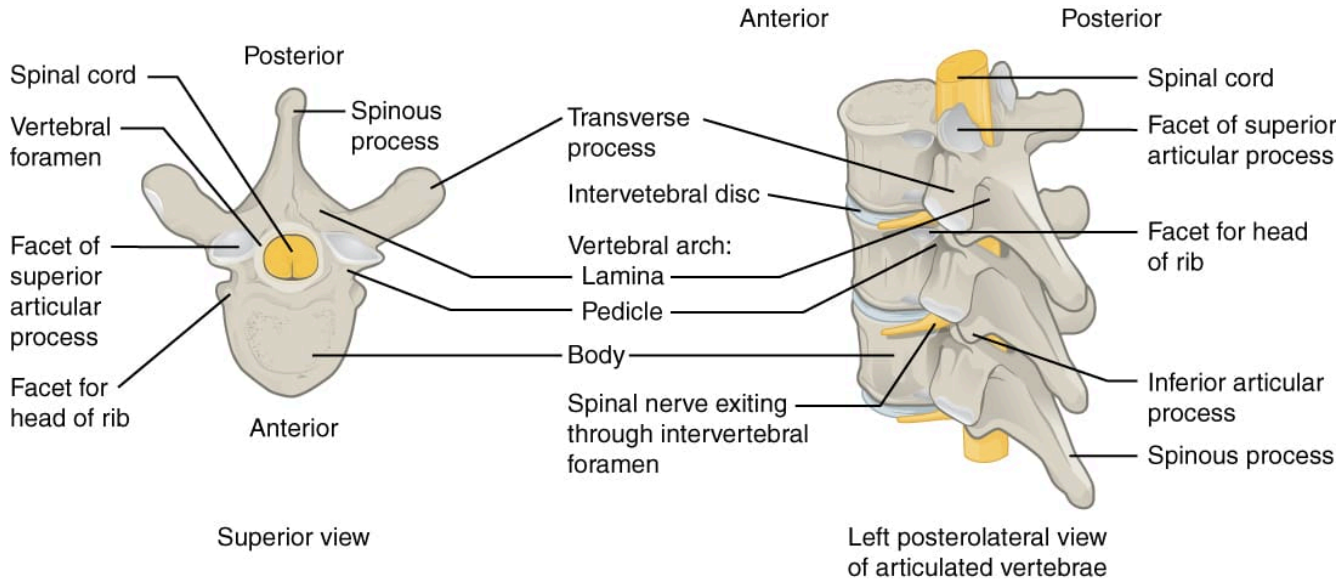


Figure 7.3.4: Anatomical comparison of a vertebra from a superior view and a left posterolateral view, illustrating key structures including processes, vertebral arch components, and the spinal cord. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.4.

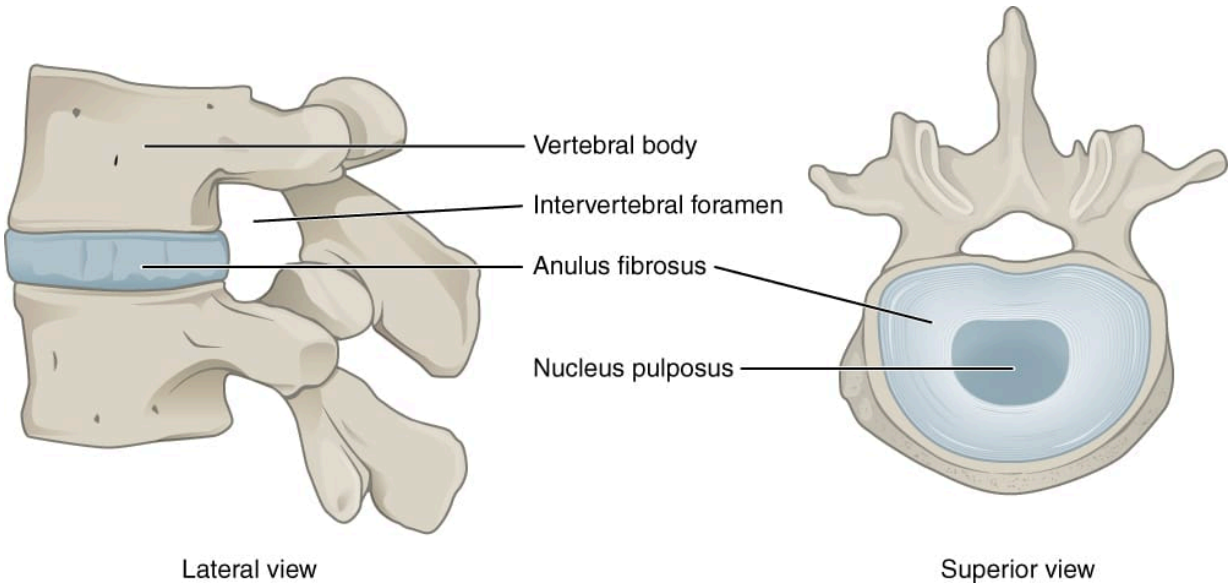


Figure 7.3.5: Illustration comparing lateral and superior views of a vertebra, highlighting the intervertebral disc and its major structural components. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.5.

Regional Modifications of Vertebrae

In addition to the general characteristics of a typical vertebra described above, vertebrae also display characteristic size and structural features that vary between the different vertebral column regions. Thus, cervical vertebrae are smaller than lumbar vertebrae due to differences in the proportion of body weight that each supports. Thoracic vertebrae have sites for rib attachment, and the vertebrae that give rise to the sacrum and coccyx have fused together into single bones.

Cervical Vertebrae

Typical cervical vertebrae, such as C4 or C5, have several characteristic features that differentiate them from thoracic or lumbar vertebrae (Figure 7.3.6). Cervical vertebrae have a small body, reflecting the fact that they carry the least amount of body weight. Cervical vertebrae usually have a bifid (Y-shaped) spinous process. The spinous processes of the C3–C6 vertebrae are short, but the spine of C7 is much longer. You can find these vertebrae by running your finger down the midline of the posterior neck until you encounter the prominent C7 spine located at the base of the neck. The transverse processes of the cervical vertebrae are sharply curved (U-shaped) to allow for passage of the cervical spinal nerves. Each transverse process also has an opening called the transverse foramen. An important artery that supplies the brain ascends up the neck by passing through these openings. The superior and inferior articular processes of the cervical vertebrae are flattened and largely face upward or downward, respectively.

The first and second cervical vertebrae are further modified, giving each a distinctive appearance. The first cervical (C1) vertebra is also called the atlas, because this is the vertebra that supports the skull on top of the vertebral column (in Greek mythology, Atlas was the god who supported the heavens on his shoulders). The C1 vertebra does not have a body or spinous process. Instead, it is ring-shaped, consisting of an anterior arch and a posterior arch. The transverse processes of the atlas are longer and extend more laterally than do the transverse processes of any other cervical vertebrae. The superior articular processes face upward and are deeply curved for articulation with the occipital condyles on the base of the skull. The inferior articular processes are flat and face downward to join with the superior articular processes of the C2 vertebra.

The second cervical (C2) vertebra is called the axis, because it serves as the axis for rotation when turning the head toward the right or left. The axis resembles typical cervical vertebrae in most respects, but is easily distinguished by the dens (odontoid process), a bony projection that extends upward from the vertebral body. The dens joins with the inner aspect of the anterior arch of the atlas, where it is held in place by the transverse ligament.

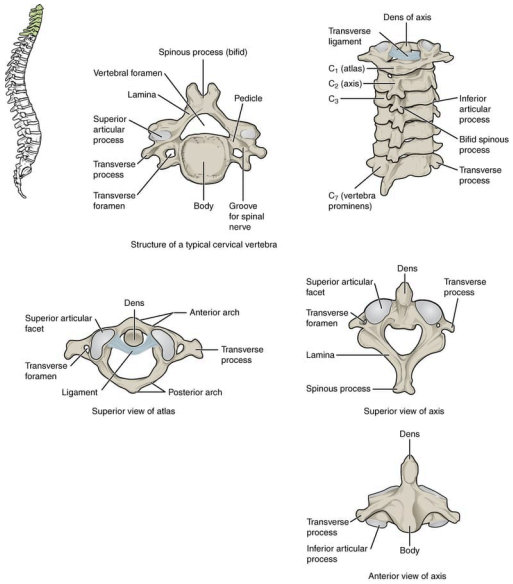


Figure 7.3.6: Illustrations comparing the structure of cervical vertebrae, including a typical vertebra, the atlas, the axis, and a cervical vertebral column segment. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.6.

Thoracic Vertebrae

The bodies of the thoracic vertebrae are larger than those of cervical vertebrae (Figure 7.3.7). The characteristic feature for a typical midthoracic vertebra is the spinous process, which is long and has a pronounced downward angle that causes it to

overlap the next inferior vertebra. The superior articular facets of thoracic vertebrae face anteriorly and the inferior facets face posteriorly. These orientations are important determinants for the type and range of movements available to the thoracic region of the vertebral column.

Thoracic vertebrae have several additional articulation sites, each of which is called a facet, where a rib is attached. Most thoracic vertebrae have two facets located on the lateral sides of the body, each of which is called a costal facet (costal = “rib”). These are for articulation with the head (end) of a rib. An additional facet is located on the transverse process for articulation with the tubercle of a rib.

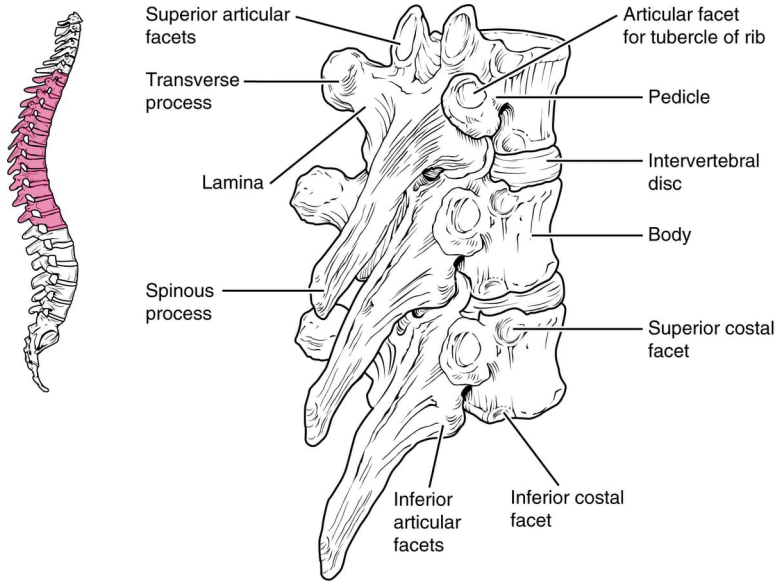


Figure 7.3.7: Illustration of thoracic vertebrae highlighting key anatomical structures, including costal facets, articular processes, transverse processes, and intervertebral discs. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.7.

The vertebral body is the large anterior portion of each vertebra. Its functions are to support body weight, provide a surface for attachment of intervertebral discs, and contain facets involved in rib articulation.

The intervertebral disc is located between adjacent vertebral bodies. Its functions are to act as a shock absorber and allow flexibility and controlled movement of the spine.

The vertebral arch extends posteriorly from the vertebral body and is composed of the pedicle and lamina. Its functions are to enclose and protect the spinal cord and provide structural strength.

The spinous process is a long projection that extends posteriorly and downward. Its functions are to serve as an attachment site for muscles and ligaments and help regulate movement of the thoracic spine.

The transverse process is a lateral projection extending from each vertebra. Its functions are to provide attachment for muscles and to contain a facet for rib articulation.

The superior and inferior articular processes are projections that connect adjacent vertebrae. Their functions are to form joints that guide movement of the spine, limit excessive motion, and provide stability.

The thoracic vertebrae also include specialized costal facets, which are rib articulation points. The superior costal facet is located on the vertebral body and articulates with the head of a rib. The inferior costal facet lies below the superior costal facet on the vertebral body and also participates in articulation with ribs. The articular facet for tubercle of rib is located on the transverse process. Its functions are to connect with the tubercle of a rib and help stabilize the rib connection.

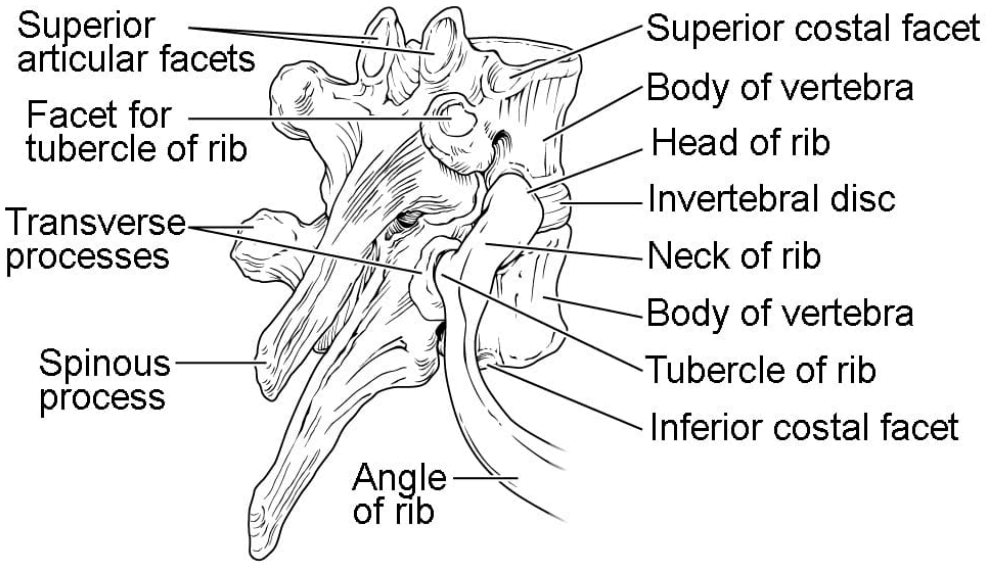


Figure 7.3.8: Illustration of thoracic vertebrae articulating with ribs, highlighting costal facets, articular processes, transverse processes, intervertebral discs, and rib anatomy including the head, neck, tubercle, and angle. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.8.

The thoracic vertebrae include specialized costal facets, which are joint surfaces for rib attachment. The superior costal facet is located on the vertebral body and articulates with the head of a rib. The inferior costal facet is located below the superior costal facet and also participates in articulation with the rib head. The facet for tubercle of rib is located on the transverse process and articulates with the tubercle of the rib, providing additional stability for rib movement.

Lumbar Vertebrae

Lumbar vertebrae carry the greatest amount of body weight and are thus characterized by the large size and thickness of the vertebral body (Figure 7.3.9). They have short transverse processes and a short, blunt spinous process that projects posteriorly. The articular processes are large, with the superior process facing medially and the inferior facing laterally.

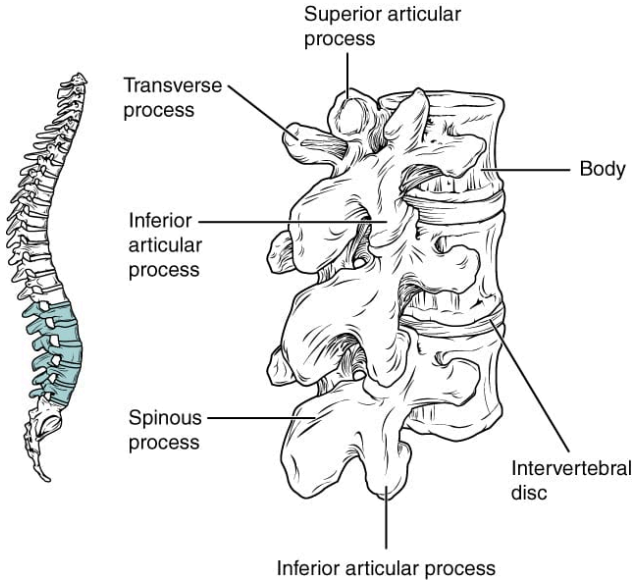


Figure 7.3.9: Illustration of lumbar vertebrae showing major anatomical landmarks, including the vertebral body, articular processes, spinous process, transverse process, and intervertebral discs. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.9.

The vertebral body is the large, thick anterior portion of each lumbar vertebra. Its functions are to support the majority of body

weight, provide stability for the lower back, and serve as the main connection point for intervertebral discs.

The intervertebral disc is located between adjacent vertebral bodies. Its functions are to act as a shock absorber, maintain spacing between vertebrae, and allow flexibility for bending forward and backward and for slight rotation.

The superior articular process is located on the upper part of each vertebra. Its functions are to connect to the vertebra above, help guide and limit movement, and provide stability to the spine.

The inferior articular process is located on the lower part of each vertebra. Its functions are to connect with the vertebra below, work with the superior articular process to stabilize the spinal column, and help control range of motion.

The transverse process extends laterally from each vertebra. Its functions are to serve as an attachment site for muscles and ligaments and support movement of the lower back.

The spinous process is a posterior projection extending from each vertebra. Its functions are to provide attachment for muscles and ligaments and help control movement of the spine and maintain posture.

The lumbar region is the part of the vertebral column located between the thoracic spine and the sacrum. It contains five lumbar vertebrae, L1 through L5. Its functions are to support the upper body, allow significant flexion and extension, and provide strength and stability while maintaining mobility.

Sacrum and Coccyx

The sacrum is a triangular-shaped bone that is thick and wide across its superior base where it is weight bearing and then tapers down to an inferior, non-weight bearing apex (Figure 7.3.10). It is formed by the fusion of five sacral vertebrae, a process that does not begin until after the age of 20. On the anterior surface of the older adult sacrum, the lines of vertebral fusion can be seen as four transverse ridges. On the posterior surface, running down the midline, is the median sacral crest, a bumpy ridge that is the remnant of the fused spinous processes (median = “midline”; while medial = “toward, but not necessarily at, the midline”). Similarly, the fused transverse processes of the sacral vertebrae form the lateral sacral crest.

The sacral promontory is the anterior lip of the superior base of the sacrum. Lateral to this is the roughened auricular surface, which joins with the ilium portion of the hipbone to form the immobile sacroiliac joints of the pelvis. Passing inferiorly through the sacrum is a bony tunnel called the sacral canal, which terminates at the sacral hiatus near the inferior tip of the sacrum. The anterior and posterior surfaces of the sacrum have a series of paired openings called sacral foramina (singular = foramen) that connect to the sacral canal. Each of these openings is called a posterior (dorsal) sacral foramen or anterior (ventral) sacral foramen. These openings allow for the anterior and posterior branches of the sacral spinal nerves to exit the sacrum. The superior articular process of the sacrum, one of which is found on either side of the superior opening of the sacral canal, articulates with the inferior articular processes from the L5 vertebra.

The coccyx, or tailbone, is derived from the fusion of four very small coccygeal vertebrae (Figure 7.3.10). It articulates with the inferior tip of the sacrum. It is not weight bearing in the standing position, but may receive some body weight when sitting.

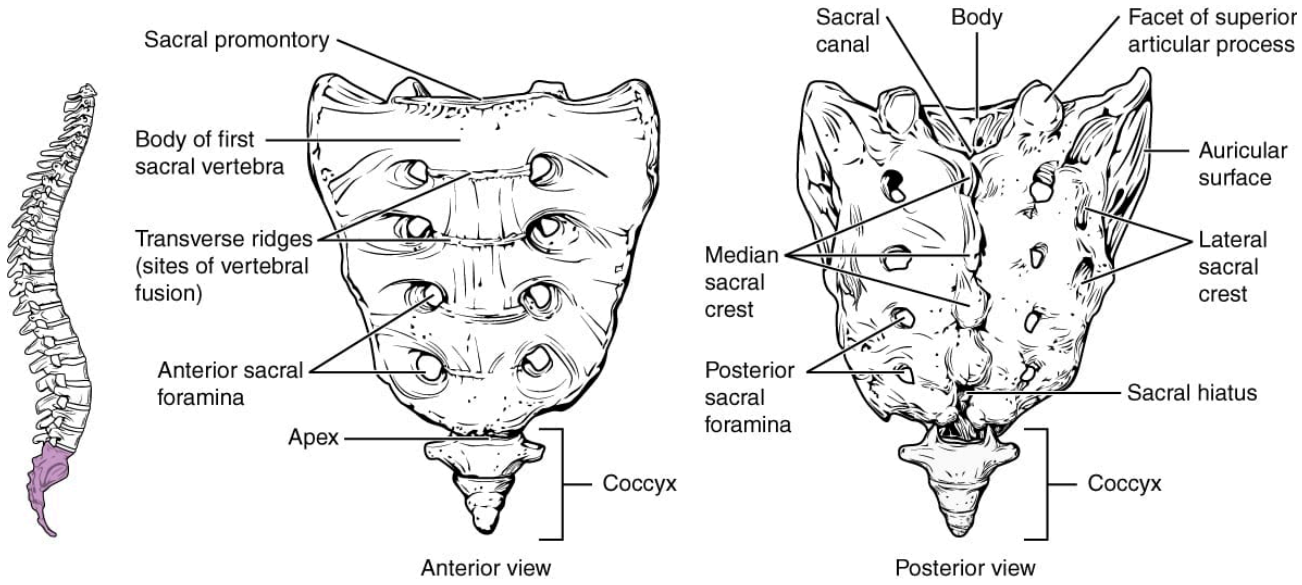


Figure 7.3.10: Illustration showing anterior and posterior views of the sacrum and coccyx, highlighting key features such as the sacral promontory, sacral foramina, sacral crests, auricular surface, sacral canal, sacral hiatus, and coccyx. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.10.

Intervertebral Discs and Ligaments of the Vertebral Column

The bodies of adjacent vertebrae are strongly anchored to each other by an intervertebral disc. This structure provides padding between the bones during weight bearing, and because it can change shape, also allows for movement between the vertebrae. Although the total amount of movement available between any two adjacent vertebrae is small, when these movements are summed together along the entire length of the vertebral column, large body movements can be produced. Ligaments that extend along the length of the vertebral column also contribute to its overall support and stability.

Intervertebral Disc

An intervertebral disc is a fibrocartilaginous pad that fills the gap between adjacent vertebral bodies (see Figure 7.3.5). Each disc is anchored to the bodies of its adjacent vertebrae, thus strongly uniting these. The discs also provide padding between vertebrae during weight bearing. Because of this, intervertebral discs are thin in the cervical region and thickest in the lumbar region, which carries the most body weight. In total, the intervertebral discs account for approximately 25 percent of your body height between the top of the pelvis and the base of the skull. Intervertebral discs are also flexible and can change shape to allow for movements of the vertebral column.

Each intervertebral disc consists of two parts. The anulus fibrosus is the tough, fibrous outer layer of the disc. It forms a circle (anulus = “ring” or “circle”) and is firmly anchored to the outer margins of the adjacent vertebral bodies. Inside is the nucleus pulposus, consisting of a softer, more gel-like material. It has a high water content that serves to resist compression and thus is important for weight bearing. With increasing age, the water content of the nucleus pulposus gradually declines. This causes the disc to become thinner, decreasing total body height somewhat, and reduces the flexibility and range of motion of the disc, making bending more difficult.

The gel-like nature of the nucleus pulposus also allows the intervertebral disc to change shape as one vertebra rocks side to side or forward and back in relation to its neighbors during movements of the vertebral column. Thus, bending forward causes compression of the anterior portion of the disc but expansion of the posterior disc. If the posterior anulus fibrosus is weakened due to injury or increasing age, the pressure exerted on the disc when bending forward and lifting a heavy object can cause the nucleus pulposus to protrude posteriorly through the anulus fibrosus, resulting in a herniated disc (“ruptured” or “slipped” disc) (Figure 7.3.11). The posterior bulging of the nucleus pulposus can cause compression of a spinal nerve at the point where it exits through the intervertebral foramen, with resulting pain and/or muscle weakness in those body regions supplied by that nerve. The most common sites for disc herniation are the L4/L5 or L5/S1 intervertebral discs, which can cause sciatica, a widespread pain that radiates from the lower back down the thigh and into the leg. Similar injuries of the C5/C6 or C6/C7 intervertebral discs, following forcible hyperflexion of the neck from a collision accident or football injury, can produce pain in the neck, shoulder, and

upper limb.

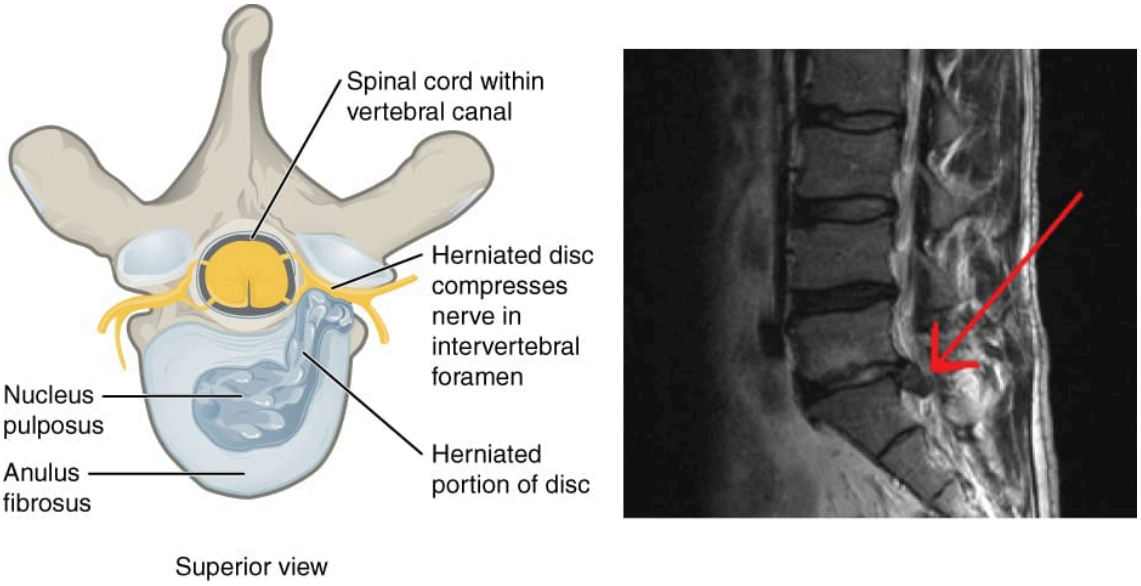


Figure 7.3.11: Anterior and posterior illustrations of the sacrum and coccyx showing key anatomical structures, including sacral promontory, sacral foramina, sacral crests, auricular surfaces, sacral hiatus, and the coccyx. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.11.

Ligaments of the Vertebral Column

Adjacent vertebrae are united by ligaments that run the length of the vertebral column along both its posterior and anterior aspects (Figure 7.3.12). These serve to resist excess forward or backward bending movements of the vertebral column, respectively.

The anterior longitudinal ligament runs down the anterior side of the entire vertebral column, uniting the vertebral bodies. It serves to resist excess backward bending of the vertebral column. Protection against this movement is particularly important in the neck, where extreme posterior bending of the head and neck can stretch or tear this ligament, resulting in a painful whiplash injury. Prior to the mandatory installation of seat headrests, whiplash injuries were common for passengers involved in a rear-end automobile collision.

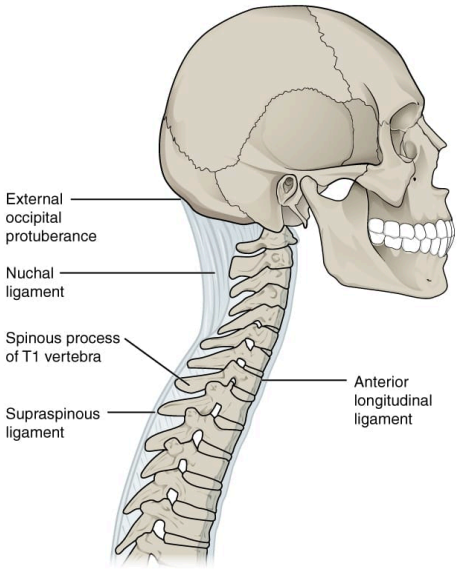


Figure 7.3.12: Lateral illustration of the skull and cervical vertebrae highlighting the nuchal ligament, supraspinous ligament, anterior longitudinal ligament, and key bony landmarks including the external occipital protuberance and spinous processes. (CC BY 4.0 ; via Axial Skeleton). Alternative text description of the Figure 7.3.12.

Career Connection

Chiropractor

Chiropractors are health professionals who use nonsurgical techniques to help patients with musculoskeletal system problems that involve the bones, muscles, ligaments, tendons, or nervous system. They treat problems such as neck pain, back pain, joint pain, or headaches. Chiropractors focus on the patient's overall health and can also provide counseling related to lifestyle issues, such as diet, exercise, or sleep problems. If needed, they will refer the patient to other medical specialists.

Chiropractors use a drug-free, hands-on approach for patient diagnosis and treatment. They will perform a physical exam, assess the patient's posture and spine, and may perform additional diagnostic tests, including taking X-ray images. They primarily use manual techniques, such as spinal manipulation, to adjust the patient's spine or other joints. They can recommend therapeutic or rehabilitative exercises, and some also include acupuncture, massage therapy, or ultrasound as part of the treatment program. In addition to those in general practice, some chiropractors specialize in sport injuries, neurology, orthopaedics, pediatrics, nutrition, internal disorders, or diagnostic imaging.

To become a chiropractor, students must have 3–4 years of undergraduate education, attend an accredited, four-year Doctor of Chiropractic (D.C.) degree program, and pass a licensure examination to be licensed for practice in their state. With the aging of the baby-boom generation, employment for chiropractors is expected to increase.

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7.4: The Thoracic Cage

Sternum, Ribs, and Rib Classifications

The thoracic cage (rib cage) forms the thorax (chest) portion of the body. It consists of the twelve pairs of ribs with their costal cartilages and the sternum as depicted in Figure 7.4.1. The ribs are anchored posteriorly to the 12 thoracic vertebrae (T1–T12). The thoracic cage protects the heart and lungs.

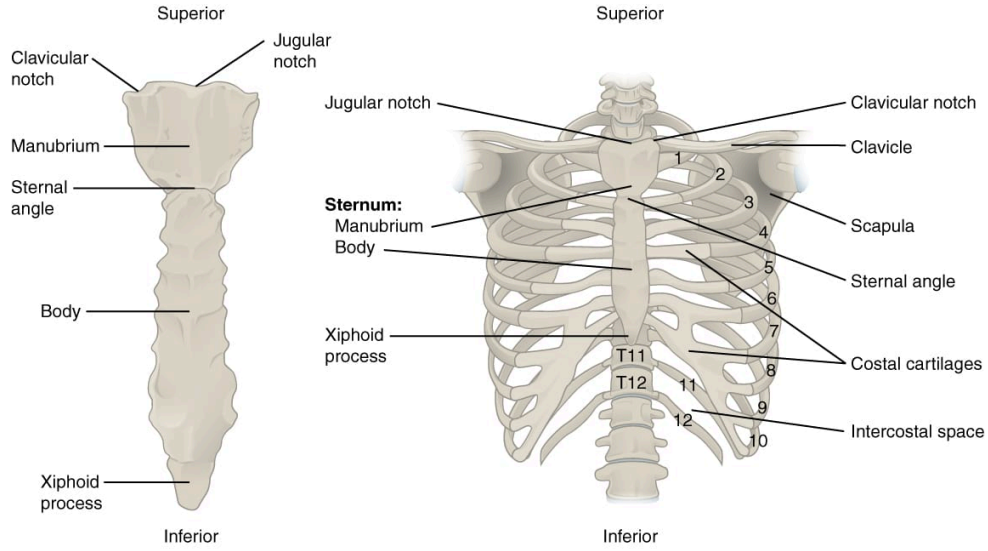


Figure 7.4.1: Anterior views of the sternum and thoracic cage showing major bony landmarks. (CC BY 4.0; via The Thoracic Cage). Alternative text of the description Figure 7.4.1.

Sternum

The sternum is the elongated bony structure that anchors the anterior thoracic cage. It consists of three parts: the manubrium, body, and xiphoid process. The manubrium is the wider, superior portion of the sternum. The top of the manubrium has a shallow, U-shaped border called the jugular (suprasternal) notch. This can be easily felt at the anterior base of the neck, between the medial ends of the clavicles. The clavicular notch is the shallow depression located on either side at the superior-lateral margins of the manubrium. This is the site of the sternoclavicular joint, between the sternum and clavicle. The first ribs also attach to the manubrium.

The elongated, central portion of the sternum is the body. The manubrium and body join together at the sternal angle, so called because the junction between these two components is not flat, but forms a slight bend. The second rib attaches to the sternum at the sternal angle. Since the first rib is hidden behind the clavicle, the second rib is the highest rib that can be identified by palpation. Thus, the sternal angle and second rib are important landmarks for the identification and counting of the lower ribs. Ribs 3–7 attach to the sternal body.

The inferior tip of the sternum is the xiphoid process. This small structure is cartilaginous early in life, but gradually becomes ossified starting during middle age.

Ribs

Each rib is a curved, flattened bone that contributes to the wall of the thorax. The ribs articulate posteriorly with the T1–T12 thoracic vertebrae, and most attach anteriorly via their costal cartilages to the sternum. There are 12 pairs of ribs. The ribs are numbered 1–12 in accordance with the thoracic vertebrae.

Parts of a Typical Rib

The posterior end of a typical rib is called the head of the rib Figure 7.4.2. This region articulates primarily with the costal facet located on the body of the same numbered thoracic vertebra and to a lesser degree, with the costal facet located on the body of the next higher vertebra. Lateral to the head is the narrowed neck of the rib. A small bump on the posterior rib surface is the tubercle of the rib, which articulates with the facet located on the transverse process of the same numbered vertebra. The remainder of the rib is the body of the rib (shaft). Just lateral to the tubercle is the angle of the rib, the point at which the rib has its greatest degree of curvature. The angles of the ribs form the most posterior extent of the thoracic cage. In the anatomical position, the angles align with the medial border of the scapula. A shallow costal groove for the passage of blood vessels and a nerve is found along the inferior margin of each rib.

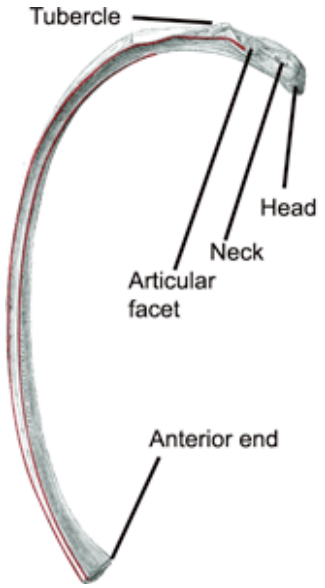


Figure 7.4.2: Anatomy of a typical rib, highlighting key structures including the head, neck, tubercle, articular facet, and anterior end along the rib's curvature. (CC-BY-SA 4.0; Henry Vandyke Carter via Wikimedia Commons). Alternative text of the description Figure 7.4.2.

Rib Classifications

The bony ribs do not extend anteriorly completely around to the sternum. Instead, each rib ends in a costal cartilage. These cartilages are made of hyaline cartilage and can extend for several inches. Most ribs are then attached, either directly or indirectly, to the sternum via their costal cartilage Figure 7.4.3. The ribs are classified into three groups based on their relationship to the sternum.

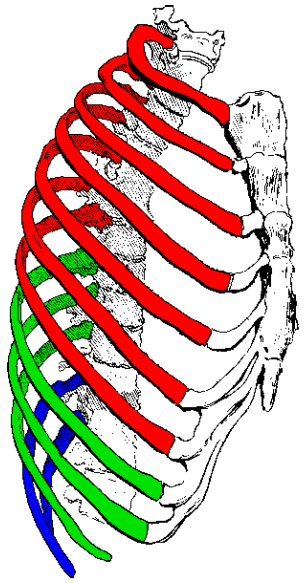


Figure 7.4.3: Classification of ribs based on their sternal connections, highlighting true ribs(1-7), false ribs(8-10), and floating ribs(11-12). (CC-BY-SA 4.0; Cristobal carrasco via Wikimedia Commons). Alternative text of the description Figure 7.4.3.

Ribs 1–7 are classified as true ribs, also called vertebrosternal ribs. The costal cartilage of each of these ribs attaches directly to the sternum. Ribs 8–12 are classified as false ribs, also called vertebrochondral ribs, because their costal cartilages do not attach directly to the sternum. In ribs 8–10, the cartilage of each rib connects to the cartilage of the rib above it, creating an indirect attachment to the sternum. Ribs 11–12 are a subgroup of false ribs called floating ribs, also known as vertebral ribs. These short ribs do not attach to the sternum at all. Instead, their small costal cartilages end within the musculature of the lateral abdominal wall.

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7.5: Terms and Definitions

Key Terms

Select to view definitions

Alveolar process of the mandible
upper border of mandibular body that contains the lower teeth

Alveolar process of the maxilla
curved, inferior margin of the maxilla that supports and anchors the upper teeth

Angle of the mandible
rounded corner located at outside margin of the body and ramus junction

Angle of the rib
portion of rib with greatest curvature; together, the rib angles form the most posterior extent of the thoracic cage

Anterior (ventral) sacral foramen
one of the series of paired openings located on the anterior (ventral) side of the sacrum

Anterior arch
anterior portion of the ring-like C1 (atlas) vertebra

Anterior cranial fossa
shallowest and most anterior cranial fossa of the cranial base that extends from the frontal bone to the lesser wing of the sphenoid bone

Anterior longitudinal ligament
ligament that runs the length of the vertebral column, uniting the anterior aspects of the vertebral bodies

Anulus fibrosus
tough, fibrous outer portion of an intervertebral disc, which is strongly anchored to the bodies of the adjacent vertebrae

Appendicular skeleton
all bones of the upper and lower limbs, plus the girdle bones that attach each limb to the axial skeleton

Articular tubercle
smooth ridge located on the inferior skull, immediately anterior to the mandibular fossa

Atlas
first cervical (C1) vertebra

Axial skeleton
central, vertical axis of the body, including the skull, vertebral column, and thoracic cage

Axis
second cervical (C2) vertebra

Body of the rib
shaft portion of a rib

Brain case
portion of the skull that contains and protects the brain, consisting of the eight bones that form the cranial base and rounded upper skull

Calvaria
(also, skullcap) rounded top of the skull

Carotid canal
zig-zag tunnel providing passage through the base of the skull for the internal carotid artery to the brain; begins anteromedial to the styloid process and terminates in the middle cranial cavity, near the posterior-lateral base of the sella turcica

Cervical curve
posteriorly concave curvature of the cervical vertebral column region; a secondary curve of the vertebral column

Cervical vertebrae
seven vertebrae numbered as C1–C7 that are located in the neck region of the vertebral column

Clavicular notch
paired notches located on the superior-lateral sides of the sternal manubrium, for articulation with the clavicle

Coccyx
small bone located at inferior end of the adult vertebral column that is formed by the fusion of four coccygeal vertebrae; also referred to as the “tailbone”

Condylar process of the mandible
thickened upward projection from posterior margin of mandibular ramus

Condyle
oval-shaped process located at the top of the condylar process of the mandible

Coronal suture
joint that unites the frontal bone to the right and left parietal bones across the top of the skull

Coronoid process of the mandible
flattened upward projection from the anterior margin of the mandibular ramus

Costal cartilage
hyaline cartilage structure attached to the anterior end of each rib that provides for either direct or indirect attachment of most ribs to the sternum

Costal facet
site on the lateral sides of a thoracic vertebra for articulation with the head of a rib

Costal groove
shallow groove along the inferior margin of a rib that provides passage for blood vessels and a nerve

Cranial cavity
interior space of the skull that houses the brain

Cranium
skull

Cribriform plate
small, flattened areas with numerous small openings, located to either side of the midline in the floor of the anterior cranial fossa; formed by the ethmoid bone

Crista galli
small upward projection located at the midline in the floor of the anterior cranial fossa; formed by the ethmoid bone

Dens
bony projection (odontoid process) that extends upward from the body of the C2 (axis) vertebra

Ear ossicles
three small bones located in the middle ear cavity that serve to transmit sound vibrations to the inner ear

Ethmoid air cell
one of several small, air-filled spaces located within the lateral sides of the ethmoid bone, between the orbit and upper nasal cavity

Ethmoid bone
unpaired bone that forms the roof and upper, lateral walls of the nasal cavity, portions of the floor of the anterior cranial fossa and medial wall of orbit, and the upper portion of the nasal septum

External acoustic meatus
ear canal opening located on the lateral side of the skull

External occipital protuberance
small bump located at the midline on the posterior skull

Facet
small, flattened area on a bone for an articulation (joint) with another bone, or for muscle attachment

Facial bones
fourteen bones that support the facial structures and form the upper and lower jaws and the hard palate

False ribs
vertebrochondral ribs 8–12 whose costal cartilage either attaches indirectly to the sternum via the costal cartilage of the next higher rib or does not attach to the sternum at all

Floating ribs
vertebral ribs 11–12 that do not attach to the sternum or to the costal cartilage of another rib

Fontanelle
expanded area of fibrous connective tissue that separates the brain case bones of the skull prior to birth and during the first year after birth

Foramen lacerum
irregular opening in the base of the skull, located inferior to the exit of carotid canal

Foramen magnum
large opening in the occipital bone of the skull through which the spinal cord emerges and the vertebral arteries enter the cranium

Foramen ovale of the middle cranial fossa
oval-shaped opening in the floor of the middle cranial fossa

Foramen rotundum
round opening in the floor of the middle cranial fossa, located between the superior orbital fissure and foramen ovale

Foramen spinosum
small opening in the floor of the middle cranial fossa, located lateral to the foramen ovale

Frontal bone
unpaired bone that forms forehead, roof of orbit, and floor of anterior cranial fossa

Frontal sinus
air-filled space within the frontal bone; most anterior of the paranasal sinuses

Glabella
slight depression of frontal bone, located at the midline between the eyebrows

Greater wings of sphenoid bone
lateral projections of the sphenoid bone that form the anterior wall of the middle cranial fossa and an area of the lateral skull

Hard palate
bony structure that forms the roof of the mouth and floor of the nasal cavity, formed by the palatine process of the maxillary bones and the horizontal plate of the palatine bones

Head of the rib
posterior end of a rib that articulates with the bodies of thoracic vertebrae

Horizontal plate
medial extension from the palatine bone that forms the posterior quarter of the hard palate

Hyoid bone
small, U-shaped bone located in upper neck that does not contact any other bone

Hypoglossal canal
paired openings that pass anteriorly from the anterior-lateral margins of the foramen magnum deep to the occipital condyles

Hypophyseal (pituitary) fossa
shallow depression on top of the sella turcica that houses the pituitary (hypophyseal) gland

Inferior articular process
bony process that extends downward from the vertebral arch of a vertebra that articulates with the superior articular process of the next lower vertebra

Inferior nasal concha
one of the paired bones that project from the lateral walls of the nasal cavity to form the largest and most inferior of the nasal conchae

Infraorbital foramen
opening located on anterior skull, below the orbit

Infratemporal fossa
space on lateral side of skull, below the level of the zygomatic arch and deep (medial) to the ramus of the mandible

Internal acoustic meatus
opening into petrous ridge, located on the lateral wall of the posterior cranial fossa

Intervertebral disc
structure located between the bodies of adjacent vertebrae that strongly joins the vertebrae; provides padding, weight bearing ability, and enables vertebral column movements

Intervertebral foramen
opening located between adjacent vertebrae for exit of a spinal nerve

Jugular (suprasternal) notch
shallow notch located on superior surface of sternal manubrium

Jugular foramen
irregularly shaped opening located in the lateral floor of the posterior cranial cavity

Kyphosis
(also, humpback or hunchback) excessive posterior curvature of the thoracic vertebral column region

Lacrimal bone
paired bones that contribute to the anterior-medial wall of each orbit

Lacrimal fossa
shallow depression in the anterior-medial wall of the orbit, formed by the lacrimal bone that gives rise to the nasolacrimal canal

Lambdoid suture
inverted V-shaped joint that unites the occipital bone to the right and left parietal bones on the posterior skull

Lamina
portion of the vertebral arch on each vertebra that extends between the transverse and spinous process

Llateral pterygoid plate
paired, flattened bony projections of the sphenoid bone located on the inferior skull, lateral to the medial pterygoid plate

Lateral sacral crest
paired irregular ridges running down the lateral sides of the posterior sacrum that was formed by the fusion of the transverse processes from the five sacral vertebrae

Lesser wings of the sphenoid bone
lateral extensions of the sphenoid bone that form the bony lip separating the anterior and middle cranial fossae

Ligamentum flavum
series of short ligaments that unite the lamina of adjacent vertebrae

Lordosis
(also, swayback) excessive anterior curvature of the lumbar vertebral column region

Lumbar curve
posteriorly concave curvature of the lumbar vertebral column region; a secondary curve of the vertebral column

Lumbar vertebrae
five vertebrae numbered as L1–L5 that are located in lumbar region (lower back) of the vertebral column

Mandible
unpaired bone that forms the lower jaw bone; the only moveable bone of the skull

Mandibular foramen
opening located on the inner (medial) surface of the mandibular ramus

Mandibular fossa
oval depression located on the inferior surface of the skull

Mandibular notch
large U-shaped notch located between the condylar process and coronoid process of the mandible

Manubrium
expanded, superior portion of the sternum

Mastoid process
large bony prominence on the inferior, lateral skull, just behind the earlobe

Maxillary bone
(also, maxilla) paired bones that form the upper jaw and anterior portion of the hard palate

Maxillary sinus
air-filled space located with each maxillary bone; largest of the paranasal sinuses

Medial pterygoid plate
paired, flattened bony projections of the sphenoid bone located on the inferior skull medial to the lateral pterygoid plate; form the posterior portion of the nasal cavity lateral wall

Median sacral crest
irregular ridge running down the midline of the posterior sacrum that was formed from the fusion of the spinous processes of the five sacral vertebrae

Mental foramen
opening located on the anterior-lateral side of the mandibular body

Mental protuberance
inferior margin of anterior mandible that forms the chin

Middle cranial fossa
centrally located cranial fossa that extends from the lesser wings of the sphenoid bone to the petrous ridge

Middle nasal concha
nasal concha formed by the ethmoid bone that is located between the superior and inferior conchae

Nasal bone
paired bones that form the base of the nose

Nasal cavity
opening through skull for passage of air

Nasal conchae
curved bony plates that project from the lateral walls of the nasal cavity; include the superior and middle nasal conchae, which are parts of the ethmoid bone, and the independent inferior nasal conchae bone

Nasal septum
flat, midline structure that divides the nasal cavity into halves, formed by the perpendicular plate of the ethmoid bone, vomer bone, and septal cartilage

Nasolacrimal canal
passage for drainage of tears that extends downward from the medial-anterior orbit to the nasal cavity, terminating behind the inferior nasal conchae

Neck of the rib
narrowed region of a rib, next to the rib head

Notochord
rod-like structure along dorsal side of the early embryo; largely disappears during later development but does contribute to formation of the intervertebral discs

Nuchal ligament
expanded portion of the supraspinous ligament within the posterior neck; interconnects the spinous processes of the cervical vertebrae and attaches to the base of the skull

Nucleus pulposus
gel-like central region of an intervertebral disc; provides for padding, weight-bearing, and movement between adjacent vertebrae

Occipital bone
unpaired bone that forms the posterior portions of the brain case and base of the skull

Occipital condyle
paired, oval-shaped bony knobs located on the inferior skull, to either side of the foramen magnum

Optic canal
opening spanning between middle cranial fossa and posterior orbit

Orbit
bony socket that contains the eyeball and associated muscles

Palatine bone
paired bones that form the posterior quarter of the hard palate and a small area in floor of the orbit

Palatine process
medial projection from the maxilla bone that forms the anterior three quarters of the hard palate

Paranasal sinuses
cavities within the skull that are connected to the conchae that serve to warm and humidify incoming air, produce

mucus, and lighten the weight of the skull; consist of frontal, maxillary, sphenoidal, and ethmoidal sinuses

Parietal bone
paired bones that form the upper, lateral sides of the skull

Pedicle
portion of the vertebral arch that extends from the vertebral body to the transverse process

Perpendicular plate of the ethmoid bone
downward, midline extension of the ethmoid bone that forms the superior portion of the nasal septum

Petrous ridge
petrous portion of the temporal bone that forms a large, triangular ridge in the floor of the cranial cavity, separating the middle and posterior cranial fossae; houses the middle and inner ear structures

Posterior (dorsal) sacral foramen
one of the series of paired openings located on the posterior (dorsal) side of the sacrum

Posterior arch
posterior portion of the ring-like C1 (atlas) vertebra

Posterior cranial fossa
deepest and most posterior cranial fossa; extends from the petrous ridge to the occipital bone

Posterior longitudinal ligament
ligament that runs the length of the vertebral column, uniting the posterior sides of the vertebral bodies

Primary curve
anteriorly concave curvatures of the thoracic and sacrococcygeal regions that are retained from the original fetal curvature of the vertebral column

Pterion
H-shaped suture junction region that unites the frontal, parietal, temporal, and sphenoid bones on the lateral side of the skull

Ramus of the mandible
vertical portion of the mandible

Ribs
thin, curved bones of the chest wall

Sacral canal
bony tunnel that runs through the sacrum

Sacral foramina
series of paired openings for nerve exit located on both the anterior (ventral) and posterior (dorsal) aspects of the sacrum

Sacral hiatus
inferior opening and termination of the sacral canal

Sacral promontory
anterior lip of the base (superior end) of the sacrum

Sacrococcygeal curve
anteriorly concave curvature formed by the sacrum and coccyx; a primary curve of the vertebral column

Sacrum
single bone located near the inferior end of the adult vertebral column that is formed by the fusion of five sacral vertebrae; forms the posterior portion of the pelvis

Sagittal suture
joint that unites the right and left parietal bones at the midline along the top of the skull

Scoliosis
abnormal lateral curvature of the vertebral column

Secondary curve
posteriorly concave curvatures of the cervical and lumbar regions of the vertebral column that develop after the time of birth

Sella turcica
elevated area of sphenoid bone located at midline of the middle cranial fossa

Septal cartilage
flat cartilage structure that forms the anterior portion of the nasal septum

Skeleton
bones of the body

Skull
bony structure that forms the head, face, and jaws, and protects the brain; consists of 22 bones

Somite
one of the paired, repeating blocks of tissue located on either side of the notochord in the early embryo

Sphenoid bone
unpaired bone that forms the central base of skull

Sphenoid sinus
air-filled space located within the sphenoid bone; most posterior of the paranasal sinuses

Spinous process
unpaired bony process that extends posteriorly from the vertebral arch of a vertebra

Squamous suture
joint that unites the parietal bone to the squamous portion of the temporal bone on the lateral side of the skull

Sternal angle
junction line between manubrium and body of the sternum and the site for attachment of the second rib to the sternum

Sternum
flattened bone located at the center of the anterior chest

Styloid process
downward projecting, elongated bony process located on the inferior aspect of the skull

Stylomastoid foramen
opening located on inferior skull, between the styloid process and mastoid process

Superior articular process
bony process that extends upward from the vertebral arch of a vertebra that articulates with the inferior articular process of the next higher vertebra

Ssuperior articular process of the sacrum
paired processes that extend upward from the sacrum to articulate (join) with the inferior articular processes from the L5 vertebra

Superior nasal concha
smallest and most superiorly located of the nasal conchae; formed by the ethmoid bone

Superior nuchal line
paired bony lines on the posterior skull that extend laterally from the external occipital protuberance

Superior orbital fissure
irregularly shaped opening between the middle cranial fossa and the posterior orbit

Supraorbital foramen
opening located on anterior skull, at the superior margin of the orbit

Supraorbital margin
superior margin of the orbit

Supraspinous ligament
ligament that interconnects the spinous processes of the thoracic and lumbar vertebrae

Suture
junction line at which adjacent bones of the skull are united by fibrous connective tissue

Temporal bone
paired bones that form the lateral, inferior portions of the skull, with squamous, mastoid, and petrous portions

Temporal fossa
shallow space on the lateral side of the skull, above the level of the zygomatic arch

Temporal process of the zygomatic bone
short extension from the zygomatic bone that forms the anterior portion of the zygomatic arch

Thoracic cage
consists of 12 pairs of ribs and sternum

Thoracic curve
anteriorly concave curvature of the thoracic vertebral column region; a primary curve of the vertebral column

Thoracic vertebrae
twelve vertebrae numbered as T1–T12 that are located in the thoracic region (upper back) of the vertebral column

Transverse foramen
opening found only in the transverse processes of cervical vertebrae

Transverse process
paired bony processes that extends laterally from the vertebral arch of a vertebra

True ribs
vertebrosternal ribs 1–7 that attach via their costal cartilage directly to the sternum

Tubercle of the rib
small bump on the posterior side of a rib for articulation with the transverse process of a thoracic vertebra

Vertebra
individual bone in the neck and back regions of the vertebral column

Vertebral (spinal) canal
bony passageway within the vertebral column for the spinal cord that is formed by the series of individual vertebral foramina

Vertebral arch
bony arch formed by the posterior portion of each vertebra that surrounds and protects the spinal cord

Vertebral column
entire sequence of bones that extend from the skull to the tailbone

Vertebral foramen
opening associated with each vertebra defined by the vertebral arch that provides passage for the spinal cord

Vomer bone
unpaired bone that forms the inferior and posterior portions of the nasal septum

Xiphoid process
small process that forms the inferior tip of the sternum

Zygomatic arch
elongated, free-standing arch on the lateral skull, formed anteriorly by the temporal process of the zygomatic bone and posteriorly by the zygomatic process of the temporal bone

Zygomatic bone
cheekbone; paired bones that contribute to the lateral orbit and anterior zygomatic arch

Zygomatic process of the temporal bone
extension from the temporal bone that forms the posterior portion of the zygomatic arch

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7.6: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. Which of the following is part of the axial skeleton?
   A. Shoulder bones
   B. Thigh bone
   C. Foot bones
   D. Vertebral column

2. Which of the following is a primary function of the axial skeleton?
   A. Allowing for movement of the wrist and hand
   B. Protecting nerves and blood vessels at the elbow
   C. Supporting and protecting the trunk and central nervous system
   D. Allowing for movements of the ankle and foot

3. Which statement correctly describes the axial skeleton?
   A. It consists of 126 bones.
   B. It forms the vertical axis of the body.
   C. It includes all bones of the trunk and the limbs.
   D. It includes only the bones of the lower limbs.

4. Which of the following is a bone of the brain case (neurocranium) rather than the facial skeleton?
   A. Parietal bone
   B. Zygomatic bone
   C. Maxillary bone
   D. Lacrimal bone

5. The lambdoid suture joins the parietal bone to which other cranial bone?
   A. Frontal bone
   B. Occipital bone
   C. Other parietal bone
   D. Temporal bone

6. Which statement correctly describes the middle cranial fossa?
   A. It is bounded anteriorly by the petrous ridge of the temporal bone.
   B. It is bounded posteriorly by the lesser wing of the sphenoid bone.
   C. It is divided at the midline by a small area of the ethmoid bone called the crista galli.
   D. It contains the foramen rotundum, foramen ovale, and foramen spinosum.

7. The paranasal sinuses are best described as which of the following?
   A. Air-filled spaces found within the frontal, maxilla, sphenoid, and ethmoid bones only

B. Air-filled spaces found within all bones of the skull

C. Air-filled spaces that are not connected to the nasal cavity

D. Air-filled spaces divided at the midline by the nasal septum

8. Which of the following is a notable feature of the sphenoid bone?
   A. Sella turcica
   B. Squamous portion
   C. Glabella
   D. Zygomatic process

9. Which bony opening of the skull is correctly matched to its location?
   A. Carotid canal, located in the anterior cranial fossa
   B. Superior orbital fissure, located at the superior margin of the anterior orbit
   C. Mental foramen, located just below the orbit on the maxilla
   D. Hypoglossal canal, located in the posterior cranial fossa of the occipital bone

10. The cervical region of the vertebral column normally consists of how many vertebrae?
    A. Seven vertebrae
    B. Twelve vertebrae
    C. Five vertebrae
    D. A single bone derived from the fusion of five vertebrae

11. The primary (accommodation) curvatures of the vertebral column have which characteristic?
    A. They include the lumbar curvature.

    B. They are remnants of the original fetal C-shaped curvature.

    C. They include the cervical curvature.
    D. They develop only after birth.

12. Which statement correctly describes a typical vertebra?
    A. The vertebral foramen passes through the vertebral body.
    B. The superior articular process projects downward to articulate with the vertebra below.
    C. The lamina spans between the transverse process and the spinous process.
    D. It has a pair of laterally projecting spinous processes.

13. A typical lumbar vertebra can be distinguished by which feature?
    A. A short, thick, and rounded spinous process
    B. A bifid spinous process
    C. Costal facets for articulation with ribs
    D. A transverse foramen in each transverse process

14. Which ligament or structure is found only in association with the cervical region of the vertebral column?
    A. Nuchal ligament
    B. Ligamentum flavum
    C. Supraspinous ligament
    D. Anterior longitudinal ligament

15. Which statement about the sternum is accurate?
    A. It consists only of the manubrium and xiphoid process.
    B. The sternal angle is located between the manubrium and the body.
    C. It receives direct costal cartilage attachments from all 12 pairs of ribs.
    D. It articulates directly with the thoracic vertebral bodies.

16. The sternal angle is which of the following?
    A. The junction between the body and xiphoid process
    B. The site for attachment of the clavicle
    C. The site for attachment of the floating ribs

D. The junction between the manubrium and body

17. The tubercle of a typical rib has which function?
A. Articulation with the transverse process of a thoracic vertebra
B. Articulation with the body of a thoracic vertebra
C. Providing a groove for passage of blood vessels and a nerve
D. Representing the area of greatest rib curvature

18. True ribs are defined as which of the following?
A. Ribs 8–12
B. Ribs attached via their costal cartilage to the next higher rib
C. Ribs made entirely of bone without costal cartilage
D. Ribs attached via their costal cartilage directly to the sternum

19. Which statement correctly describes embryonic development of the axial skeleton?
A. Intramembranous ossification forms most of the facial bones and the cranial vault.
B. Endochondral ossification forms the ribs and sternum.
C. The notochord directly produces the cartilage models for the vertebrae.
D. Hyaline cartilage models give rise to most of the flat bones of the skull.

20. What is a fontanelle in the context of skull development?
A. The cartilage model for a vertebra that later is converted into bone
B. The early rod-like structure that runs the length of the embryo
C. The area of fibrous connective tissue between fetal cranial bones at birth
D. The structure that gives rise to the facial bones and vertebrae

21. Which bone is part of the axial skeleton rather than the appendicular skeleton?
A. Scapula
B. Clavicle
C. Sacrum
D. Humerus

22. Which pair correctly matches a vertebral region with a defining structural feature?
A. Thoracic region and transverse foramina
B. Lumbar region and costal facets for rib articulation
C. Cervical region and bifid spinous processes (except C1 and C7)
D. Sacral region and unfused vertebral bodies

23. Which of the following best describes the functional significance of secondary curvatures (cervical and lumbar) of the vertebral column?
A. They are present at birth and help accommodate thoracic organs.
B. They develop after birth and help align the body's weight over the lower limbs.
C. They reduce the flexibility of the vertebral column.
D. They are associated only with the thoracic and sacral regions.

24. Damage to the carotid canal would most directly threaten which structure or function?
A. Passage of the spinal cord into the vertebral canal
B. Passage of the internal carotid artery into the cranial cavity
C. Passage of the facial nerve to the face
D. Passage of the hypoglossal nerve to the tongue

25. Which skull bone contributes to the formation of the nasal septum along with the vomer?
A. Sphenoid bone
B. Ethmoid bone
C. Temporal bone
D. Zygomatic bone

26. Which movement is most directly limited by damage to the anterior longitudinal ligament of the vertebral column?

A. Flexion of the spine
B. Extension of the spine
C. Lateral flexion of the spine
D. Axial rotation of the spine

27. In an adult with osteoporosis, compression fractures of the vertebral bodies most directly affect which part of the axial skeleton?
A. Brain case
B. Vertebral column
C. Pectoral girdle
D. Pelvic girdle

28. Which of the following is a direct consequence of premature closure (early ossification) of cranial fontanelles in an infant?
A. Increased flexibility of the vertebral column
B. Restricted skull growth and potential increased intracranial pressure
C. Failure of the notochord to form
D. Inability of the primary curvatures to develop

29. Which bone is NOT part of the brain case but is part of the facial skeleton?
A. Occipital bone
B. Sphenoid bone
C. Maxillary bone
D. Temporal bone

30. Which feature distinguishes a typical thoracic vertebra from cervical and lumbar vertebrae?
A. Presence of transverse foramina
B. Presence of large kidney-shaped vertebral bodies
C. Presence of costal facets on the body and transverse processes
D. Presence of a bifid spinous process

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7.7: Critical Thinking Self-Check

Challenge Yourself

a. Critical thinking helps you move beyond memorizing bone names to understanding how the axial skeleton works in real people and real situations.

b. Use the short-essay, case-based questions at the end of this chapter as a self-check:
   - Start with 1–2 sentences that give your direct answer (main idea).
   - Then write 4–6 sentences that explain *why or how*, linking structure to function (for example, vertebral shape → movement, disc structure → shock absorption).
   - Use precise terms from this chapter (for example: vertebral body, spinous process, intervertebral disc, nucleus pulposus, annulus fibrosus, lordosis, kyphosis, scoliosis, atlas, axis, rib, sternum).

c. Whenever possible, show a clear cause → effect relationship (for example, "Because the thoracic vertebrae have ..... they are better suited for .....").

d. Diagram (optional but encouraged): A small labeled sketch can clarify logic.

Try to answer from memory first, then check the chapter. If you cannot clearly explain your reasoning, review that section before moving on.

1. The skull and vertebral column are both components of the axial skeleton that serve to protect vital parts of the central nervous system. Using specific anatomical features, explain how the distinct structural differences between the skull and the vertebral column are adapted to protect a fixed organ (the brain) versus a flexible, segmented structure (the spinal cord).
2. Astronauts in microgravity for extended periods experience significant bone loss. Using your knowledge of bone development, bone remodeling, and the relationship between mechanical stress and bone tissue, propose a detailed mechanism for how prolonged weightlessness leads to this condition and suggest a medical intervention to mitigate it.
3. A young child with a greenstick fracture and an elderly person with an osteoporotic compression fracture of the vertebra both present with pain following a fall. Explain the biological differences in the bone tissue of each patient that would predispose them to these specific fracture types. In your explanation, discuss the contrasting healing processes and long-term implications for each individual.
4. Some individuals are born with a congenital defect called spina bifida, a condition where the vertebral arch fails to form completely. Explain how this failure of bone development impacts the structural integrity and protective function of the axial skeleton.
5. Imagine you are a dietitian counseling a young female patient with a family history of osteoporosis. Explain the role of calcium and Vitamin D in bone development and remodeling during puberty, linking it to preventing future bone fragility. What specific dietary and lifestyle recommendations would you provide, and why are these habits crucial during this life stage?
6. Explain primary vs secondary spinal curvatures and how exaggerated thoracic kyphosis alters sagittal balance and erector spinae demand.
7. A 55-year-old office worker with long-standing poor posture develops chronic neck and upper back pain. On examination, you notice increased thoracic kyphosis and the head carried forward relative to the trunk. Explain how abnormal curvatures of the axial skeleton (especially increased thoracic kyphosis and forward head posture) change the loading on vertebrae, intervertebral discs, and supporting ligaments and muscles. In your answer, link specific structures (for example, vertebral bodies, spinous processes, intervertebral discs, cervical vs thoracic curves) to their functions, and show how these structural changes can lead to pain and reduced function in everyday activities such as sitting at a desk or looking at a screen.

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7.8: Alternate Text Descriptions

Figure 7.1: Facial Skull Bones

This image is a exploded front view of the facial bones of the skull with labeled, color-coded structures. The mandible forms the lower jaw at the bottom. The paired maxillae form the upper jaw on either side of the nasal opening. The zygomatic bones are positioned laterally as the cheekbones. Above the nasal opening are the paired nasal bones, with the lacrimal bones located beside them. The palatine bones are shown deeper within the skull, the vomer is centered in the midline, and the inferior nasal conchae are positioned below the nasal cavity. Labels identify each bone and show their relative positions in the facial skeleton.

Figure 7.1.1: Axial and Appendicular Skeleton

This image is of a human skeleton shown in anterior (front) and posterior (back) views. The skeleton is divided into the axial skeleton and the appendicular skeleton. The axial skeleton forms the central axis of the body and includes the skull, vertebral column, and thoracic cage. The skull includes a cranial portion, which encloses the brain, and a facial portion, which forms the face. The vertebral column extends from the skull through the trunk and supports posture while protecting the spinal cord. The thoracic cage, consisting of the ribs and sternum, protects the heart and lungs.

The appendicular skeleton includes the pectoral girdle, upper limbs, pelvic girdle, and lower limbs. The pectoral girdle consists of the clavicle and scapula and attaches the upper limbs to the axial skeleton. The upper limbs include the humerus, radius, ulna, carpals, metacarpals, and phalanges. The pelvic girdle is formed by the hip bones and connects the lower limbs to the trunk. The lower limbs include the femur, patella, tibia, fibula, tarsals, metatarsals, and phalanges. Together, these bones support body weight and enable movement.

Labels identify the cranial portion, facial portion, vertebral column, ribs, sternum, clavicle, scapula, humerus, radius, ulna, carpals, metacarpals, phalanges, hip bones, femur, patella, tibia, fibula, tarsals, and metatarsals.

Figure 7.2.1: Lateral Skull

This image illustrates a left-side view of a human skull with the cranial bones. Each bone is labeled, including the frontal, parietal, temporal, occipital, sphenoid, and ethmoid bones, with numbers indicating how many of each are present. Facial bones are shown in white for contrast, while the focus remains on identifying and distinguishing the eight cranial bones that form the protective case around the brain.

- The frontal bone forms the superior part of the orbits (eye sockets) and extends upward to meet the parietal bones at the coronal suture.
- While primarily visible from the lateral and superior views, the parietal bones are located posteriorly to the frontal bone and contribute to the cranial vault. They play a crucial role in the overall shape and protection of the brain.
- Temporal bones, also more prominent in the lateral view, are located on the sides of the skull and contribute to the structure behind the orbits.
- Sphenoid bone is partially visible in the anterior view at the lateral walls of the orbits. It spans the skull laterally, contributing to the cranial base.
- Ethmoid bone forms part of the medial wall of the orbits and the superior part of the nasal cavity. It is located posterior to the nasal bones and is partially visible in the anterior view.
- Occipital bone is the single bone that forms the posterior skull and posterior base of the cranial cavity.

This image depicts a front-facing of a human skull used for anatomical study. The skull is shown in an upright position, with the eye sockets, nasal opening, and teeth clearly visible. Labels with thin lines point to each bone and name it.

At the top of the skull, the frontal bone forms the forehead. On either side, the parietal and temporal bones contribute to the upper and side portions of the skull. Around the eye sockets, smaller bones such as the sphenoid, ethmoid, lacrimal, and zygomatic bones are identified, showing how multiple bones come together to form the orbits. The nasal bones sit at the bridge of the nose, while the maxilla forms the upper jaw and holds the upper teeth. The mandible, shown at the bottom, is the lower jaw and the only

movable skull bone.

Several small openings called foramina are also labeled, including the supraorbital foramen above the eye sockets, the infraorbital foramen below them, and the mental foramen on the front of the lower jaw. These openings indicate pathways for nerves and blood vessels. Overall, the image emphasizes how facial and cranial bones are arranged and interconnected in the anterior view of the skull.

Figure 7.2.3: Right Lateral View

This image of the human skull with major cranial bones, facial bones, sutures, and anatomical landmarks labeled. The cranial bones shown are the frontal bone, parietal bone, temporal bone, occipital bone, and greater wing of the sphenoid bone. The facial bones shown are the zygomatic bone, maxilla, mandible, nasal bone, lacrimal bone, and ethmoid bone.

Major sutures include the coronal suture between the frontal and parietal bones, the squamous suture between the parietal and temporal bones, and the lambdoid suture between the parietal and occipital bones.

Additional labeled landmarks include the zygomatic arch, pterion, external acoustic meatus, mastoid process, styloid process, articular tubercle, mandibular fossa, lacrimal fossa, temporal process, zygomatic process, and mental protuberance of the mandible. The diagram shows the arrangement and relationships of bones and landmarks visible from the right side of the skull.

Figure 7.2.4: Cranial Fossae

This image is shown in superior and lateral views of the skull. The top image is a superior view of the floor of the cranial cavity, viewed from above after the top portion of the skull has been removed. The floor is divided into three regions: the anterior cranial fossa, middle cranial fossa, and posterior cranial fossa. The anterior cranial fossa is the most anterior region and supports the frontal lobes of the brain. The middle cranial fossa lies posterior to it and supports the temporal lobes. The posterior cranial fossa is the deepest and most posterior region and supports the cerebellum and brainstem.

The bottom image is a lateral sectional view of the skull showing the brain within the cranial cavity. In this view, the anterior cranial fossa lies beneath the frontal region of the brain, the middle cranial fossa lies beneath the temporal region, and the posterior cranial fossa lies beneath the cerebellum and brainstem. Together, the two views show that the cranial cavity is organized into three major fossae that accommodate and support different regions of the brain.

Figure 7.2.5: Temporal Bone

Important landmarks of the temporal bone, as shown in the image include the following:

- External acoustic meatus (ear canal)—This is the large opening on the lateral side of the skull that is associated with the ear.
- Internal acoustic meatus—This opening is located inside the cranial cavity, on the medial side of the petrous ridge. It connects to the middle and inner ear cavities of the temporal bone.
- Mandibular fossa—This is the deep, oval-shaped depression located on the external base of the skull, just in front of the external acoustic meatus. The mandible (lower jaw) joins with the skull at this site as part of the temporomandibular joint, which allows for movements of the mandible during opening and closing of the mouth.
- Articular tubercle—The smooth ridge located immediately anterior to the mandibular fossa. Both the articular tubercle and mandibular fossa contribute to the temporomandibular joint, the joint that provides for movements between the temporal bone of the skull and the mandible.
- Styloid process—Posterior to the mandibular fossa on the external base of the skull is an elongated, downward bony projection called the styloid process, so named because of its resemblance to a stylus (a pen or writing tool). This structure serves as an attachment site for several small muscles and for a ligament that supports the hyoid bone of the neck.
- Zygomatic process - rises from the lower part of the squamous portion of the temporal bone and projects anteriorly. This forms the posterior, longer portion of the zygomatic arch. It articulates with the temporal process of the zygomatic bone to complete the zygomatic arch, functioning like "the two ends of a drawbridge.".
- Carotid canal—The carotid canal is a zig-zag shaped tunnel that provides passage through the base of the skull for one of the major arteries that supplies the brain. Its entrance is located on the outside base of the skull, anteromedial to the styloid process. The canal then runs anteromedially within the bony base of the skull, and then turns upward to its exit in the floor of the middle cranial cavity, above the foramen lacerum.

Figure 7.2.6: Anatomy of the Cranial Base

This image shows two labeled diagrams of the base of the human skull, presented from two perspectives: an inferior view on the top and a superior view on the bottom.

- The inferior view shows the underside of the skull, as if looking upward from below.
- The superior view shows the internal base of the skull from above, after the top portion has been removed.
- A small reference skull above each diagram indicates the viewing direction.

Inferior View (Underside of Skull) - The underside of the skull includes several key bones and openings:

- The maxilla forms the front portion of the hard palate, including the palatine process.
- Behind it, the palatine bone contributes to the posterior hard palate.
- The vomer is located along the midline, forming part of the nasal septum.
- On each side, the zygomatic arch and zygomatic bone contribute to the cheek structure.
- The sphenoid bone is centrally located and contains multiple openings:
  - Foramen ovale
  - Foramen spinosum
- Nearby openings include:
  - Foramen lacerum
  - Jugular foramen
  - Stylomastoid foramen
- The temporal bone contains important structures such as:
  - External auditory meatus (ear canal opening)
  - Mastoid process and styloid process
  - Mandibular fossa, where the lower jaw articulates
- At the center toward the back is the foramen magnum, a large opening for the spinal cord.
- Surrounding this are the occipital bone, occipital condyles, and external occipital protuberance.
- The entrance to the carotid canal is also labeled, indicating where major arteries enter the skull.

Superior View (Internal Skull Base) - The superior view shows the internal floor of the cranial cavity:

- The frontal bone forms the anterior portion.
- The ethmoid bone lies between the eye sockets and includes:
  - Crista galli
  - Cribriform plate
- The sphenoid bone is centrally located and features:
  - Lesser wings
  - Hypophyseal fossa (location of the pituitary gland)
  - Sella turcica (a depression housing the pituitary gland)
- Openings in this region include:
  - Optic canal (not explicitly labeled but implied near the sphenoid region)
  - Superior orbital fissure
  - Foramen rotundum
  - Foramen ovale
  - Foramen spinosum
  - Foramen lacerum
- The temporal bone forms the lateral regions and includes:
  - Petrous portion (petrous ridge)
  - Internal acoustic meatus
- The posterior region includes:
  - Occipital bone
  - Foramen magnum
  - Hypoglossal canal
  - Jugular foramen
- The parietal bones form the upper sides of the skull.

Figure 7.2.7: Posterior Skull Anatomy

This image shows a posterior view of the human skull, emphasizing the major cranial bones, sutures, and anatomical landmarks associated with brain protection, neck muscle attachment, and the connection between the skull and vertebral column.

The overall organization presents the skull from the posterior aspect, or back view. The labels in the image include parietal bones, occipital bone, temporal bones, zygomatic bone, sagittal suture, lambdoid suture, external occipital protuberance, mastoid process, superior nuchal line, foramen magnum, and occipital condyles.

The parietal bones are a paired set of bones that form the upper posterior portion of the skull. Their functions are to protect the upper regions of the brain and contribute to the overall shape and strength of the skull.

The occipital bone is located at the lower back portion of the skull. Its functions are to protect the posterior part of the brain and form the base of the skull where it connects to the spine.

The temporal bones are located on both sides of the skull near the lower regions. Their functions are to house structures related to hearing and balance and provide attachment points for muscles of the head and neck.

The zygomatic bone, shown as partially visible, is a facial bone extending toward the side of the skull. Its function is to contribute to facial structure and support the cheek region.

The labeled sutures include the sagittal suture and the lambdoid suture. The sagittal suture runs along the midline between the two parietal bones. Its function is to hold these bones together while allowing slight flexibility during development. The lambdoid suture lies between the parietal bones and the occipital bone. Its function is to connect the cranial bones and contribute to overall skull integrity.

The labeled surface landmarks and projections include the external occipital protuberance, mastoid process, and superior nuchal line. The external occipital protuberance is a raised area on the midline of the occipital bone and serves as an attachment site for ligaments and neck muscles. The mastoid process is a projection behind the ear region on each side and provides attachment for neck muscles involved in head movement. The superior nuchal line is a horizontal ridge extending across the occipital bone and serves as an attachment site for neck and upper back muscles.

The labeled opening and articulation points include the foramen magnum and occipital condyles. The foramen magnum is a large opening at the base of the occipital bone. Its function is to allow passage of the spinal cord, connecting the brain to the body. The occipital condyles are paired rounded surfaces located on either side of the foramen magnum. Their functions are to articulate with the first vertebra, the atlas, and to enable head movement, such as nodding.

Figure 7.2.8: Sphenoid Bone

This image shows the sphenoid bone in two orientations: (a) superior view on the left and (b) posterior view on the right. A small inset indicates the location of the sphenoid bone at the base of the skull.

The overall organization presents the sphenoid as a central bone at the skull base with a complex shape that includes a central body, lateral wings, and downward pterygoid plates. The labels in the image include body of the sphenoid, hypophyseal fossa (sella turcica), lesser wings, greater wings, optic canal, superior orbital fissure, foramen rotundum, foramen ovale, foramen spinosum, and pterygoid plates.

In panel (a) superior view, the body of the sphenoid is the central portion of the bone. Its function is to serve as a structural hub that connects with multiple surrounding skull bones and supports structures at the base of the brain. Within the body is the hypophyseal fossa, also called the sella turcica, which is a depression that houses the pituitary gland.

Also in the superior view, the lesser wings are thin projections extending from the upper portion of the sphenoid. Their functions are to form part of the roof of the orbit and help separate regions within the cranial cavity. The greater wings are larger lateral extensions from the sphenoid body. Their functions are to contribute to the floor and sides of the skull and orbit and to provide attachment sites for muscles.

The superior view also labels several openings. The optic canal is located near the lesser wing and transmits the optic nerve, which carries visual information from the eye to the brain. The superior orbital fissure is a gap between the greater and lesser wings that

allows passage of multiple cranial nerves and blood vessels to the eye. Three foramina are also shown. The foramen rotundum is a round opening that allows passage of a branch of the trigeminal nerve. The foramen ovale is an oval-shaped opening that transmits nerves involved in facial sensation and jaw movement. The foramen spinosum is a small opening located posterior to the foramen ovale and allows passage of blood vessels supplying the cranial membranes.

In panel (b) posterior view, the body of the sphenoid is visible as the central mass from behind and helps support the skull base while connecting multiple cranial bones. The lesser wings appear as upper projections extending from the body and contribute to the structure of the cranial floor and orbit. The greater wings appear as broad lateral extensions and help form the cranial cavity walls while also supporting facial structure. The superior orbital fissure remains visible as a large gap between the wings and serves as a pathway for nerves and blood vessels entering the orbit. The pterygoid plates are downward projections from the sphenoid bone. Their function is to provide attachment sites for muscles involved in chewing and jaw movement.

Figure 7.2.9: Sagittal Section of Skull

This image shows a right lateral section of the human skull with portions of the skull removed to reveal internal cranial and nasal structures. The image combines external skull anatomy with internal features visible in a sagittal view.

Major cranial bones labeled include the frontal, parietal, temporal, occipital, and sphenoid bones. Facial bones and related structures include the nasal bone, maxilla, palatine bone, mandible, and hyoid bone.

Internal cranial landmarks include the sella turcica (hypophyseal fossa), crista galli, cribriform plate, internal acoustic meatus, and hypoglossal canal. The sphenoid sinus is shown within the sphenoid bone.

Structures associated with the nasal cavity include the perpendicular plate, vomer, and inferior nasal concha. Together, the perpendicular plate and vomer form the nasal septum.

The mandible is labeled with the mandibular foramen, lingula, and mylohyoid line. Additional landmarks include the styloid process and the medial and lateral pterygoid plates.

The figure illustrates the spatial relationships among the cranial cavity, nasal cavity, facial skeleton, mandible, and associated anatomical landmarks as viewed from the right side.

Figure 7.2.10: Ethmoid Bone Anatomy

This image is an isolated view of the ethmoid bone oriented from superior to inferior. A small inset shows the location of the ethmoid bone within the skull between the eye sockets and above the nasal cavity. The central portion of the bone includes the crista galli, which projects upward, and the cribriform plates on either side. Extending downward from the center is the perpendicular plate. The lateral portions contain the ethmoid air cells and contribute to the medial walls of the orbits.

Projecting into the nasal cavity on each side are the superior nasal conchae and middle nasal conchae. Labels identify the crista galli, cribriform plate, perpendicular plate, superior nasal concha, middle nasal concha, ethmoid air cells, nasal cavity, and medial wall of the orbit. The figure shows how the ethmoid bone contributes to the cranial cavity, nasal cavity, and eye sockets.

Figure 7.2.11: Nasal Cavity

This image shows a medial view of the nasal cavity within the skull, highlighting internal nasal structures and air spaces. A small inset indicates the location of this region within the full skull.

The overall organization includes a main diagram showing a side view of the skull focused on the nasal cavity and a smaller inset that shows where this region is located in the skull. The labels in the image include ethmoid bone, superior nasal concha, middle nasal concha, inferior nasal concha, and sphenoidal sinus.

The ethmoid bone is located in the upper central region of the nasal cavity, between the eyes. It forms part of the medial walls and roof of the nasal cavity and gives rise to the superior and middle nasal conchae. Its functions are to support the structure of the nasal cavity, separate the nasal cavity from the cranial cavity, and contribute to airflow organization within the nose.

The diagram shows three curved bony structures projecting into the nasal cavity, called the nasal conchae, or turbinates. The

superior nasal concha is the smallest and highest concha, located near the roof of the nasal cavity. Its functions are to help regulate airflow and contribute to the warming and humidifying of inhaled air. The middle nasal concha is located below the superior concha and is larger and more prominent. Its functions are to direct airflow toward the middle nasal region and enhance filtration and conditioning of air. The inferior nasal concha is the largest concha, located at the lower part of the nasal cavity and extending along the lateral nasal wall. Its functions are to play a major role in air filtering, warming, and humidification and to increase surface area for efficient air processing.

The sphenoidal sinus is located at the posterior portion of the nasal cavity within the sphenoid bone. Its functions are to reduce skull weight, contribute to air circulation and resonance of the voice, and produce mucus that helps protect the respiratory system.

Figure 7.2.12: Maxilla

This image shows a right lateral view of the maxilla, which is the upper jaw bone, with labeled features related to the orbit, facial structure, and tooth support.

The overall organization focuses on a single maxilla bone viewed from the right side. A small inset shows the location of the maxilla within the skull, while the main image identifies labeled structural features. The labels in the image include maxilla, floor of the orbit or orbital surface, infraorbital foramen, alveolar process, frontal bone, and zygomatic process (cut).

As a whole, the maxilla forms the upper jaw and contributes to the floor of the orbit, the side of the nasal cavity, and the upper dental arch. Its functions are to provide structural support for the midface, anchor the upper teeth, and form part of the eye socket and nasal cavity.

The floor of the orbit, also described as the orbital surface, is a broad surface on the superior portion of the maxilla. It forms the lower boundary of the eye socket. Its functions are to support the eye from below and help maintain the shape and stability of the orbit.

The infraorbital foramen is a small opening located on the anterior surface of the maxilla. Its function is to allow passage of the infraorbital nerve and blood vessels, which supply sensation and circulation to the cheek, upper lip, and part of the face.

The alveolar process is the lower margin of the maxilla that contains the sockets for the upper teeth. Its functions are to hold and stabilize the teeth and to support chewing and biting forces.

The superior portion of the maxilla articulates with the frontal bone. This connection helps form the upper boundary of the nasal region and orbit and contributes to the stability of the facial skeleton.

The zygomatic process, labeled as cut in the diagram, is a projection that normally connects the maxilla to the zygomatic bone, or cheekbone. It is shown as cut to reveal internal structures. Its functions are to contribute to the lateral facial structure and help transfer forces during chewing.

Figure 7.2.13: Mandible

This image shows the right lateral view of the mandible, which is the lower jaw, with labeled structures involved in jaw movement, muscle attachment, and nerve passage.

The overall organization presents the mandible as a single bone of the lower jaw. A small inset at the top shows the mandible in relation to the skull, while the main image focuses on the detailed anatomy of the mandible from a side view. The labels in the image include body of the mandible, alveolar process, ramus of the mandible, mandibular angle, condylar process, mandibular condyle, coronoid process, mandibular notch, mylohyoid line, lingula, mandibular foramen, mental foramen, and mental protuberance.

The body of the mandible is the horizontal portion that holds the lower teeth. It includes the alveolar process, which contains the tooth sockets. Its functions are to support the teeth for chewing, also called mastication, and to provide structural shape to the lower face.

The ramus of the mandible is the vertical portion extending upward from the body. Its functions are to serve as an attachment site for muscles involved in jaw movement and to connect the body to the upper processes of the mandible.

The mandibular angle is the region where the body meets the ramus. Its function is to provide leverage for muscles that elevate and depress the jaw.

The condylar process, also labeled mandibular condyle, is the rounded projection at the upper posterior part of the ramus. Its function is to form a joint with the temporal bone of the skull and enable movement of the jaw, including opening, closing, and side-to-side motion.

The coronoid process is the anterior projection located in front of the condylar process. It serves as an attachment site for the temporalis muscle, which helps elevate the jaw.

The mandibular notch is the curved depression between the condylar process and the coronoid process. It provides separation between these two structures and serves as a passage region.

The mylohyoid line is a ridge on the inner surface of the mandible. Its function is to serve as an attachment site for the mylohyoid muscle, which supports the floor of the mouth.

The lingula is a small projection near the mandibular foramen. Its function is to serve as an attachment point for ligaments associated with jaw movement.

The mandibular foramen is an opening on the inner surface of the ramus. It allows passage of the inferior alveolar nerve and blood vessels into the mandible.

The mental foramen is an opening on the front portion of the mandible. It allows nerves and blood vessels to exit and supply the chin and lower lip.

The mental protuberance is the anterior projection of the mandible that forms the chin. Its function is to provide the shape and prominence of the chin.

Figure 7.2.14: Eye Socket

This image shows a magnified view of the bony orbit, or eye socket, identifying the bones that form the orbit and several important openings for nerves and blood vessels.

The overall organization focuses on a single eye orbit within the skull. The labels in the image include frontal bone, supraorbital margin, sphenoid bone, zygomatic bone, maxilla, ethmoid bone, lacrimal bone, nasal bone, palatine bone, supraorbital foramen, optic canal, superior orbital fissure, infraorbital foramen, and lacrimal fossa. The image shows that the orbit is a composite structure formed by several bones working together, rather than a cavity formed by one bone alone.

The frontal bone is located at the upper portion of the orbit, forming the roof. It includes the supraorbital margin along the upper edge. Its functions are to protect the eye from above, provide attachment points for structures around the eye, and support the forehead and upper orbit structure.

The sphenoid bone is located deeper within the orbit toward the back. It forms part of the posterior wall of the orbit and provides structural support. It also contains openings that serve as pathways for nerves.

The zygomatic bone forms the lateral, or outer, wall of the orbit. Its functions are to provide protection to the eye from the side and contribute to facial structure and cheek prominence.

The maxilla forms much of the floor of the orbit. Its functions are to support the eye from below, contribute to facial structure, and house the upper teeth.

The ethmoid bone forms part of the medial, or inner, wall of the orbit. It helps separate the orbit from the nasal cavity and provides structural support to delicate inner orbital structures.

The lacrimal bone is located near the inner corner of the orbit. It contains the lacrimal fossa, which houses structures involved in tear drainage.

The nasal bone is located at the bridge of the nose, near the orbit. Its function is to provide structural support to the nasal bridge.

The palatine bone contributes a small portion to the posterior floor of the orbit. Its function is to support the rear portion of the orbital floor.

The labeled openings and features include the supraorbital foramen, optic canal, superior orbital fissure, infraorbital foramen, and lacrimal fossa. The supraorbital foramen is located on the upper margin of the orbit and allows passage of nerves and blood vessels to the forehead region. The optic canal is located toward the back of the orbit and transmits the optic nerve, which carries visual information from the eye to the brain. The superior orbital fissure is a gap in the posterior orbit that allows multiple nerves and blood vessels to pass between the brain and the eye. The infraorbital foramen is located below the orbit in the maxilla and provides a passage for nerves and blood vessels supplying the face. The lacrimal fossa is a depression near the medial orbit that houses structures involved in tear collection and drainage.

Figure 7.2.15: Nasal Cavity

This image shows a sagittal section, or side-view cut, of the nasal cavity and surrounding skull structures, with labeled bones, sinuses, and components of the nasal septum.

The overall organization presents a side view of the head focused on the nasal cavity. The labels in the image include nasal septum, perpendicular plate of the ethmoid bone, vomer bone, septal cartilage, frontal bone, frontal sinus, sphenoid bone, sphenoid sinus, ethmoid bone, crista galli, nasal bone, palatine process of the maxilla, horizontal plate of the palatine bone, and the maxillary sinus region.

The nasal septum forms the midline partition inside the nasal cavity. Its labeled components are the perpendicular plate of the ethmoid bone in the superior portion, the vomer bone in the posterior-inferior portion, and the septal cartilage in the anterior portion. The nasal septum divides the nasal cavity into left and right passages, helps regulate and direct airflow, and provides structural support for the nose.

In the frontal region, the labeled structures are the frontal bone and the frontal sinus. The frontal bone is located above the nasal cavity, and the frontal sinus is a hollow space within this bone. The frontal bone helps protect the brain. The frontal sinus reduces skull weight and contributes to air conditioning and voice resonance.

In the sphenoid region, the labeled structures are the sphenoid bone and the sphenoid sinus. The sphenoid bone is located deeper in the skull behind the nasal cavity, and the sphenoid sinus is a cavity within it. The sphenoid bone provides structural support at the base of the skull. The sphenoid sinus helps lighten the skull and supports airflow.

In the ethmoid region, the labeled structures are the ethmoid bone and the crista galli. The ethmoid bone lies between the eyes and contributes to the superior part of the nasal septum. The crista galli is a vertical projection of the ethmoid bone. The ethmoid region supports structures of the nasal cavity and brain, and the crista galli provides attachment for membranes that help stabilize the brain.

The nasal bone is located at the upper part of the nose. Its function is to provide structural support and shape to the nasal bridge.

The palate is formed by the palatine process of the maxilla and the horizontal plate of the palatine bone. These structures form the roof of the mouth and the floor of the nasal cavity. Their function is to separate the nasal cavity from the oral cavity, which allows breathing and eating to occur simultaneously.

In the maxillary sinus region, the maxillary bone forms part of the lateral nasal wall and contains adjacent sinus space. Its functions are to support the upper teeth and facial structure and to contribute to sinus functions such as air filtration and moisture regulation.

Figure 7.2.16: Paranasal Sinuses

This image presents the paranasal sinuses of the skull using two perspectives: an anterior view on the left and a lateral view on the right. Each view labels the same four sinus regions.

The overall organization is divided into two panels. The left panel shows the anterior view of the face, and the right panel shows the lateral view of the head. The labels in both panels are frontal sinus, sphenoid sinus, ethmoid air cells, and maxillary sinuses.

The frontal sinus is located in the upper region of the face above the eyes, within the frontal bone. Its functions are to reduce the

weight of the skull, contribute to voice resonance, and produce mucus that helps protect and moisten the nasal cavity.

The sphenoid sinus is located deep within the skull, behind the nasal cavity and below the brain. Its functions are to help lighten the skull, support air circulation within the sinus system, and contribute to sound resonance.

The ethmoid air cells are a cluster of small air-filled spaces located between the eyes, between the nasal cavity and the orbit, or eye socket. Their functions are to help filter and condition inhaled air, produce mucus to trap particles and pathogens, and contribute to overall sinus ventilation.

The maxillary sinuses are located in the cheek region on both sides of the nose and are the largest of the paranasal sinuses. Their functions are to reduce skull mass, warm and humidify inhaled air, and produce mucus for respiratory protection.

Figure 7.2.17: Hyoid Bone

This image shows the hyoid bone, including its position in the neck and detailed views of its structure. The diagram is divided into three sections: the anatomical location in the body, an anterior view, and a right lateral view.

The overall organization includes a top image showing the location of the hyoid bone in the neck and two lower images showing the bone itself. The labels in the figure include body, greater horns, lesser horns, mandible, and larynx. The lower portion includes an anterior (front) view and a right lateral (side) view of the hyoid bone.

In the top image, the hyoid bone is positioned in the upper neck region. It is located below the mandible, which is the lower jaw, and above the larynx, which is the voice box. The hyoid bone functions as a support structure for the tongue and upper airway. It also serves as an attachment site for muscles involved in speech and swallowing.

In the anterior view, the hyoid bone has a central region labeled the body. Extending outward from each side are the greater horns, which curve laterally. Smaller projections near the upper region are labeled the lesser horns. The body provides a central anchoring point for muscles. The greater horns provide attachment for muscles that move the tongue, larynx, and pharynx. The lesser horns serve as additional attachment points for ligaments and muscles.

In the right lateral view, the curved three-dimensional shape of the hyoid bone is shown from the side. The body appears as a central mass, and the horns extend backward. This shape allows for flexible movement, which supports coordinated actions involved in swallowing, breathing, and speech production.

Figure 7.3.1: Anatomy of the Vertebral Column

This image shows the vertebral column, or spine, in two views: a posterior view of the full body on the left and a lateral view of the body on the right. The diagram labels the major spinal regions, the number of vertebrae in each region, and the natural curves of the spine.

The overall organization shows the vertebral column extending from the base of the skull to the pelvis. The labels in the image include the cervical region, thoracic region, lumbar region, sacrum, coccyx, intervertebral discs, cervical curve, thoracic curve, lumbar curve, and sacrococcygeal curve. The left image shows the spine from the back, and the right image emphasizes the spine's natural curves from the side.

The cervical region is located in the neck and contains 7 cervical vertebrae, C1 through C7. Its functions are to support and allow movement of the head and to form the cervical curve, which bends forward.

The thoracic region is located in the upper back and contains 12 thoracic vertebrae, T1 through T12. Its functions are to provide attachment points for the ribs, form the thoracic curve, which bends backward, and help protect organs in the chest cavity.

The lumbar region is located in the lower back and contains 5 lumbar vertebrae, L1 through L5. These vertebrae are larger and thicker than those in other regions. Their functions are to support a large portion of body weight, allow bending and movement of the lower torso, and form the lumbar curve, which bends forward.

The sacrum is composed of fused vertebrae that form a triangular structure at the base of the spine. Its functions are to connect the vertebral column to the pelvis and help transfer body weight to the lower limbs.

The coccyx is a small structure made of fused vertebrae located below the sacrum. Its functions are to serve as an attachment site for ligaments and muscles and provide minor support when sitting.

The intervertebral discs are located between adjacent vertebrae. Their functions are to act as shock absorbers and allow flexibility and movement of the spine.

The lateral view labels the natural spinal curves. These include the cervical curve, which bends forward, the thoracic curve, which bends backward, the lumbar curve, which bends forward, and the sacrococcygeal curve, which bends backward. Together, these curves help distribute body weight, absorb shock, and maintain balance and posture.

Figure 7.3.2: Abnormal curvatures of Spine

This image shows abnormal curvatures of the vertebral column shown in three panels. The left panel shows scoliosis in a rear-view illustration of a person with an abnormal lateral curvature of the vertebral column, accompanied by an X-ray showing a pronounced side-to-side spinal curve. The middle panel shows kyphosis in a side-view illustration and a photograph of a person bending forward, demonstrating an exaggerated posterior curvature of the thoracic vertebral column. The right panel shows lordosis in a side-view illustration with an exaggerated inward curvature of the lumbar region, accompanied by a silhouette of a woman in late pregnancy pressing against her lower back for support, illustrating increased lumbar curvature. Together, the panels show scoliosis as an abnormal lateral curvature, kyphosis as an excessive thoracic curvature, and lordosis as an excessive lumbar curvature.

Figure 7.3.3: Normal and Compressed Vertebrae

This image presents two detailed line drawings of vertebrae positioned side by side for comparison. The drawing on the left shows a set of healthy, normal vertebrae. These vertebrae appear evenly shaped, with consistent thickness in the bone structure and well-defined intervertebral spaces. The alignment is straight, indicating typical curvature and proper structural support. The drawing on the right depicts vertebrae affected by bone loss. In this illustration, the bones appear thinner and more irregular, with noticeable collapse or compression along their front edges. This change in shape causes the vertebrae to tilt forward, producing an exaggerated spinal curvature. The comparison highlights how reduced bone density weakens the vertebral bodies and contributes to increased spinal bending over time.

Figure 7.3.4: The Structure of a Typical Vertebra

This image shows the structure of a typical vertebra and articulated vertebrae. The left panel shows a superior view of a single vertebra. Labels identify the vertebral body, vertebral arch, pedicle, lamina, vertebral foramen, spinous process, transverse processes, facet of the superior articular process, facet for head of rib, and spinal cord. The vertebral body forms the anterior portion of the vertebra, while the vertebral arch surrounds the vertebral foramen, which contains the spinal cord. The spinous and transverse processes project from the vertebra, and articular facets mark the locations where vertebrae articulate with adjacent vertebrae and, in the thoracic region, with ribs.

The right panel shows a left posterolateral view of several articulated vertebrae. The vertebrae are stacked and separated by intervertebral discs located between adjacent vertebral bodies. Labels identify the vertebral body, vertebral arch, lamina, pedicle, spinous process, superior and inferior articular processes, facet for head of rib, intervertebral disc, spinal cord, spinal nerve, and intervertebral foramen. The intervertebral foramina are openings formed between adjacent vertebrae through which spinal nerves exit the vertebral column. The figure shows the anatomical relationships among adjacent vertebrae, intervertebral discs, the spinal cord, and emerging spinal nerves.

Figure 7.3.5: The Structure of an Intervertebral Disc

This image shows the structure of an intervertebral disc positioned between adjacent vertebrae, presented in two views: a lateral view on the left and a superior view on the right. The figure explains how the disc connects vertebral bodies and supports movement and shock absorption.

The overall organization includes two panels. The left panel shows two stacked vertebrae with an intervertebral disc between them. The right panel shows a superior view of a vertebra and disc, emphasizing the internal parts of the disc. The labels in the

image include vertebral body, intervertebral disc, intervertebral foramen, spinal nerves, annulus fibrosus, nucleus pulposus, and surrounding vertebral structures, including the vertebral arch and processes.

In the left panel, the vertebral body is the large solid portion of each vertebra located anteriorly. Its functions are to support body weight and provide a stable surface for the intervertebral disc. The intervertebral disc lies between adjacent vertebral bodies and appears as a thick, flexible layer separating the bones. Its functions are to act as a shock absorber between vertebrae and allow movement and flexibility of the spine. The intervertebral foramen is the opening between adjacent vertebrae. Its function is to allow spinal nerves to exit the vertebral column and provide a pathway for communication between the spinal cord and the body.

In the right panel, the annulus fibrosus is the outer ring of the intervertebral disc. It is made of multiple layers arranged in concentric patterns. Its functions are to provide strength and support, contain the nucleus pulposus, and resist compressive and twisting forces. The nucleus pulposus is the central core of the disc. Its functions are to act as a compressible cushion, distribute pressure evenly across the disc, and help absorb shock during movement. The surrounding vertebral structures show that the disc sits between vertebral bodies, while the posterior region includes the vertebral arch and processes. Together, these structures protect the spinal cord and allow controlled movement of the spine.

Figure 7.3.6: The Structure of Cervical Vertebrae

This image presents multiple views and comparisons of cervical vertebrae, including a typical cervical vertebra, the atlas (C1), the axis (C2), and a short sequence of cervical vertebrae in order.

The overall organization is divided into several labeled sections. The labels in the figure include typical cervical vertebra, C1 (atlas), C2 (axis), C3–C6, C7 (vertebra prominens), vertebral body, vertebral foramen, vertebral arch, pedicle, lamina, spinous process, bifid spinous process, transverse processes, transverse foramen, superior articular process, groove for spinal nerve, anterior arch, posterior arch, superior articular facets, dens (odontoid process), inferior articular processes, and transverse ligament. The figure compares the structure of a typical cervical vertebra with the specialized forms of the atlas and axis and shows how the cervical vertebrae are arranged in sequence from C1 through C7.

In the section showing a typical cervical vertebra in superior view, the vertebral body is a relatively small anterior portion of the vertebra. Its function is to support the weight of the head and neck. The vertebral foramen is a large central opening that allows passage of the spinal cord. The vertebral arch, made of the pedicle and lamina, forms the curved portion behind the vertebral body. Its functions are to protect the spinal cord and provide structural integrity. The spinous process is a posterior projection, and in most cervical vertebrae it is bifid, meaning split into two parts. Its functions are to provide attachment for muscles and ligaments and support neck movement. The transverse processes project laterally and serve as attachment points for muscles. Each contains a transverse foramen, which allows passage of blood vessels supplying the brain. The superior articular process provides a joint surface for controlled movement with adjacent vertebrae. The groove for spinal nerve is a small channel that allows spinal nerves to pass safely.

The section showing the cervical vertebrae in column labels C1 (atlas), C2 (axis), C3–C6 as typical cervical vertebrae, and C7 (vertebra prominens). Together, these seven vertebrae form the flexible neck region, support head movement, and help maintain posture.

The atlas (C1) is shown in superior view. It is a ring-shaped vertebra without a body. The labeled structures include the anterior arch, posterior arch, superior articular facets, transverse foramina, and the transverse ligament that holds the dens in place. The atlas functions to support the skull and allow nodding movements, including flexion and extension of the head.

The axis (C2) is shown in both superior and anterior views. Its key feature is the dens, also called the odontoid process, which is a vertical projection extending upward from the body of the axis. The dens acts as a pivot point for the atlas and enables rotation of the head, such as turning side to side. In the superior view of the axis, the labeled structures include the dens, superior articular facets, spinous process, and transverse foramen. These structures support articulation with the atlas and allow combined rotational and stabilizing movements. In the anterior view, the axis shows the dens projecting upward, the body of the vertebra, and the inferior articular processes. These structures contribute to stability of the cervical spine and allow connections with lower vertebrae.

The figure also highlights special features of cervical vertebrae. The bifid spinous processes of most cervical vertebrae provide increased surface area for muscle attachment. The transverse ligament is a band that holds the dens against the atlas. Its function is to stabilize the joint between C1 and C2 and prevent displacement that could affect the spinal cord.

Figure 7.3.7: Structure of Thoracic Vertebrae

This image shows a lateral view of several thoracic vertebrae and identifies structures that distinguish thoracic vertebrae from other vertebral regions. A small inset highlights the thoracic region within the vertebral column.

Several thoracic vertebrae are stacked vertically, with intervertebral discs located between adjacent vertebral bodies. The vertebral bodies form the anterior portion of the vertebral column and are connected by the discs.

Projecting posteriorly from each vertebral body is the vertebral arch, formed by the pedicle and lamina. Extending from the vertebral arch are the transverse processes, spinous processes, and articular processes.

The spinous processes are long and slope downward toward the inferior vertebrae, which is a characteristic feature of the thoracic region. The transverse processes extend laterally from each vertebra.

The superior articular processes project upward, and the inferior articular processes project downward, forming joints between adjacent vertebrae.

The figure highlights three surfaces associated with rib attachment:

- Superior costal facet: located on the upper portion of the vertebral body
- Inferior costal facet: located on the lower portion of the vertebral body
- Articular facet for the tubercle of the rib: located on the transverse process

The superior and inferior costal facets articulate with the head of a rib, while the articular facet on the transverse process articulates with the tubercle of a rib.

Intervertebral discs are shown between neighboring vertebral bodies throughout the thoracic region.

The figure demonstrates how thoracic vertebrae are specialized to support and articulate with the rib cage. The superior and inferior costal facets on the vertebral bodies, together with the articular facet on the transverse process, form joints with the ribs. These articulations help stabilize the thoracic cage while still permitting the limited movements necessary for breathing and trunk motion. The downward-projecting spinous processes and interconnected articular processes provide additional support and stability to the thoracic region of the vertebral column.

Figure 7.3.8: Articulation of a Thoracic Vertebra and Rib

This image shows a lateral view of several thoracic vertebrae with an attached rib, illustrating the anatomical relationship between the vertebral column and the rib cage.

Several thoracic vertebrae are stacked vertically and separated by intervertebral discs. Each vertebra includes a large anterior vertebral body and a posterior vertebral arch formed by the pedicle and lamina. Extending from the vertebra are the spinous process, transverse process, and superior and inferior articular processes.

The rib attaches to the vertebra at two locations:

- Head of the rib: articulates with the superior costal facet and inferior costal facet on adjacent vertebral bodies
- Tubercle of the rib: articulates with the facet for the tubercle of the rib on the transverse process

The neck of the rib is the narrow region between the head and the tubercle. Lateral to the tubercle, the rib bends at the angle of the rib before continuing around the thoracic cage.

The superior articular facets are located on the upper portion of the vertebra and form joints with the vertebra above. The inferior articular process projects downward and forms a joint with the vertebra below. The spinous process extends posteriorly and inferiorly, which is characteristic of thoracic vertebrae.

The figure highlights three structures involved in rib articulation:

- Superior costal facet: on the upper portion of the vertebral body

- Inferior costal facet: on the lower portion of the vertebral body
- Facet for the tubercle of the rib: on the transverse process

Together, these facets form joints between the rib and the vertebrae.

The figure demonstrates how thoracic vertebrae are specialized to support and articulate with the ribs. The head of the rib articulates with costal facets on the vertebral bodies, while the tubercle articulates with a facet on the transverse process. These joints anchor the ribs to the vertebral column and provide the stability and limited mobility necessary for movements of the thoracic cage during breathing. The articular processes connect adjacent vertebrae and help guide movement while maintaining alignment of the thoracic spine.

Figure 7.3.9: Structure of Lumbar Vertebrae

This image shows a lateral view of several lumbar vertebrae stacked vertically. A small inset identifies the lumbar region within the vertebral column.

The vertebrae are separated by intervertebral discs, which lie between adjacent vertebral bodies. The vertebral body forms the large anterior portion of each vertebra and is noticeably larger than the vertebral bodies in the cervical and thoracic regions, reflecting the greater weight-bearing role of the lumbar spine.

Projecting posteriorly from each vertebra are the spinous processes, which are broad and relatively short compared with the long, downward-sloping spinous processes of thoracic vertebrae. Extending laterally from each vertebra are the transverse processes.

The figure also labels the superior articular processes and inferior articular processes, which project upward and downward from adjacent vertebrae. These processes form joints between neighboring lumbar vertebrae and help maintain alignment of the vertebral column.

The labeled structures include:

- Vertebral body: located anteriorly and separated from adjacent vertebral bodies by intervertebral discs
- Intervertebral disc: located between neighboring vertebral bodies
- Transverse process: extending laterally from the vertebral arch
- Superior articular process: projecting upward to articulate with the vertebra above
- Inferior articular process: projecting downward to articulate with the vertebra below
- Spinous process: projecting posteriorly from the vertebral arch

The figure demonstrates structural features that enable the lumbar vertebrae to support the greatest amount of body weight while maintaining flexibility in the lower back. The large vertebral bodies and intervertebral discs help bear compressive forces, while the superior and inferior articular processes form joints that stabilize the lumbar spine and guide movement. Together, these structures allow flexion, extension, and limited rotation of the lower back while supporting the upper body.

Figure 7.3.10: The Sacrum and Coccyx

This image shows the sacrum and coccyx in two views: an anterior view on the left and a posterior view on the right. A small inset shows the location of the sacrum within the vertebral column.

The overall organization presents the sacrum as a triangular bone formed by fused vertebrae at the base of the vertebral column, with the coccyx attached to its inferior end. The labels in the figure include body of first sacral vertebra, sacral promontory, transverse ridges, anterior sacral foramina, apex of sacrum, coccyx, sacral canal, median sacral crest, posterior sacral foramina, lateral sacral crest, sacral hiatus, auricular surface, and superior articular facet. The figure emphasizes structures related to nerve passage, muscle and ligament attachment, and connection to the pelvis.

In the anterior view, the body of the first sacral vertebra forms the upper portion of the sacrum. Its function is to support weight transferred from the lumbar spine and contribute to the load-bearing surface. The sacral promontory is a projecting edge at the superior part of the sacrum. Its functions are to mark the boundary between the lumbar spine and sacrum and serve as an anatomical landmark in the pelvis. The transverse ridges are horizontal ridges across the anterior surface. Their function is to represent the fusion lines of the original sacral vertebrae, showing the developmental history of the bone. The anterior sacral foramina are openings on the anterior surface that allow passage of spinal nerves and blood vessels. The apex of the sacrum is

the inferior tip that connects to the coccyx. The coccyx is a small fused bone extending below the sacrum. Its functions are to serve as an attachment site for ligaments and muscles and provide support when sitting.

In the posterior view, the sacral canal is a continuation of the vertebral canal running through the sacrum. Its function is to house and protect the lower portion of the spinal nerves. The median sacral crest is a vertical ridge along the midline. Its functions are to represent fused spinous processes and serve as an attachment site for ligaments. The posterior sacral foramina are openings on the posterior surface that allow passage of spinal nerves exiting the sacrum. The lateral sacral crest consists of ridges lateral to the median crest and provides attachment points for muscles and ligaments. The sacral hiatus is an opening at the lower end of the sacral canal. Its functions are to allow access to the sacral canal and provide passage for nerve structures. The auricular surface lies on the lateral side of the sacrum and articulates with the ilium, forming part of the sacroiliac joint, which transfers weight to the lower limbs. The superior articular facet is located on the upper part of the sacrum and joins with the last lumbar vertebra, L5, helping provide movement and stability between the lumbar spine and sacrum.

Figure 7.3.11: Anterior and Posterior Views of the Sacrum and Coccyx

This image shows two detailed anatomical views of the sacrum and coccyx. On the left is the anterior view, where the broad upper surface forms the sacral promontory. The fused sacral vertebrae are visible as transverse ridges running horizontally across the bone. Four pairs of anterior sacral foramina line each side, providing passage for spinal nerves. The sacrum narrows toward the bottom, ending at the apex, which connects to the small triangular coccyx. On the right is the posterior view, which displays the irregular contours and ridges formed by fused vertebral elements. The median sacral crest, created by fused spinous processes, runs down the center. Lateral sacral crests lie to each side, and the posterior sacral foramina appear as a set of openings similar to those on the anterior surface. The sacral canal extends downward through the bone and ends at the sacral hiatus near the lower end. The auricular surfaces, shaped for articulation with the hip bones, are labeled along the sides. The coccyx appears at the bottom in both views.

Figure 7.3.12: Ligaments of the Cervical Vertebral Column

This image shows a side view of the skull and cervical portion of the vertebral column with several ligaments labeled. At the back of the skull, the external occipital protuberance is identified as the attachment site for the nuchal ligament, which extends downward along the cervical spinous processes. The supraspinous ligament continues this line of connection inferiorly. Each cervical vertebra is drawn with its spinous process visible. Along the front of the vertebral bodies, the anterior longitudinal ligament is labeled, illustrating its role in stabilizing the vertebral column from the anterior side. The diagram provides a clear overview of how these ligaments connect the skull to the cervical spine and help maintain posture and spinal alignment.

Figure 7.4.1: The Thoracic Cage

Two anterior views of the thoracic skeleton. Panel (a) shows the sternum alone. The superior manubrium contains the jugular notch at the midline and clavicular notches on either side. The manubrium joins the body of the sternum at the sternal angle. The xiphoid process forms the small inferior tip of the sternum.

Panel (b) shows the thoracic cage. The sternum is located at the midline and consists of the manubrium, body, and xiphoid process. Twelve pairs of ribs curve from the thoracic vertebrae toward the anterior chest wall. Costal cartilages connect the anterior ends of many ribs to the sternum. Intercostal spaces are visible between adjacent ribs. The clavicles and portions of the scapulae are shown as adjacent skeletal structures. Thoracic vertebrae T1 through T12 are visible posterior to the ribs. Labels identify the jugular notch, clavicular notches, clavicles, scapulae, sternal angle, costal cartilages, intercostal spaces, and ribs 1 through 12. Orientation is indicated with superior at the top and inferior at the bottom.

Figure 7.4.2: Anatomy of a Rib

This image shows a single rib, identifying its major anatomical regions and the surfaces involved in articulation and support within the thoracic cage.

The overall organization presents the rib as a curved, elongated bone. One end connects to the vertebral column, and the opposite end connects toward the sternum through costal cartilage. The labels in the image include head of rib, neck of rib, tubercle of rib, articular facet, shaft (body) of rib, angle of rib, and anterior end of rib.

At the posterior, or vertebral, end of the rib, the head of the rib is the rounded end. Its functions are to articulate with the vertebral bodies at the costal facets and to form part of the joint between the rib and the spine. The neck of the rib is the narrowed segment between the head and the shaft. Its functions are to connect the head to the rest of the rib and provide stability and alignment between articulation points. The tubercle of the rib is a projection near the junction of the neck and shaft. Its functions are to articulate with the transverse process of a thoracic vertebra and help stabilize rib movement. The articular facet is the smooth surface on the tubercle. Its functions are to form a joint with the vertebra and allow controlled movement of the rib.

The shaft, or body, of the rib is the long curved portion extending from the posterior end. Its functions are to provide structural support for the thoracic cage and contribute to the shape and expansion of the chest. The angle of the rib is the point where the rib begins to curve forward. Its functions are to enhance the shape of the thoracic cage and allow flexibility during breathing movements.

The anterior end of the rib is the flattened end opposite the head. Its function is to connect to the costal cartilage, which then connects toward the sternum, allowing flexibility in the rib cage during breathing.

Figure 7.4.3: Rib Classifications

This image is an oblique anterior view of the thoracic cage shows the ribs color-coded by classification. Ribs 1–7 are colored red and represent the true ribs, which attach directly to the sternum through their own costal cartilages. Ribs 8–10 are colored green and represent the false ribs, whose costal cartilages join the cartilage of the rib above, creating an indirect connection to the sternum. Ribs 11–12 are colored blue and represent the floating ribs, which have no anterior attachment to the sternum. The sternum, thoracic vertebrae, and other skeletal structures are shown in gray to provide anatomical context.

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8: THE APPENDICULAR SKELETON

Chapter Overview

The human appendicular skeleton consists of the limb bones and the girdles that anchor them to the axial skeleton, enabling movement, manipulation, and locomotion. It is composed of 126 bones organized into the pectoral (shoulder) girdles, upper limbs, pelvic (hip) girdle, and lower limbs.

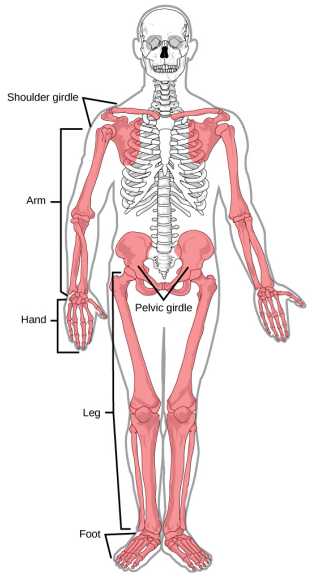


Figure 8.1: Anterior view of a human skeleton with the appendicular skeleton highlighted in pink and the axial skeleton shown in gray. Labels identify the shoulder girdle, arm, hand, pelvic girdle, leg, and foot. The shoulder girdles include the clavicles and scapulae and connect the upper limbs to the axial skeleton. The pelvic girdle connects the lower limbs to the trunk. The highlighted appendicular skeleton consists of the pectoral girdles, upper limbs, pelvic girdle, and lower limbs. (CC BY-SC 4.0; via LibreTexts Biology). Alternative text description of the Figure 8.1 .

Pectoral Girdle

The pectoral girdle, formed by the clavicle and scapula, attaches each upper limb to the axial skeleton while allowing a high degree of mobility. The clavicle links the sternum to the scapula, supports the upper limb, transmits forces to the trunk, and protects underlying neurovascular structures. The scapula lies on the posterior thorax and provides large surfaces and processes (such as the spine, acromion, coracoid process, and fossae) for muscle attachment and forms part of the glenohumeral joint via the glenoid cavity.

Bones of the Upper Limb: Arm, Forearm, and Hand

The upper limbs - including the humerus, radius, ulna, carpals, metacarpals, and phalanges - are specialized for precise, coordinated movements of the hands. Each upper limb has 30 bones divided into the arm, forearm, and hand. The humerus is the single bone of the arm, articulating proximally with the scapula and distally with the radius and ulna, and bearing tubercles, fossae, and epicondyles for articulation and muscle attachment. The forearm contains the medial ulna and lateral radius, which together form the elbow, radioulnar, and wrist articulations; they are linked by an interosseous membrane and terminate distally in styloid processes, with only the radius directly articulating with the carpal bones. The wrist contains eight carpals arranged in proximal and distal rows, forming the radiocarpal and midcarpal joints and the carpal tunnel. The palm is formed by five metacarpals, and the digits by 14 phalanges, with three phalanges in each finger and two in the thumb.

Pelvic Girdle and Pelvis: Bones, Landmarks, and Sexual Dimorphism

The pelvic girdle consists of the right and left hip bones, which unite anteriorly at the pubic symphysis and articulate posteriorly with the sacrum at the sacroiliac joints; together with the sacrum and coccyx, they form the pelvis. The pelvis supports body weight, transfers it to the lower limbs, and provides broad surfaces for muscle attachment. Each hip bone is formed by the ilium, ischium, and pubis, which fuse around the acetabulum, the socket of the hip joint. Major landmarks include the iliac crest and spines, the ischial tuberosity and spine, the pubic body and rami, the obturator foramen, and the greater and lesser sciatic notches and foramina. The pelvis is divided into greater (false) and lesser (true) pelves by the pelvic brim; the pelvic outlet forms its inferior opening. The female pelvis is wider, with a larger subpubic angle and broader greater sciatic notch, reflecting adaptation for childbirth.

Bones of the Lower Limb: Thigh, Leg, and Foot

The lower limbs - femur, tibia, fibula, tarsals, metatarsals, and phalanges - are adapted for support, balance, and efficient bipedal walking and running. Each lower limb also contains 30 bones, organized into the thigh, leg, and foot. The femur, the thigh bone, articulates proximally with the acetabulum and distally with the tibia and patella; its head, neck, trochanters, condyles, epicondyles, and shaft ridges provide sites for weight-bearing and muscle attachment. The patella, a sesamoid bone within a tendon, protects the anterior knee and improves mechanical leverage. The leg contains the weight-bearing tibia medially and the slender fibula laterally, united by an interosseous membrane. The tibia articulates with the femur at the knee and forms the medial malleolus at the ankle, while the fibula contributes to lateral ankle stability via the lateral malleolus. The tarsal bones form the posterior foot and ankle, with the talus articulating with the tibia and fibula, and the calcaneus forming the heel; additional tarsals (navicular, cuneiforms, cuboid) link to the five metatarsals. The toes have a similar phalangeal pattern to the fingers, with three phalanges in each lesser toe and two in the great toe.

Embryologic Development and Ossification of Appendicular Bones

Developmentally, appendicular bones arise from mesenchyme in limb buds that appear in the fourth week of embryonic life. Limb growth is driven by the apical ectodermal ridge, with differentiation into hyaline cartilage models by the sixth week and limb rotation by the seventh week. Most appendicular bones ossify via endochondral ossification, beginning at primary ossification centers in the diaphyses around the twelfth fetal week, followed by secondary centers in the epiphyses. Epiphyseal plates between these centers enable lengthwise growth until they close and fuse in adulthood. The clavicle is an exception, forming primarily by intramembranous ossification beginning in the fifth week and continuing into early adulthood.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own.

By the end of this chapter, students should be able to:

- Compare the axial and appendicular skeletons, describing their major functions and components.
- Identify and locate the major bones of the pectoral girdle and upper limb, including clavicle, scapula, humerus, radius, ulna, carpals, metacarpals, and phalanges, on diagrams, models, and the human body.
- Identify and locate the major bones of the pelvic girdle and lower limb, including hip (coxal) bones, femur, patella, tibia, fibula, tarsals, metatarsals, and phalanges, on diagrams, models, and the human body.
- Describe the key surface markings (bone features) of major appendicular bones (e.g., glenoid cavity, olecranon fossa, greater trochanter, medial malleolus) and relate them to muscle attachment, joint formation, or passage of nerves and vessels.
- Explain the structure and function of the pectoral and pelvic girdles, including how they articulate with the axial skeleton and how their structure supports mobility vs. stability.
- Describe the major joints of the upper and lower limbs (e.g., shoulder, elbow, wrist, hip, knee, ankle) and relate joint structure to range of motion.
- Trace the functional anatomy of the upper and lower limbs by relating bone structure to common movements (flexion, extension, abduction, adduction, rotation) at major joints.

- Compare biological male and biological female pelves, describing structural differences and their functional significance.
- Apply anatomical terminology (proximal/distal, medial/lateral, anterior/posterior) accurately when describing locations and relationships of appendicular bones.
- Relate clinical conditions or injuries (e.g., fractures of the clavicle, Colles' fracture, hip fractures, knee injuries, flatfoot) to the underlying anatomy of the appendicular skeleton.

8.1: The Pectoral Girdle

8.2: Bones of the Upper Limb

8.3: The Pelvic Girdle and Pelvis

8.4: Bones of the Lower Limb

8.5: Terms and Definitions

8.6: Chapter Review Questions

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8.1: The Pectoral Girdle

Anatomy of the Pectoral Girdle

The appendicular skeleton includes all of the limb bones, plus the bones that unite each limb with the axial skeleton (Figure 8.1.1). The bones that attach each upper limb to the axial skeleton form the pectoral girdle (shoulder girdle). This consists of two bones, the scapula and clavicle (Figure 8.1.2). The clavicle (collarbone) is an S-shaped bone located on the anterior side of the shoulder. It is attached on its medial end to the sternum of the thoracic cage, which is part of the axial skeleton. The lateral end of the clavicle articulates (joins) with the scapula just above the shoulder joint. You can easily palpate, or feel with your fingers, the entire length of your clavicle.

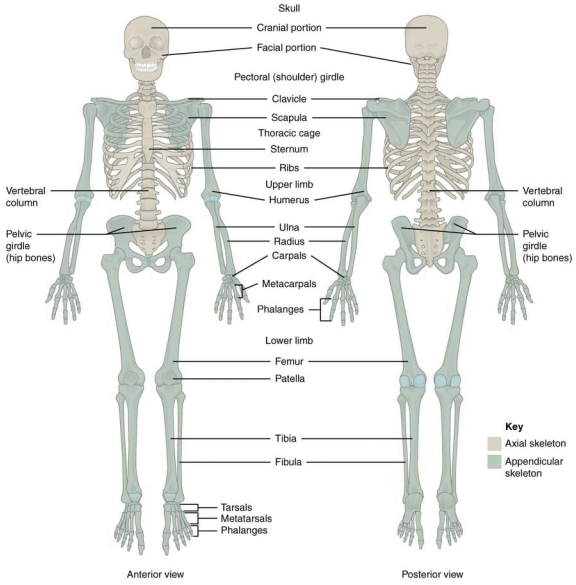


Figure 8.1.1: The axial skeleton forms the central axis of the body and consists of the skull, vertebral column, and thoracic cage. The appendicular skeleton consists of the pectoral and pelvic girdles, the limb bones, and the bones of the hands and feet. (CC BY 4.0; Carly Manz via Fundamentals of Human Anatomy Laboratory Manual). Alternative text description of the Figure 8.1.1.

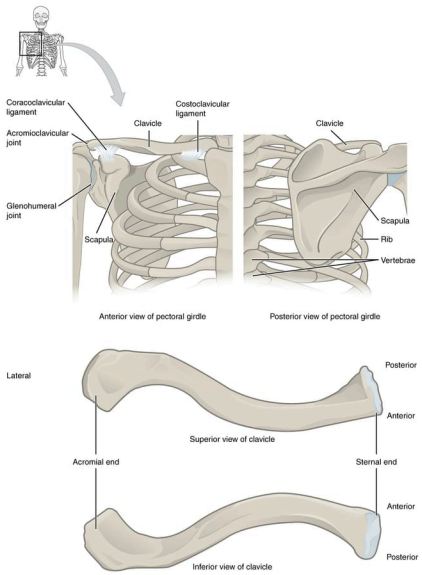


Figure 8.1.2: The pectoral girdle consists of the clavicle and the scapula, which serve to attach the upper limb to the sternum of the axial skeleton. (CC BY 3.0; Pectorial Girdle by OpenStax). Alternative text description of the Figure 8.1.2.

Clavicle

The clavicle is the only long bone that lies in a horizontal position in the body (Figure 8.1.2). The clavicle has several important functions. First, anchored by muscles from above, it serves as a strut that extends laterally to support the scapula. This in turn holds the shoulder joint superiorly and laterally from the body trunk, allowing for maximal freedom of motion for the upper limb. The clavicle also transmits forces acting on the upper limb to the sternum and axial skeleton. Finally, it serves to protect the underlying nerves and blood vessels as they pass between the trunk of the body and the upper limb.

The clavicle has three regions: the medial end, the lateral end, and the shaft. The medial end, known as the sternal end of the clavicle, has a triangular shape and articulates with the manubrium portion of the sternum. This forms the sternoclavicular joint, which is the only bony articulation between the pectoral girdle of the upper limb and the axial skeleton. This joint allows considerable mobility, enabling the clavicle and scapula to move in upward/downward and anterior/posterior directions during shoulder movements. The sternoclavicular joint is indirectly supported by the costoclavicular ligament (costo- = “rib”), which spans the sternal end of the clavicle and the underlying first rib. The lateral or acromial end of the clavicle articulates with the acromion of the scapula, the portion of the scapula that forms the bony tip of the shoulder. There are some sex differences in the morphology of the clavicle. In females, the clavicle tends to be shorter, thinner, and less curved. In males, the clavicle is heavier and longer, and has a greater curvature and rougher surfaces where muscles attach, features that are more pronounced in manual workers.

The clavicle is the most commonly fractured bone in the body. Such breaks often occur because of the force exerted on the clavicle when a person falls onto their outstretched arms, or when the lateral shoulder receives a strong blow. Because the sternoclavicular joint is strong and rarely dislocated, excessive force results in the breaking of the clavicle, usually between the middle and lateral portions of the bone. If the fracture is complete, the shoulder and lateral clavicle fragment will drop due to the weight of the upper limb, causing the person to support the sagging limb with their other hand. Muscles acting across the shoulder will also pull the shoulder and lateral clavicle anteriorly and medially, causing the clavicle fragments to override. The clavicle overlies many important blood vessels and nerves for the upper limb, but fortunately, due to the anterior displacement of a broken clavicle, these structures are rarely affected when the clavicle is fractured.

Scapula

The scapula is also part of the pectoral girdle and thus plays an important role in anchoring the upper limb to the body. The scapula is located on the posterior side of the shoulder. It is surrounded by muscles on both its anterior (deep) and posterior (superficial) sides, and thus does not articulate with the ribs of the thoracic cage.

The scapula has several important landmarks (Figure 8.1.3). The three margins or borders of the scapula, named for their positions

within the body, are the superior border of the scapula, the medial border of the scapula, and the lateral border of the scapula. The suprascapular notch is located lateral to the midpoint of the superior border. The corners of the triangular scapula, at either end of the medial border, are the superior angle of the scapula, located between the medial and superior borders, and the inferior angle of the scapula, located between the medial and lateral borders. The inferior angle is the most inferior portion of the scapula, and is particularly important because it serves as the attachment point for several powerful muscles involved in shoulder and upper limb movements. The remaining corner of the scapula, between the superior and lateral borders, is the location of the glenoid cavity (glenoid fossa). This shallow depression articulates with the humerus bone of the arm to form the glenohumeral joint (shoulder joint). The small bony bumps located immediately above and below the glenoid cavity are the supraglenoid tubercle and the infraglenoid tubercle, respectively. These provide attachments for muscles of the arm.

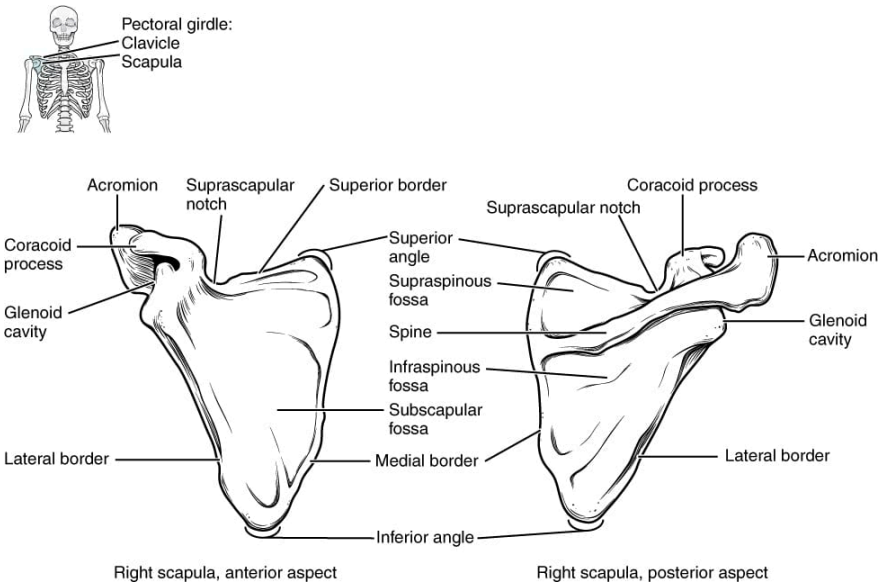


Figure 8.1.3: The isolated scapula is shown here from its anterior (deep) side and its posterior (superficial) side. (CC BY 3.0; Pectoral Girdle by OpenStax). Alternative text description of the Figure 8.1.3.

In the anterior view of the pectoral girdle, the clavicle is a curved bone extending horizontally from the sternum to the scapula. Its functions are to act as a strut that holds the shoulder away from the body and to transmit forces from the upper limb to the axial skeleton. The scapula is a flat bone positioned on the posterior thoracic cage. Its functions are to provide attachment for muscles controlling shoulder movement and serve as a base for arm mobility. The acromioclavicular joint is the junction between the clavicle and scapula. Its functions are to allow limited movement of the clavicle relative to the scapula and maintain alignment of the shoulder. The glenohumeral joint is the articulation between the scapula and humerus. Its functions are to enable a wide range of arm movements and provide flexibility at the shoulder. The coracoclavicular ligament connects the clavicle to a projection of the scapula. Its functions are to stabilize the clavicle and prevent separation of the shoulder joint. The costoclavicular ligament connects the clavicle to a rib. Its functions are to anchor the clavicle to the thoracic cage and limit excessive movement.

In the posterior view of the pectoral girdle, the scapula is shown as a broad, flat bone lying against the ribs. Its functions are to provide extensive surface area for muscle attachment and enable movement of the shoulder blade. The figure also shows the relationship of the scapula to the ribs and indirectly to the vertebral column through muscles. This relationship allows mobility of the scapula during arm movement and supports coordinated motion of the upper limb.

In the superior view of the clavicle, the acromial end is the lateral end. Its function is to articulate with the scapula as part of the acromioclavicular joint. The sternoclavicular, or sternal, end is the medial end. Its function is to articulate with the sternum and form the sternoclavicular joint. The clavicle is shown as a curved bone with a double bend along its length. This shape provides flexibility and strength and helps absorb forces applied to the shoulder.

In the inferior view of the clavicle, the underside of the bone shows surface features that serve as attachment areas for ligaments. These features provide anchoring points for the costoclavicular ligament and coracoclavicular ligament. The orientation labels identify anterior versus posterior and medial versus lateral so that the correct anatomical positioning of the clavicle can be determined.

The scapula also has two prominent projections. Toward the lateral end of the superior border, between the suprascapular notch

and glenoid cavity, is the hook-like coracoid process (coracoid = “shaped like a crow’s beak”). This process projects anteriorly and curves laterally. At the shoulder, the coracoid process is located inferior to the lateral end of the clavicle. It is anchored to the clavicle by a strong ligament, and serves as the attachment site for muscles of the anterior chest and arm. On the posterior aspect, the spine of the scapula is a long and prominent ridge that runs across its upper portion. Extending laterally from the spine is a flattened and expanded region called the acromion or acromial process. The acromion forms the bony tip of the superior shoulder region and articulates with the lateral end of the clavicle, forming the acromioclavicular joint. Together, the clavicle, acromion, and spine of the scapula form a V-shaped bony line that provides for the attachment of neck and back muscles that act on the shoulder, as well as muscles that pass across the shoulder joint to act on the arm.

The scapula has three depressions, each of which is called a fossa (plural = fossae). Two of these are found on the posterior scapula, above and below the scapular spine. Superior to the spine is the narrow supraspinous fossa, and inferior to the spine is the broad infraspinous fossa. The anterior (deep) surface of the scapula forms the broad subscapular fossa. All of these fossae provide large surface areas for the attachment of muscles that cross the shoulder joint to act on the humerus.

The acromioclavicular joint transmits forces from the upper limb to the clavicle. The ligaments around this joint are relatively weak. A hard fall onto the elbow or outstretched hand can stretch or tear the acromioclavicular ligaments, resulting in a moderate injury to the joint. However, the primary support for the acromioclavicular joint comes from a very strong ligament called the coracoclavicular ligament (Figure 8.1.3). This connective tissue band anchors the coracoid process of the scapula to the inferior surface of the acromial end of the clavicle and thus provides important indirect support for the acromioclavicular joint. Following a strong blow to the lateral shoulder, such as when a hockey player is driven into the boards, a complete dislocation of the acromioclavicular joint can result. In this case, the acromion is thrust under the acromial end of the clavicle, resulting in ruptures of both the acromioclavicular and coracoclavicular ligaments. The scapula then separates from the clavicle, with the weight of the upper limb pulling the shoulder downward. This dislocation injury of the acromioclavicular joint is known as a “shoulder separation” and is common in contact sports such as hockey, football, or martial arts.

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8.2: Bones of the Upper Limb

Anatomy of the Upper Limb

The upper limb is divided into three regions. These consist of the arm, located between the shoulder and elbow joints; the forearm, which is between the elbow and wrist joints; and the hand, which is located distal to the wrist. There are 30 bones in each upper limb (Figure 8.2.1). The humerus is the single bone of the upper arm, and the ulna (medially) and the radius (laterally) are the paired bones of the forearm. The base of the hand contains eight bones, each called a carpal bone, and the palm of the hand is formed by five bones, each called a metacarpal bone. The fingers and thumb contain a total of 14 bones, each of which is a phalanx bone of the hand.

Humerus

The humerus is the single bone of the upper arm region (Figure 8.2.1). At its proximal end is the head of the humerus. This is the large, round, smooth region that faces medially. The head articulates with the glenoid cavity of the scapula to form the glenohumeral (shoulder) joint. The margin of the smooth area of the head is the anatomical neck of the humerus. Located on the lateral side of the proximal humerus is an expanded bony area called the greater tubercle. The smaller lesser tubercle of the humerus is found on the anterior aspect of the humerus. Both the greater and lesser tubercles serve as attachment sites for muscles that act across the shoulder joint. Passing between the greater and lesser tubercles is the narrow intertubercular groove (sulcus), which is also known as the bicipital groove because it provides passage for a tendon of the biceps brachii muscle. The surgical neck is located at the base of the expanded, proximal end of the humerus, where it joins the narrow shaft of the humerus. The surgical neck is a common site of arm fractures. The deltoid tuberosity is a roughened, V-shaped region located on the lateral side in the middle of the humerus shaft. As its name indicates, it is the site of attachment for the deltoid muscle.

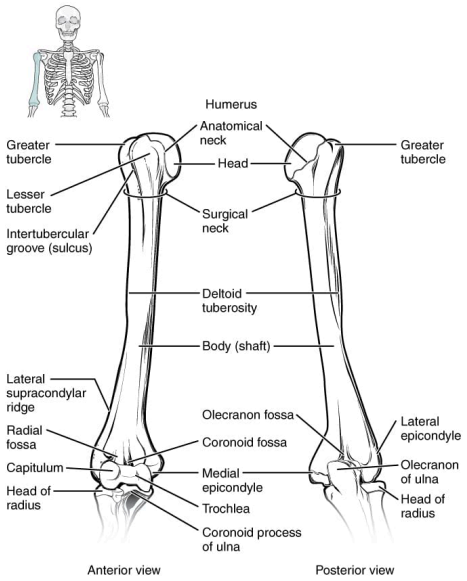


Figure 8.2.1: The humerus is the single bone of the upper arm region. It articulates with the radius and ulna bones of the forearm to form the elbow joint. (CC BY 4.0; Aylin Marz; Ganesan Kamatchi; Joseph D'Silva; Krishnan Prabhakaran; Rajeev Chandra; and Solomon Isekeije via Anatomy and Physiology Laboratory Manual for Nursing and Allied Health). Alternative text description of the Figure 8.2.1.

At the proximal end, the head of the humerus is a rounded structure that articulates with the glenoid cavity of the scapula to form the glenohumeral, or shoulder, joint. The anatomical neck is the slight constriction immediately surrounding the head and serves as an attachment site for the joint capsule. The surgical neck is the narrower region below the tubercles and acts as a transition zone between the head and shaft. It is also a common site of fracture that can affect arm function. The greater tubercle is a large lateral projection that serves as an attachment site for rotator cuff muscles, helping support shoulder stability and movement. The lesser tubercle is a smaller anterior projection that provides attachment for muscles involved in arm rotation. The intertubercular

groove, also called the sulcus, lies between the greater and lesser tubercles and houses the tendon of the biceps brachii, guiding tendon movement.

The shaft, or body, of the humerus is the long cylindrical middle region. Its functions are to provide strength and support and to serve as an attachment site for numerous muscles. The deltoid tuberosity is a roughened area on the lateral surface of the shaft and serves as the attachment site for the deltoid muscle, which moves the arm. The lateral supracondylar ridge is a ridge near the distal portion of the bone that provides attachment for muscles and connective tissues.

At the distal end, the capitulum is the rounded surface on the lateral side. Its function is to articulate with the head of the radius and support movements of the forearm. The trochlea is the spool-shaped surface on the medial side. Its function is to articulate with the ulna and enable bending and straightening at the elbow. The medial epicondyle is a projection on the medial side that serves as an attachment site for muscles controlling the forearm and hand. The lateral epicondyle is a projection on the lateral side that provides attachment for muscles involved in forearm movement. The radial fossa is a depression above the capitulum that accommodates the radius during elbow flexion. The coronoid fossa is a depression above the trochlea that receives the coronoid process of the ulna during elbow movement. In the posterior view, the olecranon fossa is the large depression on the posterior distal humerus that receives the olecranon of the ulna during elbow extension.

Distally, the humerus becomes flattened. The prominent bony projection on the medial side is the medial epicondyle of the humerus. The much smaller lateral epicondyle of the humerus is found on the lateral side of the distal humerus. The roughened ridge of bone above the lateral epicondyle is the lateral supracondylar ridge. All of these areas are attachment points for muscles that act on the forearm, wrist, and hand. The powerful grasping muscles of the anterior forearm arise from the medial epicondyle, which is thus larger and more robust than the lateral epicondyle that gives rise to the weaker posterior forearm muscles.

The distal end of the humerus has two articulation areas, which join the ulna and radius bones of the forearm to form the elbow joint. The more medial of these areas is the trochlea, a spindle- or pulley-shaped region (trochlea = “pulley”), which articulates with the ulna bone. Immediately lateral to the trochlea is the capitulum (“small head”), a knob-like structure located on the anterior surface of the distal humerus. The capitulum articulates with the radius bone of the forearm. Just above these bony areas are two small depressions. These spaces accommodate the forearm bones when the elbow is fully bent (flexed). Superior to the trochlea is the coronoid fossa, which receives the coronoid process of the ulna, and above the capitulum is the radial fossa, which receives the head of the radius when the elbow is flexed. Similarly, the posterior humerus has the olecranon fossa, a larger depression that receives the olecranon process of the ulna when the forearm is fully extended.

Ulna

The ulna is the medial bone of the forearm. It runs parallel to the radius, which is the lateral bone of the forearm (Figure 8.2.2). The proximal end of the ulna resembles a crescent wrench with its large, C-shaped trochlear notch. This region articulates with the trochlea of the humerus as part of the elbow joint. The inferior margin of the trochlear notch is formed by a prominent lip of bone called the coronoid process of the ulna. Just below this on the anterior ulna is a roughened area called the ulnar tuberosity. To the lateral side and slightly inferior to the trochlear notch is a small, smooth area called the radial notch of the ulna. This area is the site of articulation between the proximal radius and the ulna, forming the proximal radioulnar joint. The posterior and superior portions of the proximal ulna make up the olecranon process, which forms the bony tip of the elbow.

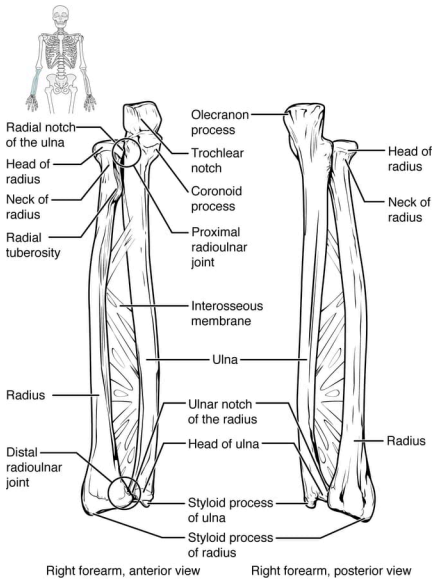


Figure 8.2.2: The ulna is located on the medial side of the forearm, and the radius is on the lateral side. These bones are attached to each other by an interosseous membrane. (CC BY 4.0; Aylin Marz; Ganesan Kamatchi; Joseph D'Silva; Krishnan Prabhakaran; Rajeev Chandra; and Solomon Isekeije via Anatomy and Physiology Laboratory Manual for Nursing and Allied Health). Alternative text description of the Figure 8.2.2.

More distal is the shaft of the ulna. The lateral side of the shaft forms a ridge called the interosseous border of the ulna. This is the line of attachment for the interosseous membrane of the forearm, a sheet of dense connective tissue that unites the ulna and radius bones. The small, rounded area that forms the distal end is the head of the ulna. Projecting from the posterior side of the ulnar head is the styloid process of the ulna, a short bony projection. This serves as an attachment point for a connective tissue structure that unites the distal ends of the ulna and radius.

In the anatomical position, with the elbow fully extended and the palms facing forward, the arm and forearm do not form a straight line. Instead, the forearm deviates laterally by 5–15 degrees from the line of the arm. This deviation is called the carrying angle. It allows the forearm and hand to swing freely or to carry an object without hitting the hip. The carrying angle is larger in females to accommodate their wider pelvis.

Radius

The radius runs parallel to the ulna, on the lateral (thumb) side of the forearm (Figure 8.2.3). The head of the radius is a disc-shaped structure that forms the proximal end. The small depression on the surface of the head articulates with the capitulum of the humerus as part of the elbow joint, whereas the smooth, outer margin of the head articulates with the radial notch of the ulna at the proximal radioulnar joint. The neck of the radius is the narrowed region immediately below the expanded head. Inferior to this point on the medial side is the radial tuberosity, an oval-shaped, bony protuberance that serves as a muscle attachment point. The shaft of the radius is slightly curved and has a small ridge along its medial side. This ridge forms the interosseous border of the radius, which, like the similar border of the ulna, is the line of attachment for the interosseous membrane that unites the two forearm bones. The distal end of the radius has a smooth surface for articulation with two carpal bones to form the radiocarpal joint or wrist joint. On the medial side of the distal radius is the ulnar notch of the radius. This shallow depression articulates with the head of the ulna, which together form the distal radioulnar joint. The lateral end of the radius has a pointed projection called the styloid process of the radius. This provides attachment for ligaments that support the lateral side of the wrist joint. Compared to the styloid process of the ulna, the styloid process of the radius projects more distally, thereby limiting the range of movement for lateral deviations of the hand at the wrist joint.

Carpal Bones

The wrist and base of the hand are formed by a series of eight small carpal bones. The carpal bones are arranged in two rows, forming a proximal row of four carpal bones and a distal row of four carpal bones. The bones in the proximal row, running from the lateral (thumb) side to the medial side, are the scaphoid (“boat-shaped”), lunate (“moon-shaped”), triquetrum (“three-cornered”), and pisiform (“pea-shaped”) bones. The small, rounded pisiform bone articulates with the anterior surface of the triquetrum bone. The pisiform thus projects anteriorly, where it forms the bony bump that can be felt at the medial base of your hand. The

distal bones (lateral to medial) are the trapezium (“table”), trapezoid (“resembles a table”), capitate (“head-shaped”), and hamate (“hooked bone”) bones. The hamate bone is characterized by a prominent bony extension on its anterior side called the hook of the hamate bone.

A helpful mnemonic for remembering the arrangement of the carpal bones is “So Long To Pinky, Here Comes The Thumb.” This mnemonic starts on the lateral side and names the proximal bones from lateral to medial (scaphoid, lunate, triquetrum, pisiform), then makes a U-turn to name the distal bones from medial to lateral (hamate, capitate, trapezoid, trapezium). Thus, it starts and finishes on the lateral side.

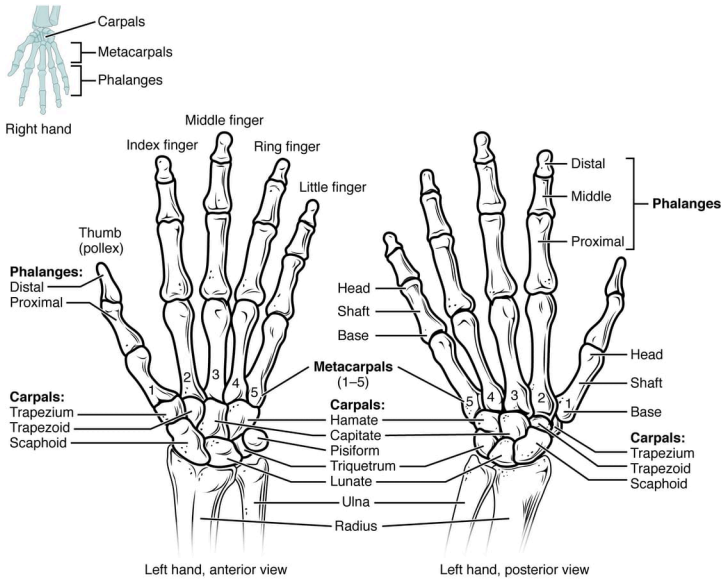


Figure 8.2.3: The eight carpal bones form the base of the hand. These are arranged into proximal and distal rows of four bones each. The metacarpal bones form the palm of the hand. The thumb and fingers consist of the phalanx bones. (CC BY 4.0; Aylin Marz; Ganesan Kamatchi; Joseph D'Silva; Krishnan Prabhakaran; Rajeev Chandra; and Solomon Isekeije via Anatomy and Physiology Laboratory Manual for Nursing and Allied Health). Alternative text description of the Figure 8.2.3.

The carpal bones form the base of the hand. This is represented in the radiograph (X-ray image) of the hand that shows the relationships of the hand bones to the skin creases of the hand (Figure 8.2.4). Within the carpal bones, the four proximal bones are united to each other by ligaments to form a unit. Only three of these bones, the scaphoid, lunate, and triquetrum, contribute to the radiocarpal joint. The scaphoid and lunate bones articulate directly with the distal end of the radius, whereas the triquetrum bone articulates with a fibrocartilaginous pad that spans the radius and styloid process of the ulna. The distal end of the ulna thus does not directly articulate with any of the carpal bones.

The four distal carpal bones are also held together as a group by ligaments. The proximal and distal rows of carpal bones articulate with each other to form the midcarpal joint. Together, the radiocarpal and midcarpal joints are responsible for all movements of the hand at the wrist. The distal carpal bones also articulate with the metacarpal bones of the hand.

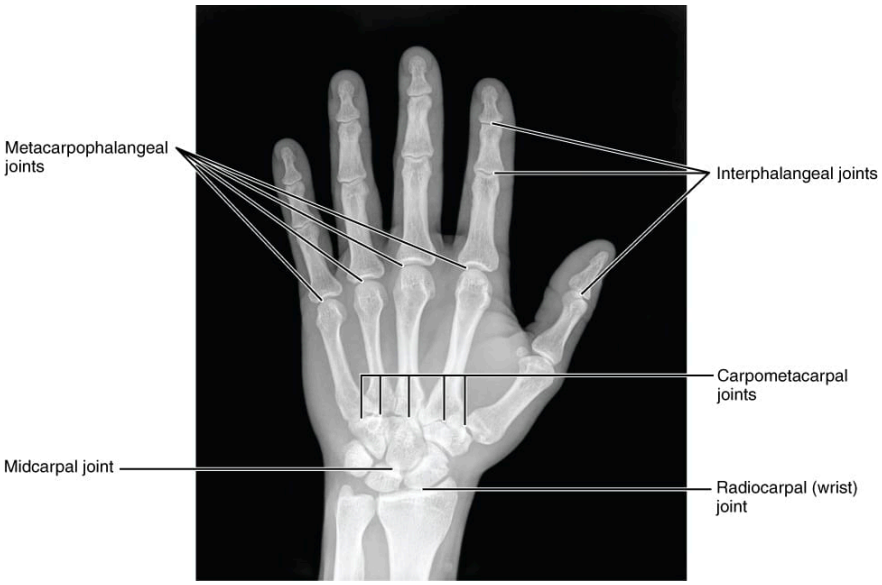


Figure 8.2.4: This radiograph shows the position of the bones within the hand. Note the carpal bones that form the base of the hand. (CC BY 4.0; via Bones of the Upper Limb). Alternative text description of the Figure 8.2.4.

In the articulated hand, the carpal bones form a U-shaped grouping. A strong ligament called the flexor retinaculum spans the top of this U-shaped area to maintain this grouping of the carpal bones. The flexor retinaculum is attached laterally to the trapezium and scaphoid bones, and medially to the hamate and pisiform bones. Together, the carpal bones and the flexor retinaculum form a passageway called the carpal tunnel, with the carpal bones forming the walls and floor, and the flexor retinaculum forming the roof of this space (Figure 8.2.5). The tendons of nine muscles of the anterior forearm and an important nerve pass through this narrow tunnel to enter the hand. Overuse of the muscle tendons or wrist injury can produce inflammation and swelling within this space. This produces compression of the nerve, resulting in carpal tunnel syndrome, which is characterized by pain or numbness, and muscle weakness in those areas of the hand supplied by this nerve.

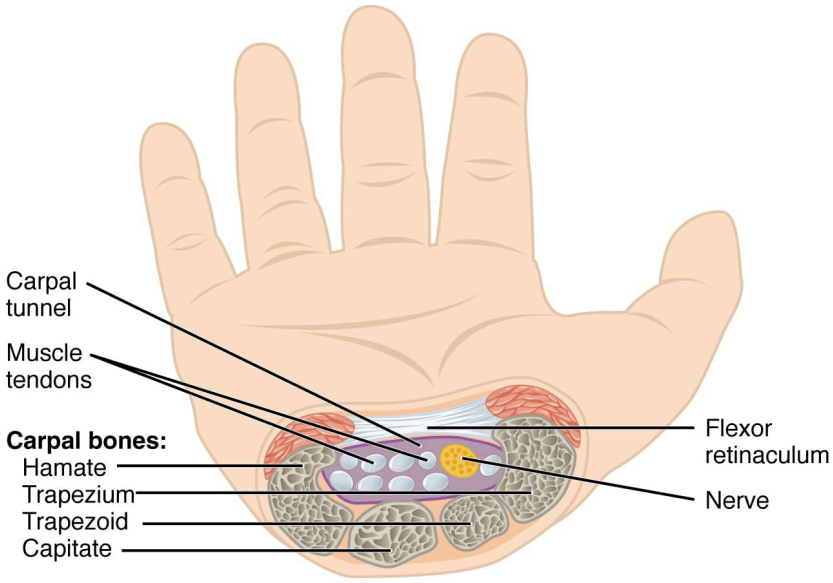


Figure 8.2.5: The carpal tunnel is the passageway by which nine muscle tendons and a major nerve enter the hand from the anterior forearm. The walls and floor of the carpal tunnel are formed by the U-shaped grouping of the carpal bones, and the roof is formed by the flexor retinaculum, a strong ligament that anteriorly unites the bones. (CC BY 4.0; via Bones of the Upper Limb). Alternative text description of the Figure 8.2.5.

Metacarpal Bones

The palm of the hand contains five elongated metacarpal bones. These bones lie between the carpal bones of the wrist and the bones of the fingers and thumb. The proximal end of each metacarpal bone articulates with one of the distal carpal bones. Each of these articulations is a carpometacarpal joint (Figure 8.2.6). The expanded distal end of each metacarpal bone articulates at the metacarpophalangeal joint with the proximal phalanx bone of the thumb or one of the fingers. The distal end also forms the knuckles of the hand, at the base of the fingers. The metacarpal bones are numbered 1–5, beginning at the thumb.

The first metacarpal bone, at the base of the thumb, is separated from the other metacarpal bones. This allows it a freedom of motion that is independent of the other metacarpal bones, which is very important for thumb mobility. The remaining metacarpal bones are united together to form the palm of the hand. The second and third metacarpal bones are firmly anchored in place and are immobile. However, the fourth and fifth metacarpal bones have limited anterior-posterior mobility, a motion that is greater for the fifth bone. This mobility is important during power gripping with the hand. The anterior movement of these bones, particularly the fifth metacarpal bone, increases the strength of contact for the medial hand during gripping actions.

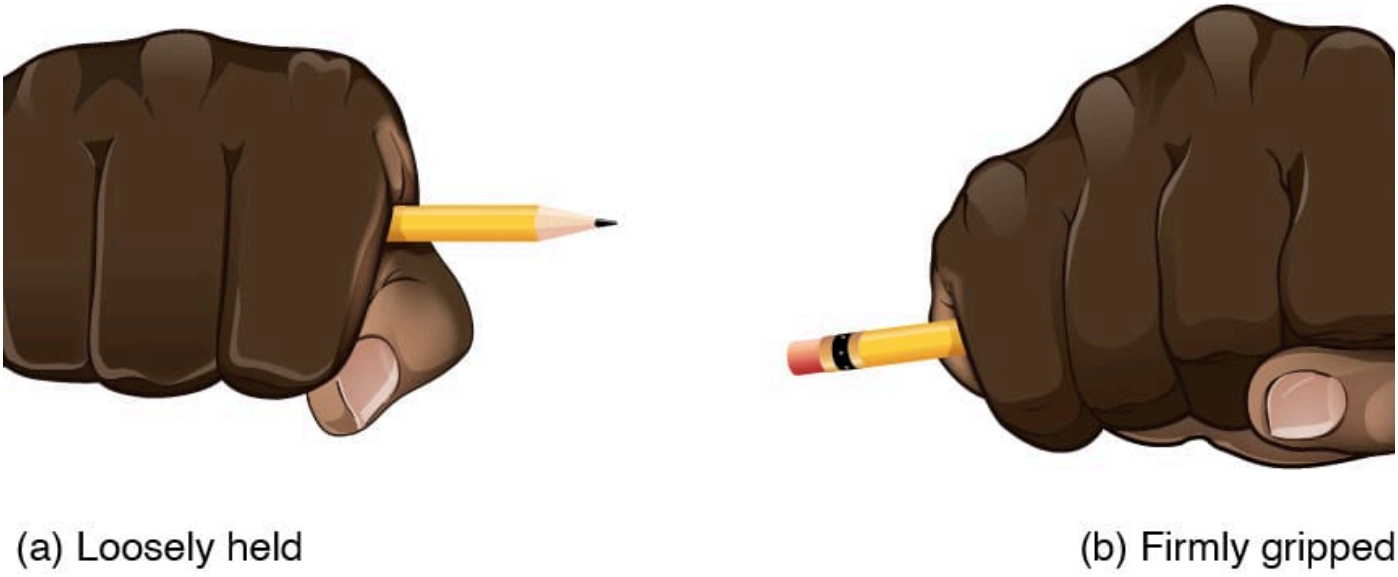


Figure 8.2.6: During tight gripping—compare (b) to (a)—the fourth and, particularly, the fifth metatarsal bones are pulled anteriorly. This increases the contact between the object and the medial side of the hand, thus improving the firmness of the grip. (CC BY 4.0; via Bones of the Upper Limb). Alternative text description of the Figure 8.2.6.

Phalanx Bones

The fingers and thumb contain 14 bones, each of which is called a phalanx bone (plural = phalanges), named after the ancient Greek phalanx (a rectangular block of soldiers). The thumb (pollex) is digit number 1 and has two phalanges, a proximal phalanx, and a distal phalanx bone. Digits 2 (index finger) through 5 (little finger) have three phalanges each, called the proximal, middle, and distal phalanx bones. An interphalangeal joint is one of the articulations between adjacent phalanges of the digits (Figure ({8{.}2{.}\eatSpaces{7} \endSpaces}\)).

Disorders of the...

Appendicular System: Fractures of Upper Limb Bones

Due to our constant use of the hands and the rest of our upper limbs, an injury to any of these areas will cause a significant loss of functional ability. Many fractures result from a hard fall onto an outstretched hand. The resulting transmission of force up the limb may result in a fracture of the humerus, radius, or scaphoid bones. These injuries are especially common in elderly people whose bones are weakened due to osteoporosis.

Falls onto the hand or elbow, or direct blows to the arm, can result in fractures of the humerus. Following a fall, fractures at the surgical neck, the region at which the expanded proximal end of the humerus joins with the shaft, can result in an impacted fracture, in which the distal portion of the humerus is driven into the proximal portion. Falls or blows to the arm can also produce transverse or spiral fractures of the humeral shaft.

In children, a fall onto the tip of the elbow frequently results in a distal humerus fracture. In these, the olecranon of the ulna is driven upward, resulting in a fracture across the distal humerus, above both epicondyles (supracondylar fracture), or a fracture between the epicondyles, thus separating one or both of the epicondyles from the body of the humerus (intercondylar fracture). With these injuries, the immediate concern is possible compression of the artery to the forearm due to swelling of the surrounding tissues. If compression occurs, the resulting ischemia (lack of oxygen) due to reduced blood flow can quickly produce irreparable damage to the forearm muscles. In addition, four major nerves for shoulder and upper limb muscles are closely associated with different regions of the humerus, and thus, humeral fractures may also damage these nerves.

Another frequent injury following a fall onto an outstretched hand is a Colles fracture (“col-lees”) of the distal radius. This involves a complete transverse fracture across the distal radius that drives the separated distal fragment of the radius posteriorly and superiorly. This injury results in a characteristic “dinner fork” bend of the forearm just above the wrist due to the posterior displacement of the hand. This is the most frequent forearm fracture and is a common injury in persons over the age of 50, particularly in older people with osteoporosis. It also commonly occurs following a high-speed fall onto the hand during activities such as snowboarding or skating.

The most commonly fractured carpal bone is the scaphoid, often resulting from a fall onto the hand. Deep pain at the lateral wrist may yield an initial diagnosis of a wrist sprain, but a radiograph taken several weeks after the injury, after tissue swelling has subsided, will reveal the fracture. Due to the poor blood supply to the scaphoid bone, healing will be slow and there is the danger of bone necrosis and subsequent degenerative joint disease of the wrist.

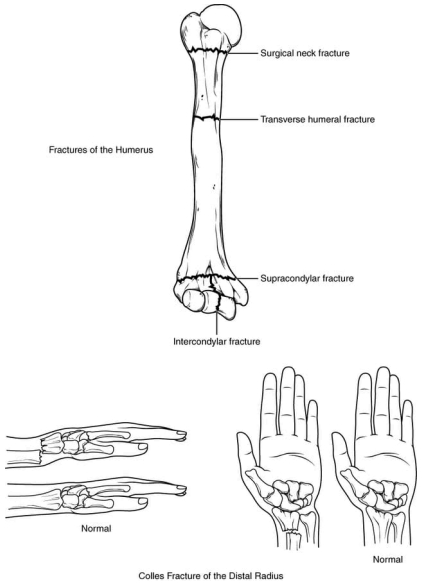


Figure 8.2.7: Falls or direct blows can result in fractures of the surgical neck or shaft of the humerus. Falls onto the elbow can fracture the distal humerus. A Colles fracture of the distal radius is the most common forearm fracture. (CC BY 4.0; via Bones of the Upper Limb). Alternative text description of the Figure 8.2.7.

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8.3: The Pelvic Girdle and Pelvis

Anatomy of the Pelvic Girdle and Pelvis

The pelvic girdle (hip girdle) is formed by a single bone, the hip bone or coxal bone (coxal = “hip”), which serves as the attachment point for each lower limb. Each hip bone, in turn, is firmly joined to the axial skeleton via its attachment to the sacrum of the vertebral column. The right and left hip bones also converge anteriorly to attach to each other. The bony pelvis is the entire structure formed by the two hip bones, the sacrum, and, attached inferiorly to the sacrum, the coccyx (Figure 8.3.1).

Unlike the bones of the pectoral girdle, which are highly mobile to enhance the range of upper limb movements, the bones of the pelvis are strongly united to each other to form a largely immobile, weight-bearing structure. This is important for stability because it enables the weight of the body to be easily transferred laterally from the vertebral column, through the pelvic girdle and hip joints, and into either lower limb whenever the other limb is not bearing weight. Thus, the immobility of the pelvis provides a strong foundation for the upper body as it rests on top of the mobile lower limbs.

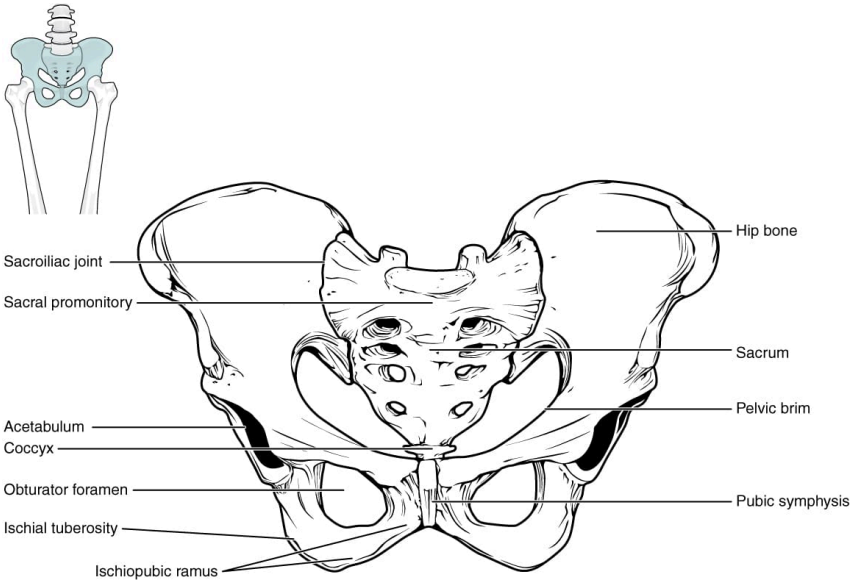


Figure 8.3.1: The pelvic girdle is formed by a single hip bone. The hip bone attaches the lower limb to the axial skeleton through its articulation with the sacrum. The right and left hip bones, plus the sacrum and the coccyx, together form the pelvis. (CC BY 4.0 ; via The Pelvic Girdle and Pelvis). Alternate text description of the Figure 8.3.1.

Hip Bone

The hip bone, or coxal bone, forms the pelvic girdle portion of the pelvis. The paired hip bones are the large, curved bones that form the lateral and anterior aspects of the pelvis. Each adult hip bone is formed by three separate bones that fuse together during the late teenage years. These bony components are the ilium, ischium, and pubis (Figure 8.3.2). These names are retained and used to define the three regions of the adult hip bone.

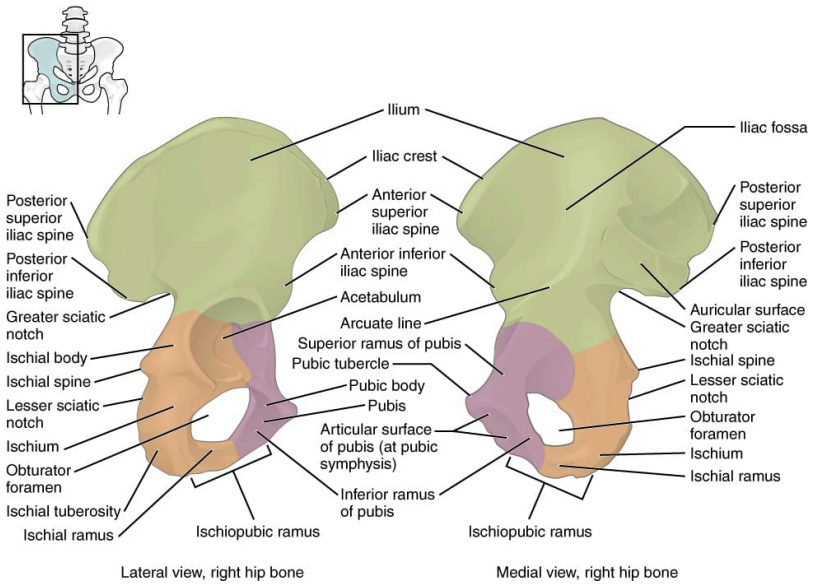


Figure 8.3.2: The adult hip bone consists of three regions. The ilium forms the large, fan-shaped superior portion, the ischium forms the posteroinferior portion, and the pubis forms the anteromedial portion. (CC BY 4.0 ; via The Pelvic Girdle and Pelvis). Alternate text description of the Figure 8.3.2.

Ilium

The ilium is the fan-like, superior region that forms the largest part of the hip bone. It is firmly united to the sacrum at the largely immobile sacroiliac joint (Figure 8.3.3). The ischium forms the posteroinferior region of each hip bone. It supports the body when sitting. The pubis forms the anterior portion of the hip bone. The pubis curves medially, where it joins to the pubis of the opposite hip bone at a specialized joint called the pubic symphysis.

When you place your hands on your waist, you can feel the arching, superior margin of the ilium along your waistline. This curved, superior margin of the ilium is the iliac crest. The rounded, anterior termination of the iliac crest is the anterior superior iliac spine. This important bony landmark can be felt at your anterolateral hip. Inferior to the anterior superior iliac spine is a rounded protuberance called the anterior inferior iliac spine. Both of these iliac spines serve as attachment points for muscles of the thigh. Posteriorly, the iliac crest curves downward to terminate as the posterior superior iliac spine. Muscles and ligaments surround but do not cover this bony landmark, thus sometimes producing a depression seen as a “dimple” located on the lower back. More inferiorly is the posterior inferior iliac spine. This is located at the inferior end of a large, roughened area called the auricular surface of the ilium. The auricular surface articulates with the auricular surface of the sacrum to form the sacroiliac joint. Both the posterior superior and posterior inferior iliac spines serve as attachment points for the muscles and very strong ligaments that support the sacroiliac joint.

The shallow depression located on the anteromedial (internal) surface of the upper ilium is called the iliac fossa. The inferior margin of this space is formed by the arcuate line of the ilium, the ridge formed by the pronounced change in curvature between the upper and lower portions of the ilium. The large, inverted U-shaped indentation located on the posterior margin of the lower ilium is called the greater sciatic notch.

Ischium

The ischium forms the posterolateral portion of the hip bone. The large, roughened area of the inferior ischium is the ischial tuberosity. This serves as the attachment for the posterior thigh muscles and also carries the weight of the body when sitting. You can feel the ischial tuberosity if you wiggle your pelvis against the seat of a chair. Projecting superiorly and anteriorly from the ischial tuberosity is a narrow segment of bone called the ischial ramus. The slightly curved posterior margin of the ischium above the ischial tuberosity is the lesser sciatic notch. The bony projection separating the lesser sciatic notch and greater sciatic notch is the ischial spine.

Pubis

The pubis forms the anterior portion of the hip bone. The enlarged medial portion of the pubis is the pubic body. Located superiorly on the pubic body is a small bump called the pubic tubercle. The superior pubic ramus is the segment of bone that passes laterally from the pubic body to join the ilium. The narrow ridge running along the superior margin of the superior pubic ramus is the pectineal line of the pubis.

The pubic body is joined to the pubic body of the opposite hip bone by the pubic symphysis. Extending downward and laterally from the body is the inferior pubic ramus. The pubic arch is the bony structure formed by the pubic symphysis, and the bodies and inferior pubic rami of the adjacent pubic bones. The inferior pubic ramus extends downward to join the ischial ramus. Together, these form the single ischiopubic ramus, which extends from the pubic body to the ischial tuberosity. The inverted V-shape formed as the ischiopubic rami from both sides come together at the pubic symphysis is called the subpubic angle.

Pelvis

The pelvis consists of four bones: the right and left hip bones, the sacrum, and the coccyx. The pelvis has several important functions. Its primary role is to support the weight of the upper body when sitting and to transfer this weight to the lower limbs when standing. It serves as an attachment point for trunk and lower limb muscles, and also protects the internal pelvic organs. When standing in the anatomical position, the pelvis is tilted anteriorly. In this position, the anterior superior iliac spines and the pubic tubercles lie in the same vertical plane, and the anterior (internal) surface of the sacrum faces forward and downward.

The three areas of each hip bone, the ilium, pubis, and ischium, converge centrally to form a deep, cup-shaped cavity called the acetabulum. This is located on the lateral side of the hip bone and is part of the hip joint. The large opening in the anteroinferior hip bone between the ischium and pubis is the obturator foramen. This space is largely filled in by a layer of connective tissue and serves for the attachment of muscles on both its internal and external surfaces.

Several ligaments unite the bones of the pelvis (Figure 8.3.3). The largely immobile sacroiliac joint is supported by a pair of strong ligaments that are attached between the sacrum and ilium portions of the hip bone. These are the anterior sacroiliac ligament on the anterior side of the joint and the posterior sacroiliac ligament on the posterior side. Also spanning the sacrum and hip bone are two additional ligaments. The sacrospinous ligament runs from the sacrum to the ischial spine, and the sacrotuberous ligament runs from the sacrum to the ischial tuberosity. These ligaments help to support and immobilize the sacrum as it carries the weight of the body.

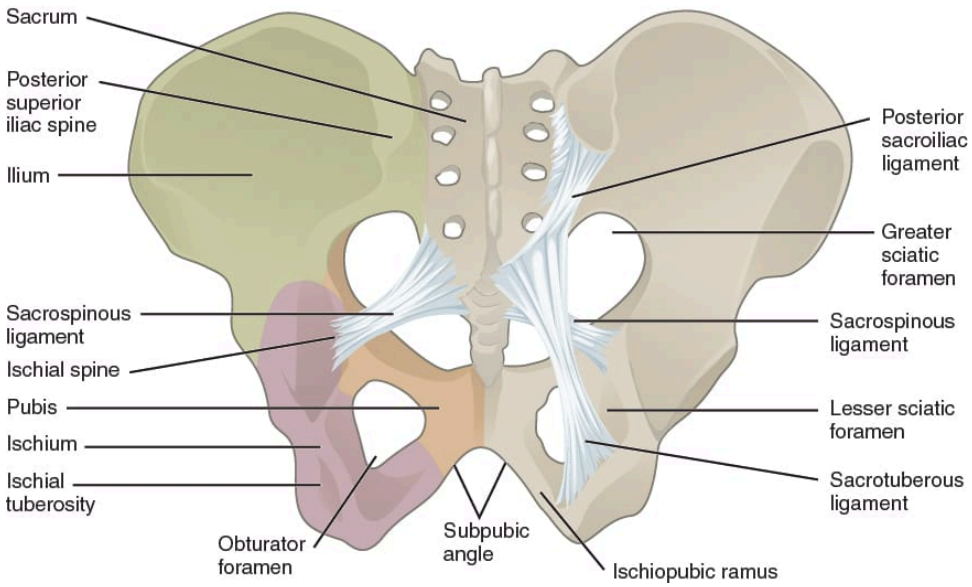


Figure 8.3.3: The posterior sacroiliac ligament supports the sacroiliac joint. The sacrospinous ligament spans the sacrum to the ischial spine, and the sacrotuberous ligament spans the sacrum to the ischial tuberosity. The sacrospinous and sacrotuberous ligaments contribute to the formation of the greater and lesser sciatic foramina. (CC BY 4.0 ; via The Pelvic Girdle and Pelvis). Alternate text description of the Figure 8.3.3 .

The sacrospinous and sacrotuberous ligaments also help to define two openings on the posterolateral sides of the pelvis through

which muscles, nerves, and blood vessels for the lower limb exit. The superior opening is the greater sciatic foramen. This large opening is formed by the greater sciatic notch of the hip bone, the sacrum, and the sacrospinous ligament. The smaller, more inferior lesser sciatic foramen is formed by the lesser sciatic notch of the hip bone, together with the sacrospinous and sacrotuberous ligaments.

The space enclosed by the bony pelvis is divided into two regions (Figure 8.3.4). The broad, superior region, defined laterally by the large, fan-like portion of the upper hip bone, is called the greater pelvis (greater pelvic cavity; false pelvis). This broad area is occupied by portions of the small and large intestines, and because it is more closely associated with the abdominal cavity, it is sometimes referred to as the false pelvis. More inferiorly, the narrow, rounded space of the lesser pelvis (lesser pelvic cavity; true pelvis) contains the bladder and other pelvic organs, and thus is also known as the true pelvis. The pelvic brim (also known as the pelvic inlet) forms the superior margin of the lesser pelvis, separating it from the greater pelvis. The pelvic brim is defined by a line formed by the upper margin of the pubic symphysis anteriorly, and the pectineal line of the pubis, the arcuate line of the ilium, and the sacral promontory (the anterior margin of the superior sacrum) posteriorly. The inferior limit of the lesser pelvic cavity is called the pelvic outlet. This large opening is defined by the inferior margin of the pubic symphysis anteriorly, and the ischiopubic ramus, the ischial tuberosity, the sacrotuberous ligament, and the inferior tip of the coccyx posteriorly. Because of the anterior tilt of the pelvis, the lesser pelvis is also angled, giving it an anterosuperior (pelvic inlet) to posteroinferior (pelvic outlet) orientation.

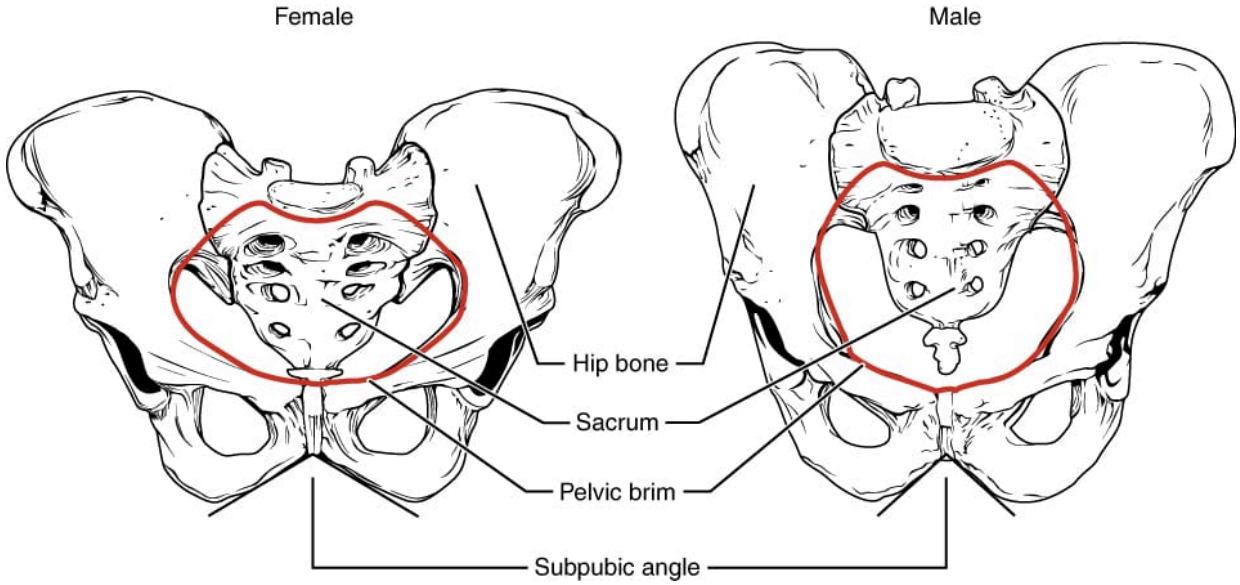


Figure 8.3.4: The female pelvis is adapted for childbirth and is broader, with a larger subpubic angle, a rounder pelvic brim, and a wider and more shallow lesser pelvic cavity than the male pelvis. (CC BY 4.0 ; via The Pelvic Girdle and Pelvis). Alternate text description of the Figure 8.3.4.

Comparison of the Female and Male Pelvis

The differences between the adult female and male pelvis relate to function and body size. In general, the bones of the male pelvis are thicker and heavier, adapted for support of the male's heavier physical build and stronger muscles. The greater sciatic notch of the male hip bone is narrower and deeper than the broader notch of females. Because the female pelvis is adapted for childbirth, it is wider than the male pelvis, as evidenced by the distance between the anterior superior iliac spines (Figure 8.3.4). The ischial tuberosities of females are also farther apart, which increases the size of the pelvic outlet. Because of this increased pelvic width, the subpubic angle is larger in females (greater than 80 degrees) than it is in males (less than 70 degrees). The female sacrum is wider, shorter, and less curved, and the sacral promontory projects less into the pelvic cavity, thus giving the female pelvic inlet (pelvic brim) a more rounded or oval shape compared to males. The lesser pelvic cavity of females is also wider and more shallow than the narrower, deeper, and tapering lesser pelvis of males. Because of the obvious differences between female and male hip bones, this is the one bone of the body that allows for the most accurate sex determination. Table 8.3.1 provides an overview of the general differences between the female and male pelvis.

Table 8.3.1: Overview of Differences between the Female and Male Pelvis

Pelvic Characteristic	Female pelvis	Male pelvis
Pelvic weight	Bones of the pelvis are lighter and thinner	Bones of the pelvis are thicker and heavier
Pelvic inlet shape	Pelvic inlet has a round or oval shape	Pelvic inlet is heart-shaped
Lesser pelvic cavity shape	Lesser pelvic cavity is shorter and wider	Lesser pelvic cavity is longer and narrower
Subpubic angle	Subpubic angle is greater than 80 degrees	Subpubic angle is less than 70 degrees
Pelvic outlet shape	Pelvic outlet is rounded and larger	Pelvic outlet is smaller

Career Connection

Forensic Pathology and Forensic Anthropology

A forensic pathologist (also known as a medical examiner) is a medically trained physician who has been specifically trained in pathology to examine the bodies of the deceased to determine the cause of death. A forensic pathologist applies understanding of disease as well as toxins, blood and DNA analysis, firearms and ballistics, and other factors to assess the cause and manner of death. At times, a forensic pathologist will be called to testify under oath in situations that involve a possible crime. Forensic pathology is a field that has received much media attention on television shows or following a high-profile death.

While forensic pathologists are responsible for determining whether the cause of someone's death was natural, by suicide, accidental, or by homicide, there are times when uncovering the cause of death is more complex, and other skills are needed. Forensic anthropology brings the tools and knowledge of physical anthropology and human osteology (the study of the skeleton) to the task of investigating a death. A forensic anthropologist assists medical and legal professionals in identifying human remains. The science behind forensic anthropology involves the study of archeological excavation; the examination of hair; an understanding of plants, insects, and footprints; the ability to determine how much time has elapsed since the person died; the analysis of past medical history and toxicology; the ability to determine whether there are any postmortem injuries or alterations of the skeleton; and the identification of the decedent (deceased person) using skeletal and dental evidence.

Due to the extensive knowledge and understanding of excavation techniques, a forensic anthropologist is an integral and invaluable team member to have on-site when investigating a crime scene, especially when the recovery of human skeletal remains is involved. When remains are bought to a forensic anthropologist for examination, they must first determine whether the remains are in fact human. Once the remains have been identified as belonging to a person and not to an animal, the next step is to approximate the individual's age, sex, race, and height. The forensic anthropologist does not determine the cause of death, but rather provides information to the forensic pathologist, who will use all of the data collected to make a final determination regarding the cause of death.

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8.4: Bones of the Lower Limb

Structures of the Lower Limb

Like the upper limb, the lower limb is divided into three regions. The thigh is that portion of the lower limb located between the hip joint and knee joint. The leg is specifically the region between the knee joint and the ankle joint. Distal to the ankle is the foot. The lower limb contains 30 bones. These are the femur, patella, tibia, fibula, tarsal bones, metatarsal bones, and phalanges. The femur is the single bone of the thigh. The patella is the kneecap and articulates with the distal femur. The tibia is the larger, weight-bearing bone located on the medial side of the leg, and the fibula is the thin bone of the lateral leg. The bones of the foot are divided into three groups. The posterior portion of the foot is formed by a group of seven bones, each of which is known as a tarsal bone, whereas the mid-foot contains five elongated bones, each of which is a metatarsal bone. The toes contain 14 small bones, each of which is a phalanx bone of the foot.

Femur

The femur, or thigh bone, is the single bone of the thigh region (Figure 8.4.1). It is the longest and strongest bone of the body, and accounts for approximately one-quarter of a person's total height. The rounded, proximal end is the head of the femur, which articulates with the acetabulum of the hip bone to form the hip joint. The fovea capitis is a minor indentation on the medial side of the femoral head that serves as the site of attachment for the ligament of the head of the femur. This ligament spans the femur and acetabulum, but is weak and provides little support for the hip joint. It does, however, carry an important artery that supplies the head of the femur.

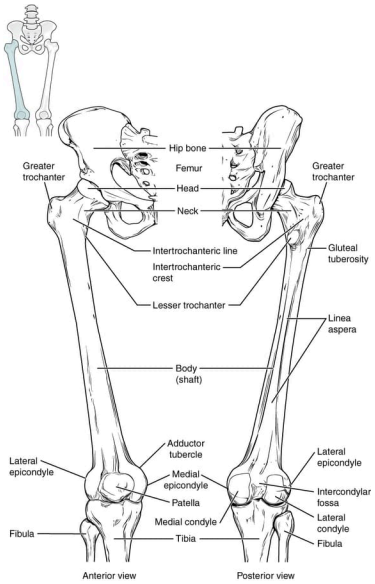


Figure 8.4.1: The femur is the single bone of the thigh region. It articulates superiorly with the hip bone at the hip joint, and inferiorly with the tibia at the knee joint. The patella only articulates with the distal end of the femur. (CC BY 4.0 ; via Bones of the Lower Limb). Alternate text description of the Figure 8.4.1.

Patella

The patella (kneecap) is largest sesamoid bone of the body (Figure 8.4.1). A sesamoid bone is a bone that is incorporated into the tendon of a muscle where that tendon crosses a joint. The sesamoid bone articulates with the underlying bones to prevent damage to the muscle tendon due to rubbing against the bones during movements of the joint. The patella is found in the tendon of the quadriceps femoris muscle, the large muscle of the anterior thigh that passes across the anterior knee to attach to the tibia. The patella articulates with the patellar surface of the femur and thus prevents rubbing of the muscle tendon against the distal femur. The patella also lifts the tendon away from the knee joint, which increases the leverage power of the quadriceps

femoris muscle as it acts across the knee. The patella does not articulate with the tibia.

Homeostatic Imbalances

Runner's Knee

Runner's knee, also known as patellofemoral syndrome, is the most common overuse injury among runners. It is most frequent in adolescents and young adults, and is more common in females. It often results from excessive running, particularly downhill, but may also occur in athletes who do a lot of knee bending, such as jumpers, skiers, cyclists, weight lifters, and soccer players. It is felt as a dull, aching pain around the front of the knee and deep to the patella. The pain may be felt when walking or running, going up or down stairs, kneeling or squatting, or after sitting with the knee bent for an extended period.

Patellofemoral syndrome may be initiated by a variety of causes, including individual variations in the shape and movement of the patella, a direct blow to the patella, or flat feet or improper shoes that cause excessive turning in or out of the feet or leg. These factors may cause in an imbalance in the muscle pull that acts on the patella, resulting in an abnormal tracking of the patella that allows it to deviate too far toward the lateral side of the patellar surface on the distal femur.

Because the hips are wider than the knee region, the femur has a diagonal orientation within the thigh, in contrast to the vertically oriented tibia of the leg (Figure 8.4.2). The Q-angle is a measure of how far the femur is angled laterally away from vertical. The Q-angle is normally 10–15 degrees, with females typically having a larger Q-angle due to their wider pelvis. During extension of the knee, the quadriceps femoris muscle pulls the patella both superiorly and laterally, with the lateral pull greater in females due to their large Q-angle. This makes females more vulnerable to developing patellofemoral syndrome than males. Normally, the large lip on the lateral side of the patellar surface of the femur compensates for the lateral pull on the patella, and thus helps to maintain its proper tracking.

However, if the pull produced by the medial and lateral sides of the quadriceps femoris muscle is not properly balanced, abnormal tracking of the patella toward the lateral side may occur. With continued use, this produces pain and could result in damage to the articulating surfaces of the patella and femur, and the possible future development of arthritis. Treatment generally involves stopping the activity that produces knee pain for a period of time, followed by a gradual resumption of activity. Proper strengthening of the quadriceps femoris muscle to correct for imbalances is also important to help prevent reoccurrence.

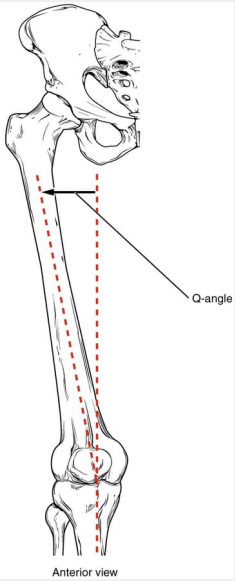


Figure 8.4.2: The Q-angle is a measure of the amount of lateral deviation of the femur from the vertical line of the tibia. Adult females have a larger Q-angle due to their wider pelvis than adult males. (CC BY 4.0 ; via Bones of the Lower Limb). Alternate text description of the Figure 8.4.2.

Tibia

The tibia (shin bone) is the medial bone of the leg and is larger than the fibula, with which it is paired (Figure 8.4.3). The tibia is the main weight-bearing bone of the lower leg and the second longest bone of the body, after the femur. The medial side of the tibia is located immediately under the skin, allowing it to be easily palpated down the entire length of the medial leg.

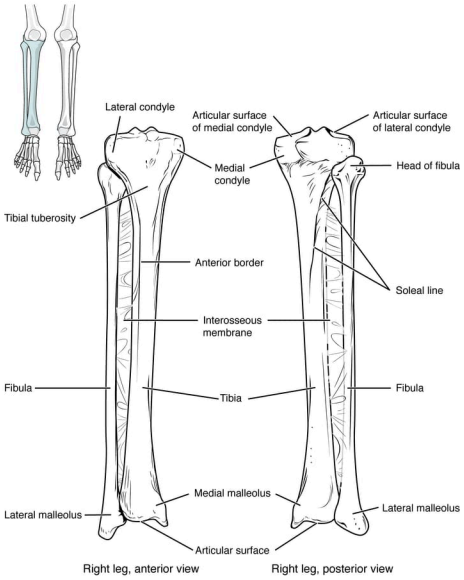


Figure 8.4.3: The tibia is the larger, weight-bearing bone located on the medial side of the leg. The fibula is the slender bone of the lateral side of the leg and does not bear weight. (CC BY 4.0 ; via Bones of the Lower Limb). Alternate text description of the Figure 8.4.3.

Fibula

The fibula is the slender bone located on the lateral side of the leg (Figure 8.4.3). The fibula does not bear weight. It serves primarily for muscle attachments and thus is largely surrounded by muscles. Only the proximal and distal ends of the fibula can be palpated.

The head of the fibula is the small, knob-like, proximal end of the fibula. It articulates with the inferior aspect of the lateral tibial condyle, forming the proximal tibiofibular joint. The thin shaft of the fibula has the interosseous border of the fibula, a narrow ridge running down its medial side for the attachment of the interosseous membrane that spans the fibula and tibia. The distal end of the fibula forms the lateral malleolus, which forms the easily palpated bony bump on the lateral side of the ankle. The deep (medial) side of the lateral malleolus articulates with the talus bone of the foot as part of the ankle joint. The distal fibula also articulates with the fibular notch of the tibia.

Tarsal Bones

The posterior half of the foot is formed by seven tarsal bones (Figure 8.4.4). The most superior bone is the talus. This has a relatively square-shaped, upper surface that articulates with the tibia and fibula to form the ankle joint. Three areas of articulation form the ankle joint: The superomedial surface of the talus bone articulates with the medial malleolus of the tibia, the top of the talus articulates with the distal end of the tibia, and the lateral side of the talus articulates with the lateral malleolus of the fibula. Inferiorly, the talus articulates with the calcaneus (heel bone), the largest bone of the foot, which forms the heel. Body weight is transferred from the tibia to the talus to the calcaneus, which rests on the ground. The medial calcaneus has a prominent bony extension called the sustentaculum tali (“support for the talus”) that supports the medial side of the talus bone.

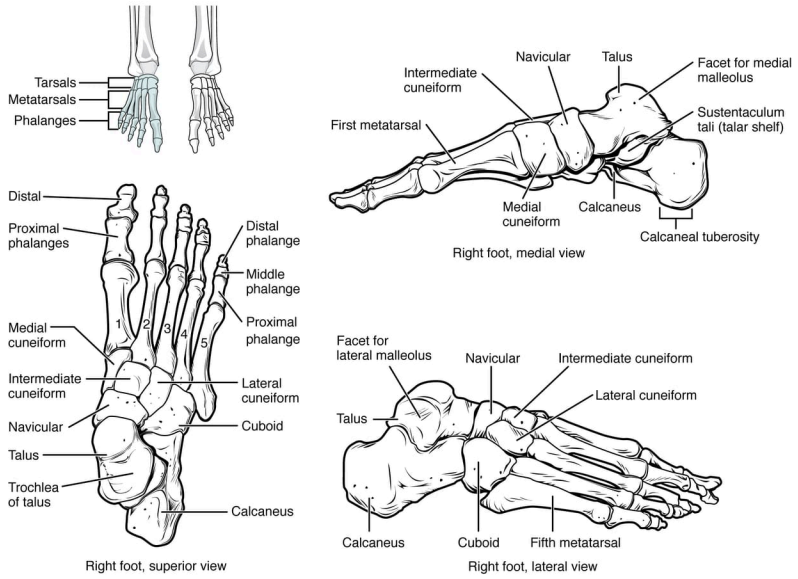


Figure 8.4.4: The bones of the foot are divided into three groups. The posterior foot is formed by the seven tarsal bones. The mid-foot has the five metatarsal bones. The toes contain the phalanges. (CC BY 4.0 ; via Bones of the Lower Limb). Alternate text description of the Figure 8.4.4.

Metatarsal Bones

The anterior half of the foot is formed by the five metatarsal bones, which are located between the tarsal bones of the posterior foot and the phalanges of the toes (Figure 8.4.4). These elongated bones are numbered 1–5, starting with the medial side of the foot. The first metatarsal bone is shorter and thicker than the others. The second metatarsal is the longest. The base of the metatarsal bone is the proximal end of each metatarsal bone. These articulate with the cuboid or cuneiform bones. The base of the fifth metatarsal has a large, lateral expansion that provides for muscle attachments. This expanded base of the fifth metatarsal can be felt as a bony bump at the midpoint along the lateral border of the foot. The expanded distal end of each metatarsal is the head of the metatarsal bone. Each metatarsal bone articulates with the proximal phalanx of a toe to form a metatarsophalangeal joint. The heads of the metatarsal bones also rest on the ground and form the ball (anterior end) of the foot.

Phalanges

The toes contain a total of 14 phalanx bones (phalanges), arranged in a similar manner as the phalanges of the fingers (Figure 8.4.4). The toes are numbered 1–5, starting with the big toe (hallux). The big toe has two phalanx bones, the proximal and distal phalanges. The remaining toes all have proximal, middle, and distal phalanges. A joint between adjacent phalanx bones is called an interphalangeal joint.

Arches of the Foot

When the foot comes into contact with the ground during walking, running, or jumping activities, the impact of the body weight puts a tremendous amount of pressure and force on the foot. During running, the force applied to each foot as it contacts the ground can be up to 2.5 times your body weight. The bones, joints, ligaments, and muscles of the foot absorb this force, thus greatly reducing the amount of shock that is passed superiorly into the lower limb and body. The arches of the foot play an important role in this shock-absorbing ability. When weight is applied to the foot, these arches will flatten somewhat, thus absorbing energy. When the weight is removed, the arch rebounds, giving “spring” to the step. The arches also serve to distribute body weight side to side and to either end of the foot.

The foot has a transverse arch, a medial longitudinal arch, and a lateral longitudinal arch. The transverse arch forms the medial-lateral curvature of the mid-foot. It is formed by the wedge shapes of the cuneiform bones and bases (proximal ends) of the first to fourth metatarsal bones. This arch helps to distribute body weight from side to side within the foot, thus allowing the foot to accommodate uneven terrain.

The longitudinal arches run down the length of the foot. The lateral longitudinal arch is relatively flat, whereas the medial

longitudinal arch is larger (taller). The longitudinal arches are formed by the tarsal bones posteriorly and the metatarsal bones anteriorly. These arches are supported at either end, where they contact the ground. Posteriorly, this support is provided by the calcaneus bone and anteriorly by the heads (distal ends) of the metatarsal bones. The talus bone, which receives the weight of the body, is located at the top of the longitudinal arches. Body weight is then conveyed from the talus to the ground by the anterior and posterior ends of these arches. Strong ligaments unite the adjacent foot bones to prevent disruption of the arches during weight bearing. On the bottom of the foot, additional ligaments tie together the anterior and posterior ends of the arches. These ligaments have elasticity, which allows them to stretch somewhat during weight bearing, thus allowing the longitudinal arches to spread. The stretching of these ligaments stores energy within the foot, rather than passing these forces into the leg. Contraction of the foot muscles also plays an important role in this energy absorption. When the weight is removed, the elastic ligaments recoil and pull the ends of the arches closer together. This recovery of the arches releases the stored energy and improves the energy efficiency of walking.

Stretching of the ligaments that support the longitudinal arches can lead to pain. This can occur in overweight individuals, with people who have jobs that involve standing for long periods of time (such as a waitress), or walking or running long distances. If stretching of the ligaments is prolonged, excessive, or repeated, it can result in a gradual lengthening of the supporting ligaments, with subsequent depression or collapse of the longitudinal arches, particularly on the medial side of the foot. This condition is called pes planus (“flat foot” or “fallen arches”).

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8.5: Terms and Definitions

Key Terms

Select to view definitions

Acetabulum
large, cup-shaped cavity located on the lateral side of the hip bone; formed by the junction of the ilium, pubis, and ischium portions of the hip bone

Acromial end of the clavicle
lateral end of the clavicle that articulates with the acromion of the scapula

Acromial process
acromion of the scapula

Acromioclavicular joint
articulation between the acromion of the scapula and the acromial end of the clavicle

Acromion
flattened bony process that extends laterally from the scapular spine to form the bony tip of the shoulder

Adductor tubercle
small, bony bump located on the superior aspect of the medial epicondyle of the femur

Anatomical neck
line on the humerus located around the outside margin of the humeral head

Ankle joint
joint that separates the leg and foot portions of the lower limb; formed by the articulations between the talus bone of the foot inferiorly, and the distal end of the tibia, medial malleolus of the tibia, and lateral malleolus of the fibula superiorly

Anterior border of the tibia
narrow, anterior margin of the tibia that extends inferiorly from the tibial tuberosity

Anterior inferior iliac spine
small, bony projection located on the anterior margin of the ilium, below the anterior superior iliac spine

Anterior sacroiliac ligament
strong ligament between the sacrum and the ilium portions of the hip bone that supports the anterior side of the sacroiliac joint

Anterior superior iliac spine
rounded, anterior end of the iliac crest

Apical ectodermal ridge
enlarged ridge of ectoderm at the distal end of a limb bud that stimulates growth and elongation of the limb

Arcuate line of the ilium
smooth ridge located at the inferior margin of the iliac fossa; forms the lateral portion of the pelvic brim

Arm
region of the upper limb located between the shoulder and elbow joints; contains the humerus bone

Auricular surface of the ilium
roughened area located on the posterior, medial side of the ilium of the hip bone; articulates with the auricular surface of the sacrum to form the sacroiliac joint

Aase of the metatarsal bone
expanded, proximal end of each metatarsal bone

Aicipital groove
intertubercular groove; narrow groove located between the greater and lesser tubercles of the humerus

Calcaneus
heel bone; posterior, inferior tarsal bone that forms the heel of the foot

Capitate
from the lateral side, the third of the four distal carpal bones; articulates with the scaphoid and lunate proximally, the trapezoid laterally, the hamate medially, and primarily with the third metacarpal distally

Capitulum
knob-like bony structure located anteriorly on the lateral, distal end of the humerus

Carpal bone
one of the eight small bones that form the wrist and base of the hand; these are grouped as a proximal row consisting of (from lateral to medial) the scaphoid, lunate, triquetrum, and pisiform bones, and a distal row containing (from lateral to medial) the trapezium, trapezoid, capitate, and hamate bones

Carpal tunnel
passageway between the anterior forearm and hand formed by the carpal bones and flexor retinaculum

Carpometacarpal joint
articulation between one of the carpal bones in the distal row and a metacarpal bone of the hand

Clavicle
collarbone; elongated bone that articulates with the manubrium of the sternum medially and the acromion of the scapula laterally

Coracoclavicular ligament
strong band of connective tissue that anchors the coracoid process of the scapula to the lateral clavicle; provides important indirect support for the acromioclavicular joint

Coracoid process
short, hook-like process that projects anteriorly and laterally from the superior margin of the scapula

Coronoid fossa
depression on the anterior surface of the humerus above the trochlea; this space receives the coronoid process of the ulna when the elbow is maximally flexed

Coronoid process of the ulna
projecting bony lip located on the anterior, proximal ulna; forms the inferior margin of the trochlear notch

Costoclavicular ligament
band of connective tissue that unites the medial clavicle with the first rib

Coxal bone
hip bone

Cuboid
tarsal bone that articulates posteriorly with the calcaneus bone, medially with the lateral cuneiform bone, and anteriorly with the fourth and fifth metatarsal bones

Deltoid tuberosity
roughened, V-shaped region located laterally on the mid-shaft of the humerus

Distal radioulnar joint
articulation between the head of the ulna and the ulnar notch of the radius

Distal tibiofibular joint
articulation between the distal fibula and the fibular notch of the tibia

Elbow joint
joint located between the upper arm and forearm regions of the upper limb; formed by the articulations between the trochlea of the humerus and the trochlear notch of the ulna, and the capitulum of the humerus and the head of the radius

Femur
thigh bone; the single bone of the thigh

Fibula
thin, non-weight-bearing bone found on the lateral side of the leg

Fibular notch
wide groove on the lateral side of the distal tibia for articulation with the fibula at the distal tibiofibular joint

Flexor retinaculum
strong band of connective tissue at the anterior wrist that spans the top of the U-shaped grouping of the carpal bones to form the roof of the carpal tunnel

Foot
portion of the lower limb located distal to the ankle joint

Forearm
region of the upper limb located between the elbow and wrist joints; contains the radius and ulna bones

Fossa
(plural = fossae) shallow depression on the surface of a bone

Fovea capitis
minor indentation on the head of the femur that serves as the site of attachment for the ligament to the head of the femur

Glenohumeral joint
shoulder joint; formed by the articulation between the glenoid cavity of the scapula and the head of the humerus

Glenoid cavity
(also, glenoid fossa) shallow depression located on the lateral scapula, between the superior and lateral borders

Gluteal tuberosity
roughened area on the posterior side of the proximal femur, extending inferiorly from the base of the greater trochanter

Greater pelvis
(also, greater pelvic cavity or false pelvis) broad space above the pelvic brim defined laterally by the fan-like portion of the upper ilium

Greater sciatic foramen
pelvic opening formed by the greater sciatic notch of the hip bone, the sacrum, and the sacrospinous ligament

Greater sciatic notch
large, U-shaped indentation located on the posterior margin of the ilium, superior to the ischial spine

Greater trochanter
large, bony expansion of the femur that projects superiorly from the base of the femoral neck

Greater tubercle
enlarged prominence located on the lateral side of the proximal humerus

Hallux
big toe; digit 1 of the foot

Hamate
from the lateral side, the fourth of the four distal carpal bones; articulates with the lunate and triquetrum proximally, the fourth and fifth metacarpals distally, and the capitate laterally

Hand
region of the upper limb distal to the wrist joint

Head of the femur
rounded, proximal end of the femur that articulates with the acetabulum of the hip bone to form the hip joint

Head of the fibula
small, knob-like, proximal end of the fibula; articulates with the inferior aspect of the lateral condyle of the tibia

Head of the humerus
smooth, rounded region on the medial side of the proximal humerus; articulates with the glenoid fossa of the scapula to form the glenohumeral (shoulder) joint

Head of the metatarsal bone
expanded, distal end of each metatarsal bone

Head of the radius
disc-shaped structure that forms the proximal end of the radius; articulates with the capitulum of the humerus as part of the elbow joint, and with the radial notch of the ulna as part of the proximal radioulnar joint

Head of the ulna
small, rounded distal end of the ulna; articulates with the ulnar notch of the distal radius, forming the distal radioulnar joint

Hip bone
coxal bone; single bone that forms the pelvic girdle; consists of three areas, the ilium, ischium, and pubis

Hip joint
joint located at the proximal end of the lower limb; formed by the articulation between the acetabulum of the hip bone and the head of the femur

Hook of the hamate bone
bony extension located on the anterior side of the hamate carpal bone

Humerus
single bone of the upper arm

Iliac crest
curved, superior margin of the ilium

Iliac fossa
shallow depression found on the anterior and medial surfaces of the upper ilium

Ilium
superior portion of the hip bone

Inferior angle of the scapula
inferior corner of the scapula located where the medial and lateral borders meet

Inferior pubic ramus
narrow segment of bone that passes inferiorly and laterally from the pubic body; joins with the ischial ramus to form the ischiopubic ramus

Infraglenoid tubercle
small bump or roughened area located on the lateral border of the scapula, near the inferior margin of the glenoid cavity

Infraspinous fossa
broad depression located on the posterior scapula, inferior to the spine

Intercondylar eminence
irregular elevation on the superior end of the tibia, between the articulating surfaces of the medial and lateral condyles

Intercondylar fossa
deep depression on the posterior side of the distal femur that separates the medial and lateral condyles

Intermediate cuneiform
middle of the three cuneiform tarsal bones; articulates posteriorly with the navicular bone, medially with the medial cuneiform bone, laterally with the lateral cuneiform bone, and anteriorly with the second metatarsal bone

Interosseous border of the fibula
small ridge running down the medial side of the fibular shaft; for attachment of the interosseous membrane between the fibula and tibia

Interosseous border of the radius
narrow ridge located on the medial side of the radial shaft; for attachment of the interosseous membrane between the ulna and radius bones

Interosseous border of the tibia
small ridge running down the lateral side of the tibial shaft; for attachment of the interosseous membrane between the tibia and fibula

Interosseous border of the ulna
narrow ridge located on the lateral side of the ulnar shaft; for attachment of the interosseous membrane between the ulna and radius

Interosseous membrane of the forearm
sheet of dense connective tissue that unites the radius and ulna bones

Interosseous membrane of the leg
sheet of dense connective tissue that unites the shafts of the tibia and fibula bones

Interphalangeal joint
articulation between adjacent phalanx bones of the hand or foot digits

Intertrochanteric crest
short, prominent ridge running between the greater and lesser trochanters on the posterior side of the proximal femur

Intertrochanteric line
small ridge running between the greater and lesser trochanters on the anterior side of the proximal femur

Intertubercular groove (sulcus)
bicipital groove; narrow groove located between the greater and lesser tubercles of the humerus

Ischial ramus
bony extension projecting anteriorly and superiorly from the ischial tuberosity; joins with the inferior pubic ramus to form the ischiopubic ramus

Ischial spine
pointed, bony projection from the posterior margin of the ischium that separates the greater sciatic notch and lesser sciatic notch

Ischial tuberosity
large, roughened protuberance that forms the posteroinferior portion of the hip bone; weight-bearing region of the pelvis when sitting

Ischiopubic ramus
narrow extension of bone that connects the ischial tuberosity to the pubic body; formed by the junction of the ischial ramus and inferior pubic ramus

Ischium
posteroinferior portion of the hip bone

Knee joint
joint that separates the thigh and leg portions of the lower limb; formed by the articulations between the medial and lateral condyles of the femur, and the medial and lateral condyles of the tibia

Lateral border of the scapula
diagonally oriented lateral margin of the scapula

Lateral condyle of the femur
smooth, articulating surface that forms the distal and posterior sides of the lateral expansion of the distal femur

Lateral condyle of the tibia
lateral, expanded region of the proximal tibia that includes the smooth surface that articulates with the lateral condyle of the femur as part of the knee joint

Lateral cuneiform
most lateral of the three cuneiform tarsal bones; articulates posteriorly with the navicular bone, medially with the intermediate cuneiform bone, laterally with the cuboid bone, and anteriorly with the third metatarsal bone

Lateral epicondyle of the femur
roughened area of the femur located on the lateral side of the lateral condyle

Lateral epicondyle of the humerus
small projection located on the lateral side of the distal humerus

Lateral malleolus
expanded distal end of the fibula

Lateral supracondylar ridge
narrow, bony ridge located along the lateral side of the distal humerus, superior to the lateral epicondyle

Leg
portion of the lower limb located between the knee and ankle joints

Lesser pelvis
(also, lesser pelvic cavity or true pelvis) narrow space located within the pelvis, defined superiorly by the pelvic brim (pelvic inlet) and inferiorly by the pelvic outlet

Lesser sciatic foramen
pelvic opening formed by the lesser sciatic notch of the hip bone, the sacrospinous ligament, and the sacrotuberous ligament

Lesser sciatic notch
shallow indentation along the posterior margin of the ischium, inferior to the ischial spine

Lesser trochanter
small, bony projection on the medial side of the proximal femur, at the base of the femoral neck

Lesser tubercle
small, bony prominence located on anterior side of the proximal humerus

Ligament of the head of the femur
ligament that spans the acetabulum of the hip bone and the fovea capitis of the femoral head

Limb bud
small elevation that appears on the lateral side of the embryo during the fourth or fifth week of development, which

gives rise to an upper or lower limb

Linea aspera
longitudinally running bony ridge located in the middle third of the posterior femur

Lunate
from the lateral side, the second of the four proximal carpal bones; articulates with the radius proximally, the capitate and hamate distally, the scaphoid laterally, and the triquetrum medially

Medial border of the scapula
elongated, medial margin of the scapula

Medial condyle of the femur
smooth, articulating surface that forms the distal and posterior sides of the medial expansion of the distal femur

Medial condyle of the tibia
medial, expanded region of the proximal tibia that includes the smooth surface that articulates with the medial condyle of the femur as part of the knee joint

Medial cuneiform
most medial of the three cuneiform tarsal bones; articulates posteriorly with the navicular bone, laterally with the intermediate cuneiform bone, and anteriorly with the first and second metatarsal bones

Medial epicondyle of the femur
roughened area of the distal femur located on the medial side of the medial condyle

Medial epicondyle of the humerus
enlarged projection located on the medial side of the distal humerus

Medial malleolus
bony expansion located on the medial side of the distal tibia

Metacarpal bone
one of the five long bones that form the palm of the hand; numbered 1–5, starting on the lateral (thumb) side of the hand

Metacarpophalangeal joint
articulation between the distal end of a metacarpal bone of the hand and a proximal phalanx bone of the thumb or a finger

Metatarsal bone
one of the five elongated bones that forms the anterior half of the foot; numbered 1–5, starting on the medial side of the foot

Metatarsophalangeal joint
articulation between a metatarsal bone of the foot and the proximal phalanx bone of a toe

Midcarpal joint
articulation between the proximal and distal rows of the carpal bones; contributes to movements of the hand at the wrist

Navicular
tarsal bone that articulates posteriorly with the talus bone, laterally with the cuboid bone, and anteriorly with the medial, intermediate, and lateral cuneiform bones

Neck of the femur
narrowed region located inferior to the head of the femur

Neck of the radius
narrowed region immediately distal to the head of the radius

Obturator foramen
large opening located in the anterior hip bone, between the pubis and ischium regions

Olecranon fossa
large depression located on the posterior side of the distal humerus; this space receives the olecranon process of the ulna when the elbow is fully extended

Olecranon process
expanded posterior and superior portions of the proximal ulna; forms the bony tip of the elbow

Patella
kneecap; the largest sesamoid bone of the body; articulates with the distal femur

Patellar surface
smooth groove located on the anterior side of the distal femur, between the medial and lateral condyles; site of articulation for the patella

Pectineal line
narrow ridge located on the superior surface of the superior pubic ramus

Pectoral girdle
shoulder girdle; the set of bones, consisting of the scapula and clavicle, which attaches each upper limb to the axial skeleton

Pelvic brim
pelvic inlet; the dividing line between the greater and lesser pelvic regions; formed by the superior margin of the pubic symphysis, the pectineal lines of each pubis, the arcuate lines of each ilium, and the sacral promontory

Ppelvic girdle
hip girdle; consists of a single hip bone, which attaches a lower limb to the sacrum of the axial skeleton

Pelvic inlet
pelvic brim

Pelvic outlet
inferior opening of the lesser pelvis; formed by the inferior margin of the pubic symphysis, right and left ischiopubic rami and sacrotuberous ligaments, and the tip of the coccyx

Pelvis
ring of bone consisting of the right and left hip bones, the sacrum, and the coccyx

Phalanx bone of the foot
(plural = phalanges) one of the 14 bones that form the toes; these include the proximal and distal phalanges of the big toe, and the proximal, middle, and distal phalanx bones of toes two through five

Phalanx bone of the hand
(plural = phalanges) one of the 14 bones that form the thumb and fingers; these include the proximal and distal phalanges of the thumb, and the proximal, middle, and distal phalanx bones of the fingers two through five

Pisiform
from the lateral side, the fourth of the four proximal carpal bones; articulates with the anterior surface of the triquetrum

Pollex
(also, thumb) digit 1 of the hand

Posterior inferior iliac spine
small, bony projection located at the inferior margin of the auricular surface on the posterior ilium

Posterior sacroiliac ligament
strong ligament spanning the sacrum and ilium of the hip bone that supports the posterior side of the sacroiliac

joint

Posterior superior iliac spine
rounded, posterior end of the iliac crest

Proximal radioulnar joint
articulation formed by the radial notch of the ulna and the head of the radius

Proximal tibiofibular joint
articulation between the head of the fibula and the inferior aspect of the lateral condyle of the tibia

Pubic arch
bony structure formed by the pubic symphysis, and the bodies and inferior pubic rami of the right and left pubic bones

Pubic body
enlarged, medial portion of the pubis region of the hip bone

Pubic symphysis
joint formed by the articulation between the pubic bodies of the right and left hip bones

Pubic tubercle
small bump located on the superior aspect of the pubic body

Pubis
anterior portion of the hip bone

Radial fossa
small depression located on the anterior humerus above the capitulum; this space receives the head of the radius when the elbow is maximally flexed

Radial notch of the ulna
small, smooth area on the lateral side of the proximal ulna; articulates with the head of the radius as part of the proximal radioulnar joint

Radial tuberosity
oval-shaped, roughened protuberance located on the medial side of the proximal radius

Radiocarpal joint
wrist joint, located between the forearm and hand regions of the upper limb; articulation formed proximally by the distal end of the radius and the fibrocartilaginous pad that unites the distal radius and ulna bone, and distally by the scaphoid, lunate, and triquetrum carpal bones

Radius
bone located on the lateral side of the forearm

Sacroiliac joint
joint formed by the articulation between the auricular surfaces of the sacrum and ilium

Sacrospinous ligament
ligament that spans the sacrum to the ischial spine of the hip bone

Sacrotuberous ligament
ligament that spans the sacrum to the ischial tuberosity of the hip bone

Scaphoid
from the lateral side, the first of the four proximal carpal bones; articulates with the radius proximally, the trapezoid, trapezium, and capitate distally, and the lunate medially

Scapula
shoulder blade bone located on the posterior side of the shoulder

Shaft of the femur
cylindrically shaped region that forms the central portion of the femur

Shaft of the fibula
elongated, slender portion located between the expanded ends of the fibula

Shaft of the humerus
narrow, elongated, central region of the humerus

Shaft of the radius
narrow, elongated, central region of the radius

Shaft of the tibia
triangular-shaped, central portion of the tibia

Shaft of the ulna
narrow, elongated, central region of the ulna

Soleal line
small, diagonally running ridge located on the posterior side of the proximal tibia

Spine of the scapula
prominent ridge passing mediolaterally across the upper portion of the posterior scapular surface

Sternal end of the clavicle
medial end of the clavicle that articulates with the manubrium of the sternum

Sternoclavicular joint
articulation between the manubrium of the sternum and the sternal end of the clavicle; forms the only bony attachment between the pectoral girdle of the upper limb and the axial skeleton

Styloid process of the radius
pointed projection located on the lateral end of the distal radius

Styloid process of the ulna
short, bony projection located on the medial end of the distal ulna

Subpubic angle
inverted V-shape formed by the convergence of the right and left ischiopubic rami; this angle is greater than 80 degrees in females and less than 70 degrees in males

Subscapular fossa
broad depression located on the anterior (deep) surface of the scapula

Superior angle of the scapula
corner of the scapula between the superior and medial borders of the scapula

Superior border of the scapula
superior margin of the scapula

Superior pubic ramus
narrow segment of bone that passes laterally from the pubic body to join the ilium

Supraglenoid tubercle
small bump located at the superior margin of the glenoid cavity

Suprascapular notch
small notch located along the superior border of the scapula, medial to the coracoid process

Supraspinous fossa
narrow depression located on the posterior scapula, superior to the spine

Surgical neck
region of the humerus where the expanded, proximal end joins with the narrower shaft

Sustentaculum tali
bony ledge extending from the medial side of the calcaneus bone

Talus
tarsal bone that articulates superiorly with the tibia and fibula at the ankle joint; also articulates inferiorly with the calcaneus bone and anteriorly with the navicular bone

Tarsal bone
one of the seven bones that make up the posterior foot; includes the calcaneus, talus, navicular, cuboid, medial cuneiform, intermediate cuneiform, and lateral cuneiform bones

Thigh
portion of the lower limb located between the hip and knee joints

Tibia
shin bone; the large, weight-bearing bone located on the medial side of the leg

Tibial tuberosity
elevated area on the anterior surface of the proximal tibia

Trapezium
from the lateral side, the first of the four distal carpal bones; articulates with the scaphoid proximally, the first and second metacarpals distally, and the trapezoid medially

Trapezoid
from the lateral side, the second of the four distal carpal bones; articulates with the scaphoid proximally, the second metacarpal distally, the trapezium laterally, and the capitate medially

Triquetrum
from the lateral side, the third of the four proximal carpal bones; articulates with the lunate laterally, the hamate distally, and has a facet for the pisiform

Trochlea
pulley-shaped region located medially at the distal end of the humerus; articulates at the elbow with the trochlear notch of the ulna

Trochlear notch
large, C-shaped depression located on the anterior side of the proximal ulna; articulates at the elbow with the trochlea of the humerus

Ulna
bone located on the medial side of the forearm

Ulnar notch of the radius
shallow, smooth area located on the medial side of the distal radius; articulates with the head of the ulna at the distal radioulnar joint

Ulnar tuberosity
roughened area located on the anterior, proximal ulna inferior to the coronoid process

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8.6: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. Which part of the clavicle directly articulates with the manubrium of the sternum?
   A. Shaft
   B. Sternal end
   C. Acromial end
   D. Coracoid process

2. A shoulder separation most commonly results from injury to which joint?
   A. Glenohumeral joint
   B. Costoclavicular joint
   C. Acromioclavicular joint
   D. Sternoclavicular joint

3. Which scapular feature lies between the spine of the scapula and the superior border?
   A. Suprascapular notch
   B. Glenoid cavity
   C. Superior angle
   D. Supraspinous fossa

4. Which structure is a lateral bony extension and continuation of the spine of the scapula?
   A. Acromion
   B. Coracoid process
   C. Supraglenoid tubercle
   D. Glenoid cavity

5. Which short, hook-like bony process of the scapula projects anteriorly and serves as an attachment site for ligaments and muscles?
   A. Acromial process
   B. Clavicle
   C. Coracoid process
   D. Glenoid fossa

6. Which bony landmark is located on the lateral side of the proximal humerus and serves as a major site for muscle attachment?
   A. Greater tubercle
   B. Trochlea
   C. Lateral epicondyle
   D. Lesser tubercle

7. Which region of the distal humerus articulates with the head of the radius as part of the elbow joint?

A. Trochlea
B. Styloid process
C. Capitulum
D. Olecranon process

8. Which is the lateral-most carpal bone in the proximal row of the wrist?

A. Trapezium
B. Hamate
C. Pisiform
D. Scaphoid

9. Which statement about the radius is correct?
A. It is found on the medial side of the forearm in anatomical position.
B. Its head articulates with the radial notch of the ulna.
C. It does not articulate with any of the carpal bones.
D. The radial tuberosity is located near its distal end.

10. Which bony region of the hip bone directly supports body weight when a person is sitting upright?
A. Iliac crest
B. Ischial tuberosity
C. Ischiopubic ramus
D. Pubic body

11. The ischial spine is located between which two structures?
A. Inferior pubic ramus and ischial ramus
B. Pectineal line and arcuate line
C. Lesser sciatic notch and greater sciatic notch
D. Anterior superior iliac spine and posterior superior iliac spine

12. Which statement about the pelvis is accurate?
A. The subpubic angle is generally larger in females than in males.
B. The pelvis consists only of the two hip bones and excludes the sacrum and coccyx.
C. The obturator foramen is bounded in part by the sacrospinous and sacrotuberous ligaments.
D. The space located inferior to the pelvic brim is called the greater pelvis.

13. Which bony landmark of the femur serves primarily as a site for muscle attachment rather than direct articulation?
A. Fovea capitis
B. Lesser trochanter
C. Head
D. Medial condyle

14. Which of the following structures contributes directly to the articular surfaces of the knee joint?
A. Lateral malleolus of the fibula
B. Tibial tuberosity
C. Medial condyle of the tibia
D. Lateral epicondyle of the femur

15. Which tarsal bone articulates superiorly with both the tibia and fibula to form the ankle (talocrural) joint?
A. Calcaneus
B. Cuboid
C. Navicular
D. Talus

16. Which statement about the tibia is correct?
A. It has an expanded distal end called the lateral malleolus.

B. It is not a weight-bearing bone.

C. It is firmly connected to the fibula by an interosseous membrane along their shafts.
D. It can be palpated under the skin only at its proximal and distal ends.

17. During which approximate stage of limb development does the distal limb bud flatten into a paddle-shaped hand or foot plate with digital rays?
A. Appearance of upper and lower limb buds (around week 4)
B. Flattening of the distal limb bud into a paddle shape (around week 6)
C. First appearance of hyaline cartilage models of future bones (around week 6–7)
D. Rotation of the limbs into their adult orientation (around week 7–8)

18. During endochondral ossification of a typical long bone, which event directly produces an increase in bone length during childhood and adolescence?
A. Formation of a primary ossification center within the epiphysis
B. Direct differentiation of mesenchyme into bone tissue
C. Continued growth and ossification at the epiphyseal plate
D. Complete disappearance of all epiphyseal plates before birth

19. Which statement about the clavicle is correct from a developmental standpoint?
A. It develops entirely via intramembranous ossification.
B. It develops entirely via endochondral ossification.
C. It begins ossification later than most other bones of the skeleton.
D. It is fully ossified at the time of birth.

20. Which pair correctly matches a bone to the primary type of ossification by which it forms?
A. Femur and intramembranous ossification
B. Parietal bone and intramembranous ossification
C. Metacarpal bone and intramembranous ossification
D. Scapula and pure intramembranous ossification with no endochondral contribution

21. Which feature best distinguishes the true (lesser) pelvis from the false (greater) pelvis?
A. The true pelvis is located superior to the pelvic brim and supports abdominal organs.
B. The true pelvis is bounded by the pelvic brim and lies inferior to it, surrounding the pelvic cavity.
C. The false pelvis contains the pelvic inlet and outlet.
D. The false pelvis is entirely formed by the sacrum and coccyx.

22. Which bone of the upper limb directly articulates with the carpal bones to form the radiocarpal (wrist) joint?
A. Humerus
B. Ulna
C. Radius
D. Scaphoid

23. Which landmark on the tibia provides attachment for the patellar ligament?
A. Medial malleolus
B. Tibial tuberosity
C. Medial condyle
D. Intercondylar eminence

24. Which anatomical difference is most useful in distinguishing a female pelvis from a male pelvis on a dry skeleton?
A. Narrower pelvic inlet and smaller pelvic outlet
B. Heart-shaped pelvic inlet
C. Larger, more acute subpubic angle (typically greater than 80 degrees)
D. Longer, more vertical sacrum

25. Which bony feature of the femur is located between the medial and lateral condyles on the posterior aspect and helps guide the patella?
A. Fovea capitis
B. Intercondylar fossa
C. Patellar surface
D. Linea aspera

26. Which statement accurately describes the role of the interosseous membranes in the forearm and leg?

A. They are cartilaginous joints that allow extensive rotation.
B. They are fibrous syndesmoses that help stabilize paired long bones and serve as muscle attachment sites.
C. They are synovial membranes that secrete fluid between the radius and ulna or tibia and fibula.
D. They contain growth plates responsible for longitudinal bone growth.

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8.7: Applied Thinking Self-Check

Challenge Yourself

Use these case-based short-essay questions to test how well you understand the appendicular skeleton in real-life situations.

- Use complete sentences and clear, simple English - your own words; do not copy from the textbook or other resources. Use correct anatomical terms from the chapter (for example: clavicle, scapula, humerus, radius, ulna, pelvis, acetabulum, femur, tibia, fibula).
- Explain why or how, not just what (give reasons, not only facts).
- When comparing structures (for example, upper vs lower limb, pectoral vs pelvic girdle), give at least two similarities and two differences.
- Use everyday movement examples (walking, running, throwing, writing, lifting) to show function.

If you are unsure of a term, you may look it up or make a quick sketch on scrap paper to help you think, then describe it in words.

1. A 20-year-old student notices that she can move her shoulder freely in many directions (reaching overhead, across her body, and behind her back), but her hip feels much more limited even though it is a ball-and-socket joint too.
2. The pectoral girdle is adapted for a wide range of motion, while the pelvic girdle is adapted for strength and weight support. Using this patient's shoulder and hip as examples, compare the structure and function of the pectoral and pelvic girdles. Explain how their bone shapes, joint types, and connections to the axial skeleton allow one girdle to favor mobility and the other to favor stability and weight-bearing.
3. A 16-year-old basketball player falls on his outstretched hand and fractures the surgical neck of the humerus. Short answer:
   a. Which major joint of the appendicular skeleton will be most affected functionally?
   b. Explain briefly how this fracture location can limit movements at that joint (name two movements).
4. Discuss two possible injuries of the pectoral girdle that may occur following a strong blow to the shoulder or a hard fall onto an outstretched hand.
5. The radius and ulna in the forearm, and the tibia and fibula in the leg, each form a pair of long bones linked by an interosseous membrane. Compare these two pairs: How are they similar and different in position, function, and weight-bearing role? Why is it useful for the forearm bones to move relative to each other, but less so for the leg bones?
6. How can a radiograph of a child's femur be used to determine the approximate age of that child?
7. A patient with pelvic trauma has a fracture involving the acetabulum. Short answer:
   a. The acetabulum is formed by which part of the skeleton: axial or appendicular?
   b. Which appendicular bone articulates with the acetabulum, and how might this fracture affect weight-bearing?
8. The structure of the hand and foot is similar (carpals/tarsals, metacarpals/metatarsals, phalanges), but they have different main functions (fine manipulation vs. support and locomotion). Choose three specific anatomical features that differ between hand and foot, and explain how each difference helps the hand or foot perform its main function.
9. The biological female pelvis is adapted for childbirth. Describe at least three anatomical differences between the biological male and female pelvis (for example, subpubic angle, pelvic inlet shape, or width), and explain how each difference could affect both childbirth and upright walking.
10. A 20-year-old soccer player sprains his ankle while inverting his foot sharply. Which bone of the appendicular skeleton forms the main "hinge" joint with the talus at the ankle: tibia or fibula?
11. The talus bone of the foot receives the weight of the body from the tibia. The talus bone then distributes this weight toward the ground in two directions: one-half of the body weight is passed in a posterior direction and one-half of the weight is passed in an anterior direction. Describe the arrangement of the tarsal and metatarsal bones that are involved in both the posterior and anterior distribution of body weight.

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8.8: Alternate Text Descriptions

Figure 8.1: Appendicular Skeleton

This image shows an anterior view of the human skeleton. The appendicular skeleton is highlighted in pink, while the axial skeleton, including the skull, vertebral column, ribs, and sternum, is displayed in gray. Brackets and labels identify the major divisions of the appendicular skeleton: shoulder girdle, arm, hand, pelvic girdle, leg, and foot. The shoulder girdles are located at the upper chest and connect to the upper limbs. The pelvic girdle is located at the hips and connects to the lower limbs. The highlighted bones include the clavicles, scapulae, humeri, radius, ulna, wrist bones, hand bones, hip bones, femora, patellae, tibiae, fibulae, ankle bones, and foot bones. The figure emphasizes that the appendicular skeleton consists of the girdles and limbs attached to the body's central axis.

Figure 8.1.1:Axial and Appendicular Skeletons

This image shows the human skeleton in two full-body views: an anterior view on the left and a posterior view on the right. The figure labels major bones and distinguishes the axial skeleton from the appendicular skeleton.

The overall organization presents the skeleton upright from head, or superior, to feet, or inferior. The labels in the figure include the axial skeleton, appendicular skeleton, cranial portion, facial portion, vertebral column, sternum, ribs, clavicle, scapula, humerus, radius, ulna, carpals, metacarpals, phalanges, hip bones, femur, patella, tibia, fibula, tarsals, metatarsals, costal cartilages, and intercostal spaces. The anterior and posterior views together show how the bones relate spatially and functionally across the whole body.

The axial skeleton includes the skull, vertebral column, and thoracic cage. The skull is divided into a cranial portion, which encloses the brain, and a facial portion, which forms the face. Its functions are to protect the brain and sensory organs and provide structure for facial features and jaw movement. The vertebral column is a vertical column of vertebrae extending from the skull to the pelvis. Its functions are to support the body, protect the spinal cord, and allow flexibility and posture control. The thoracic cage consists of the sternum at the front and the ribs surrounding the chest. Its functions are to protect the heart and lungs and assist in breathing movements.

The appendicular skeleton includes the girdles and limbs. The pectoral girdle includes the clavicle and scapula. Its functions are to connect the upper limbs to the axial skeleton and allow a wide range of arm movement. The upper limb includes the humerus, radius, ulna, carpals, metacarpals, and phalanges. Its functions are to support lifting and carrying and allow fine motor movements such as grasping. The pelvic girdle is formed by the hip bones. Its functions are to connect the lower limbs to the axial skeleton, support the weight of the upper body, and protect pelvic organs. The lower limb includes the femur, patella, tibia, fibula, tarsals, metatarsals, and phalanges. Its functions are to support body weight and enable walking, standing, and balance.

Additional labeled features include the costal cartilages and intercostal spaces. The costal cartilages connect the ribs to the sternum and provide flexibility for breathing movements. The intercostal spaces are the spaces between ribs and contain muscles that assist in respiration.

Figure 8.1.2: Pectoral Girdle

This is a multi-panel diagram of the pectoral girdle and clavicle.

At the top left, a small locator image indicates the shoulder region of the skeleton. The enlarged anterior view of the pectoral girdle labels the clavicle, scapula, acromioclavicular joint, glenohumeral joint, coracoclavicular ligament, and costoclavicular ligament. This panel emphasizes the major joints and ligaments connecting the clavicle and scapula.

At the top right, a posterior view of the pectoral girdle labels the clavicle, scapula, rib, and vertebrae. This panel emphasizes the relationship of the pectoral girdle to the thorax from behind.

The bottom half of the figure shows the clavicle alone in two orientations. One panel shows the superior view of the clavicle, and the other shows the inferior view of the clavicle. Both identify the acromial end laterally and the sternal end medially, with anterior

and posterior orientation labels at the sternal end.

Overall, the figure shows the position of the clavicle within the pectoral girdle, its associated joints and ligaments, and the shape and orientation of the clavicle viewed from above and below.

(shoulder blade) lies on the posterior aspect of the shoulder. It is supported by the clavicle and articulates with the humerus (arm bone) to form the shoulder joint. The scapula is a flat, triangular-shaped bone with a prominent ridge running across its posterior surface. This ridge extends out laterally, where it forms the bony tip of the shoulder and joins with the lateral end of the clavicle. By following along the clavicle, you can palpate out to the bony tip of the shoulder, and from there, you can move back across your posterior shoulder to follow the ridge of the scapula. Move your shoulder around and feel how the clavicle and scapula move together as a unit. Both of these bones serve as important attachment sites for muscles that aid with movements of the shoulder and arm.

The right and left pectoral girdles are not joined to each other, allowing each to operate independently. In addition, the clavicle of each pectoral girdle is anchored to the axial skeleton by a single, highly mobile joint. This allows for the extensive mobility of the entire pectoral girdle, which in turn enhances movements of the shoulder and upper limb.

Figure 8.1.3: Scapula

This image presents four related views of the pectoral girdle and clavicle: a small inset locating the pectoral girdle within the skeleton, an anterior view of the pectoral girdle, a posterior view of the pectoral girdle, and superior and inferior views of a single clavicle. The figure shows how the clavicle and scapula connect the upper limb to the axial skeleton and support upper-limb movement.

The overall organization shows that the pectoral girdle consists of the clavicle and scapula. The clavicle is shown separately to emphasize its shape, orientation, and ligament attachment surfaces. The labels in the figure include clavicle, scapula, acromioclavicular joint, glenohumeral joint, coracoclavicular ligament, costoclavicular ligament, acromial end, sternoclavicular region or sternal end, and orientation labels identifying anterior, posterior, medial, and lateral.

Figure 8.2.1: The humerus

This image shows the humerus, the long bone of the upper arm, in two views: an anterior view on the left and a posterior view on the right. A small inset at the top shows the location of the humerus within the upper limb of the skeleton.

The overall organization shows the humerus extending from the shoulder at the proximal end to the elbow at the distal end. The labels in the figure include head of humerus, anatomical neck, surgical neck, greater tubercle, lesser tubercle, intertubercular groove, body or shaft, deltoid tuberosity, lateral supracondylar ridge, capitulum, trochlea, medial epicondyle, lateral epicondyle, radial fossa, coronoid fossa, and olecranon fossa. The figure emphasizes the proximal features that articulate with the scapula, the shaft that supports muscle attachment, and the distal features that articulate with the radius and ulna.

Figure 8.2.2: Ulna and Radius

This image shows the right forearm in anterior and posterior views.

In the anterior view, the radius is the lateral forearm bone and the ulna is the medial forearm bone. Near the elbow, the head of the radius sits beside the radial notch of the ulna, forming the proximal radioulnar joint. The neck of the radius lies just below the head, and the radial tuberosity is a roughened area for muscle attachment. On the ulna, the olecranon process and coronoid process form the boundaries of the trochlear notch, which helps the ulna articulate with the humerus at the elbow. Between the two forearm bones, the interosseous membrane spans the shafts and helps connect and stabilize them. Near the wrist, the ulnar notch of the radius meets the head of the ulna at the distal radioulnar joint. The styloid process of the radius and styloid process of the ulna mark distal projections of each bone.

In the posterior view, the same overall relationship is shown from the back. The olecranon process is especially prominent at the proximal ulna, forming the point of the elbow. The head and neck of the radius remain visible proximally, and the interosseous membrane continues between the shafts of the radius and ulna. Distally, the figure again shows the head of the ulna and the distal ends of both bones.

Overall, the figure emphasizes that the radius and ulna are paired bones of the forearm connected by an interosseous membrane and by proximal and distal radioulnar joints. These connections allow the forearm to function as a linked unit while also permitting rotational movement of the radius relative to the ulna.

Figure 8.2.3: Bones of the Wrist and Hand

This image shows the hand skeleton with labeled anterior and posterior views. Its instructional purpose is to explain how the bones of the hand are organized into carpals, metacarpals, and phalanges, and to identify the named bones and digits. A small inset at the top identifies the three major groups of hand bones: carpals at the wrist, metacarpals in the palm, and phalanges in the fingers. The main diagrams show the left hand in anterior view on the left and posterior view on the right.

The hand is organized from proximal to distal. At the wrist are the carpals, a cluster of small bones that form the base of the hand and articulate with the forearm. The labeled carpals include the trapezium, trapezoid, scaphoid, hamate, capitate, pisiform, triquetrum, and lunate. Just proximal to the carpals, the figure labels the radius and ulna of the forearm. Distal to the carpals are the metacarpals, numbered 1 through 5 from the thumb side to the little finger side. These bones form the palm of the hand. Each metacarpal is shown with a base, shaft, and head, illustrating the standard parts of a long bone.

At the fingers are the phalanges. The thumb (pollex) has two phalanges, labeled proximal and distal. The other digits — index finger, middle finger, ring finger, and little finger — each have three phalanges: proximal, middle, and distal. Overall, the figure emphasizes that the hand skeleton is arranged in three regions — wrist, palm, and fingers — and that the thumb differs from the other digits by having two phalanges instead of three.

Figure 8.2.4: Bones of the Hand

This image is an X-ray of a human hand viewed from the front, showing all the bones from the wrist to the fingertips. Several major joints are labeled. The interphalangeal joints are marked along the fingers where the small finger bones bend. The metacarpophalangeal joints, where the fingers meet the hand, are also labeled. The wrist region shows the carpometacarpal joints, the midcarpal joint, and the radiocarpal joint, which is the main wrist joint connecting the forearm to the hand. The labels point to each joint location directly on the X-ray image, helping illustrate how the bones articulate to allow finger and wrist movement.

Figure 8.2.5: Carpal Tunnel

This image shows a cross-sectional view of the wrist and palm-side hand focused on the carpal tunnel. The carpal tunnel is shown as a passageway at the wrist. It is enclosed by the carpal bones on the deeper side and the flexor retinaculum across the top. Inside the tunnel are several muscle tendons and a nerve. The tendons are grouped together within the tunnel, while the labeled nerve lies alongside them within the same confined space.

The labeled carpal bones shown in this view include the hamate, trapezium, trapezoid, and capitate. These bones contribute to the curved bony floor and sides of the tunnel. Overall, the figure emphasizes that the carpal tunnel is a narrow passage in the wrist formed by carpal bones and the flexor retinaculum, and that it contains flexor tendons and a nerve traveling into the hand.

Figure 8.2.6: Loose and Firm Pencil Grips

This image compares two ways of holding a pencil. In panel (a), labeled Loosely held, the pencil passes horizontally through a partially closed hand. The fingers are curled around the pencil, but the thumb remains relatively open and positioned below and to the side of the pencil. More of the pencil is visible between the thumb and fingers. In panel (b), labeled Firmly gripped, the hand forms a tighter fist around the pencil. The thumb is drawn closer against the fingers, and less space is visible between the thumb and the pencil. The pencil remains horizontal in both examples, but the hand in panel (b) encloses the pencil more completely. The figure illustrates differences in hand posture associated with a lighter versus tighter grip.

Figure 8.2.7: Fractures of the Humerus

This image has two main sections. The upper section shows common fracture sites of the humerus, and the lower section shows

a Colles fracture of the distal radius compared with normal wrist anatomy.

In the upper section, the humerus is shown with four labeled fracture locations. Near the top is a surgical neck fracture. Along the shaft is a transverse humeral fracture. Near the distal end is a supracondylar fracture. At the condylar region is an intercondylar fracture. Together, these labels show that humeral fractures can occur at the proximal end, shaft, and distal end of the bone.

In the lower section, the figure compares a Colles fracture of the distal radius with a normal wrist. The fractured examples show displacement near the distal radius, altering the alignment of the wrist and hand relative to the forearm. The normal examples show the expected alignment without fracture. The side-view and front-view drawings help illustrate how the broken distal radius changes bone position compared with the normal wrist.

Overall, the figure emphasizes two teaching points: common named fracture locations of the humerus and the appearance of a Colles fracture of the distal radius compared with normal wrist anatomy.

Figure 8.3.1: The pelvic girdle

This image shows an anterior view of the bony pelvis. Its purpose is to explain how the pelvis is formed by the right and left hip bones together with the sacrum and coccyx, and to identify major landmarks that are important for support, articulation, and pelvic structure.

The hip bones form the large lateral sides of the pelvis. In the center, the sacrum forms the posterior midline portion of the pelvic ring, and the coccyx extends inferiorly below it. Each hip bone meets the sacrum at a sacroiliac joint, while the two hip bones meet each other at the pubic symphysis in the anterior midline.

The figure also labels several important landmarks. The sacral promontory is the projecting upper anterior margin of the sacrum. The pelvic brim outlines the edge of the pelvic inlet. The acetabulum is the socket on each side where the femur articulates with the pelvis. The obturator foramen is the large opening in each hip bone. The ischial tuberosity is the rough inferior projection often associated with weight-bearing when sitting, and the ischiopubic ramus forms part of the lower border of the pelvis.

Overall, the figure emphasizes how the bones and landmarks of the pelvis create a strong ring that supports body weight, connects the axial skeleton to the lower limbs, and forms the framework of the pelvic cavity.

Figure 8.3.2: The Hip Bone

This image shows two anatomical views of the right hip bone: a lateral view and a medial view. The diagram explains how the hip bone is formed by the fusion of three regions — the ilium, ischium, and pubis — and identifies important landmarks visible from the outer and inner surfaces.

The lateral view shows the outer surface of the hip bone, including the acetabulum, which forms the socket of the hip joint. The medial view shows the inner surface, including the iliac fossa and the auricular surface, where the hip bone articulates with the sacrum.

Across both views, the diagram highlights major structures of the ilium, ischium, and pubis, along with openings, notches, articular surfaces, and bony projections that contribute to pelvic structure, movement, and articulation.

Shared labels

- Ilium — the broad superior portion of the hip bone.
- Iliac crest — the superior curved border of the ilium.
- Anterior superior iliac spine — upper front projection of the ilium.
- Anterior inferior iliac spine — projection below the anterior superior iliac spine.
- Acetabulum — cup-shaped socket for articulation with the femur.
- Superior ramus of pubis — upper branch of the pubis.
- Pubic tubercle — small anterior projection on the pubis.
- Pubic body — central part of the pubis.
- Pubis — anterior-inferior portion of the hip bone.
- Articular surface of pubis (at pubic symphysis) — surface where the pubis joins the opposite pubis.
- Inferior ramus of pubis — lower branch of the pubis.

- Ischiopubic ramus — region formed by the inferior pubic ramus and ischial ramus.

Lateral view, right hip bone

- Posterior superior iliac spine — posterior superior projection of the ilium.
- Posterior inferior iliac spine — posterior projection below the posterior superior iliac spine.
- Greater sciatic notch — large posterior indentation above the ischial spine.
- Ischial body — main body of the ischium.
- Ischial spine — sharp projection between the sciatic notches.
- Lesser sciatic notch — smaller indentation below the ischial spine.
- Ischium — posteroinferior region of the hip bone.
- Obturator foramen — large opening in the lower hip bone.
- Ischial tuberosity — roughened inferior projection that bears weight in sitting.
- Ischial ramus — branch of the ischium contributing to the lower pelvis.
- Lateral view, right hip bone — identifies the outer view shown.

Medial view, right hip bone

- Iliac fossa — broad smooth depression on the internal surface of the ilium.
- Posterior superior iliac spine — posterior superior projection of the ilium.
- Posterior inferior iliac spine — projection below the posterior superior iliac spine.
- Auricular surface — articular surface for the sacrum at the sacroiliac joint.
- Greater sciatic notch — large posterior indentation above the ischial spine.
- Ischial spine — pointed projection separating the two sciatic notches.
- Lesser sciatic notch — indentation below the ischial spine.
- Obturator foramen — large opening in the lower hip bone.
- Ischium — posteroinferior portion of the hip bone.
- Ischial ramus — inferior branch of the ischium.
- Arcuate line — internal ridge contributing to the pelvic brim.
- Medial view, right hip bone — identifies the inner view shown.

Figure 8.3.3: Ligaments of the Pelvis

This image shows a posterior view of the pelvis with selected bony landmarks and ligaments. Its purpose is to explain how the sacrum and the parts of the hip bone relate to the sacrospinous and sacrotuberous ligaments, and how these structures help define the greater and lesser sciatic foramina.

The ilium, ischium, and pubis are shown as parts of the hip bone. In the midline is the sacrum, and laterally the pelvis includes landmarks such as the posterior superior iliac spine, ischial spine, ischial tuberosity, obturator foramen, and ischiopubic ramus. The subpubic angle is labeled inferiorly.

The figure also labels three ligaments: the posterior sacroiliac ligament, the sacrospinous ligament, and the sacrotuberous ligament. These ligaments span between the sacrum and parts of the hip bone and help convert the sciatic notches into the greater sciatic foramen and lesser sciatic foramen.

The figure emphasizes how the posterior pelvis is organized and how the sacrospinous and sacrotuberous ligaments help create the openings through which structures pass between the pelvis and the lower limb region. The labels include:

- Sacrum — central bone at the posterior part of the pelvis.
- Posterior superior iliac spine — posterior superior projection of the ilium.
- Ilium — broad superior portion of the hip bone.
- Sacrospinous ligament — ligament extending from the sacrum to the ischial spine.
- Ischial spine — pointed projection of the ischium.
- Pubis — anterior-inferior component of the hip bone.
- Ischium — posteroinferior component of the hip bone.
- Ischial tuberosity — rough inferior projection of the ischium.
- Obturator foramen — large opening in the hip bone.
- Subpubic angle — angle formed inferiorly between the pubic bones.

- Ischiopubic ramus — inferior bony region formed by the pubis and ischium.
- Posterior sacroiliac ligament — ligament supporting the sacroiliac region posteriorly.
- Greater sciatic foramen — large opening posterior to the pelvis.
- Lesser sciatic foramen — smaller opening inferior to the greater sciatic foramen.
- Sacrotuberous ligament — ligament extending from the sacrum to the ischial tuberosity.

Figure 8.3.4: Male and Female Pelvis

This image compares the female pelvis and the male pelvis in anterior view. Its purpose is to show broad anatomical differences in the shape of the pelvic inlet region, sacrum, and subpubic angle.

Both pelvises are labeled with the hip bone, sacrum, pelvic brim, and subpubic angle. In the female pelvis, the outlined region appears broader and more rounded, and the subpubic angle is shown as wider. In the male pelvis, the outlined region appears narrower overall, and the subpubic angle is shown as smaller.

Overall, the figure emphasizes that the female pelvis is generally broader with a wider inlet and subpubic angle, while the male pelvis is generally narrower. The labels include:

- Female — identifies the pelvis on the left as the female pelvis.
- Male — identifies the pelvis on the right as the male pelvis.
- Hip bone — the large paired bones forming the sides of the pelvis.
- Sacrum — the central bone at the posterior part of the pelvis.
- Pelvic brim — the rim outlining the pelvic inlet.
- Subpubic angle — the angle formed inferiorly between the pubic bones.

Figure 8.4.1: Femur and Patella

This image shows the femur in anterior and posterior views, with a small locator image indicating the bone's position in the lower limb. Its purpose is to identify the major anatomical landmarks of the femur and show how the bone articulates proximally with the hip bone and distally with the tibia, fibula, and patella region at the knee.

At the proximal end, the femur includes the head, which articulates with the hip bone, and the neck, which connects the head to the shaft. The greater trochanter and lesser trochanter are large projections that serve as muscle attachment sites. The figure also labels the intertrochanteric line on the anterior view and the intertrochanteric crest on the posterior view, both spanning between the trochanters.

Along the shaft, the body (shaft) forms the long central region of the bone. On the posterior view, the gluteal tuberosity and linea aspera are labeled, showing major roughened attachment sites for muscles.

At the distal end, the femur broadens to form the medial condyle and lateral condyle, which participate in the knee joint. Nearby are the medial epicondyle and lateral epicondyle, which serve as attachment sites for ligaments and muscles. The figure also labels the adductor tubercle and the intercondylar fossa on the posterior view. The patella, tibia, and fibula are shown near the knee to indicate the femur's relationship to the lower leg.

Overall, the figure emphasizes how the femur is specialized for both weight bearing and movement, with landmarks related to the hip joint, muscle attachment, and the knee joint.

Shared labels

- Hip bone — pelvic bone that articulates with the head of the femur.
- Femur — the thigh bone, the longest bone in the body.
- Head — rounded proximal part of the femur that articulates with the hip bone.
- Neck — narrowed region connecting the head to the shaft.
- Greater trochanter — large lateral projection for muscle attachment.
- Lesser trochanter — smaller posteromedial projection for muscle attachment.
- Body (shaft) — long middle portion of the femur.
- Tibia — larger medial bone of the lower leg.

- Fibula — slender lateral bone of the lower leg.

Anterior view

- Intertrochanteric line — ridge on the anterior femur between the greater and lesser trochanters.
- Lateral epicondyle — lateral projection above the condyle for ligament and muscle attachment.
- Adductor tubercle — projection near the medial epicondyle for muscle attachment.
- Medial epicondyle — medial projection above the condyle.
- Patella — kneecap shown anterior to the distal femur.
- Anterior view — front view of the femur.

Posterior view

- Intertrochanteric crest — ridge on the posterior femur between the trochanters.
- Gluteal tuberosity — roughened proximal posterior area for muscle attachment.
- Linea aspera — prominent longitudinal ridge on the posterior shaft.
- Lateral epicondyle — lateral distal projection above the condyle.
- Intercondylar fossa — deep notch between the distal condyles on the posterior femur.
- Lateral condyle — lateral articular prominence at the distal femur.
- Medial condyle — medial articular prominence at the distal femur.
- Posterior view — back view of the femur.

Figure 8.4.2: The Q-Angle

This image shows an anterior view of the lower limb focused on the alignment of the femur and knee. Its purpose is to illustrate the Q-angle, which is the angle formed by the orientation of the femur relative to a vertical line passing through the knee region.

The diagram includes the hip bone, femur, patella region, and proximal lower leg. Two dashed guide lines are drawn: one follows the oblique line of the femur toward the knee, and the other is a more vertical reference line extending downward through the knee. A small arrow near the proximal femur points toward the space between these lines, and a label identifies this relationship as the Q-angle.

Overall, the figure emphasizes that the Q-angle represents the degree to which the femur angles inward toward the knee in the frontal plane.

Figure 8.4.3: Tibia and Fibula

This image shows two anatomical drawings of the right lower leg bones: an anterior view on the left and a posterior view on the right. Each drawing includes the tibia and fibula, extending from just below the knee to the ankle. A small inset at the upper left highlights the lower leg within a simplified skeleton for orientation.
The figure emphasizes the major landmarks of the tibia, the larger and more medial bone of the leg, and the fibula, the more slender and lateral bone. The two bones are connected by the interosseous membrane. The tibia contributes more directly to weight bearing and to the knee and ankle joints, while the fibula provides lateral support and forms the lateral side of the ankle.

In the anterior view, the proximal end of the tibia is expanded into the medial condyle and lateral condyle, which help form the knee joint. Below these is the tibial tuberosity, an elevated area on the anterior tibia where the patellar ligament attaches. Farther down the shaft, the tibia shows the anterior border, a prominent ridge that can be felt under the skin.

The fibula lies lateral to the tibia. Between the shafts of the tibia and fibula is the interosseous membrane, which binds the two bones together. At the distal end, the tibia forms the medial malleolus, while the fibula forms the lateral malleolus. The distal tibia also includes an articular surface that contributes to the ankle joint.

In the posterior view, the upper tibia shows the articular surface of the medial condyle and the articular surface of the lateral condyle, which articulate with the femur at the knee. The head of fibula is visible proximally on the lateral side.

Along the posterior tibia, the soleal line is labeled. This is a diagonal ridge that serves as an attachment area for muscles of the posterior leg. The interosseous membrane is again shown between the tibia and fibula. Distally, the medial malleolus, lateral malleolus, and distal articular surface are visible. The labels are:

- Lateral condyle — lateral proximal expansion of the tibia at the knee region.
- Articular surface of medial condyle — smooth superior surface of the medial tibial condyle for articulation at the knee.
- Articular surface of lateral condyle — smooth superior surface of the lateral tibial condyle for articulation at the knee.
- Medial condyle — medial proximal expansion of the tibia.
- Head of fibula — proximal enlarged end of the fibula.
- Tibial tuberosity — roughened anterior projection below the tibial condyles where the patellar ligament attaches.
- Anterior border — prominent anterior ridge of the tibial shaft.
- Soleal line — diagonal ridge on the posterior tibia for muscle attachment.
- Interosseous membrane — fibrous sheet connecting the tibia and fibula along their shafts.
- Fibula — slender lateral bone of the lower leg.
- Tibia — larger medial bone of the lower leg and principal weight-bearing bone.
- Medial malleolus — distal medial projection of the tibia forming the inner ankle.
- Lateral malleolus — distal projection of the fibula forming the outer ankle.
- Articular surface — distal tibial surface contributing to the ankle joint.
- Right leg, anterior view — front view of the right lower leg.
- Right leg, posterior view — back view of the right lower leg.

Figure 8.4.4: Bones of the Foot

This image presents several anatomical views of the right foot. A small inset at the upper left shows the three major groups of foot bones: tarsals, metatarsals, and phalanges. The larger diagrams show the right foot in superior view, medial view, and lateral view. The tarsals form the proximal part of the foot near the ankle and heel, the metatarsals form the midfoot and forefoot, and the phalanges form the toes. The foot is organized into three main groups of bones:

- Tarsals — the proximal ankle and heel bones
- Metatarsals — the long bones of the midfoot
- Phalanges — the toe bones

The figure also shows that the toes are numbered from 1 to 5, with 1 representing the great toe side and 5 representing the little toe side. The phalanges are named by position as proximal, middle, and distal, although the great toe has only proximal and distal phalanges.

Right foot, superior view: The superior view shows the foot from above. This view emphasizes the arrangement of the metatarsals, phalanges, and many of the tarsal bones. Labeled structures include the medial cuneiform, intermediate cuneiform, lateral cuneiform, navicular, cuboid, talus, trochlea of talus, and calcaneus. The metatarsals are numbered 1 through 5, and the phalanges are labeled as proximal, middle, and distal phalanges.

Right foot, medial view: The medial view shows the inner side of the right foot. This view highlights bones associated with the medial arch and the ankle region. Labeled structures include the first metatarsal, medial cuneiform, intermediate cuneiform, navicular, talus, facet for medial malleolus, sustentaculum tali (talar shelf), calcaneus, and calcaneal tuberosity.

Right foot, lateral view: The lateral view shows the outer side of the right foot. This view highlights lateral tarsal bones and the lateral relationship of the foot to the ankle. Labeled structures include the talus, facet for lateral malleolus, navicular, intermediate cuneiform, lateral cuneiform, cuboid, calcaneus, and fifth metatarsal. The labels are:

- Tarsals — proximal bones of the foot near the ankle and heel.
- Metatarsals — long bones of the midfoot and forefoot.
- Phalanges — bones of the toes.
- Distal — farthest phalanx from the body in a toe.
- Proximal phalanges — toe bones closest to the metatarsals.
- Distal phalange — distal toe bone in the labeled example.
- Middle phalange — middle toe bone in digits that have three phalanges.
- Proximal phalange — proximal toe bone in the labeled example.
- Medial cuneiform — medial wedge-shaped tarsal bone.
- Intermediate cuneiform — middle wedge-shaped tarsal bone.
- Lateral cuneiform — lateral wedge-shaped tarsal bone.
- Navicular — tarsal bone located anterior to the talus.
- Cuboid — lateral tarsal bone anterior to the calcaneus.

- Talus — ankle bone that articulates with the tibia and fibula.
- Trochlea of talus — superior articular part of the talus.
- Calcaneus — heel bone.
- First metatarsal — metatarsal of the great toe.
- Fifth metatarsal — metatarsal of the little toe.
- Facet for medial malleolus — articular surface on the talus for the medial malleolus.
- Facet for lateral malleolus — articular surface on the talus for the lateral malleolus.
- Sustentaculum tali (talar shelf) — medial projection of the calcaneus that supports the talus.
- Calcaneal tuberosity — posterior-inferior prominence of the calcaneus forming the heel.
- Right foot, superior view — top view of the right foot.
- Right foot, medial view — inner side view of the right foot.
- Right foot, lateral view — outer side view of the right foot.
- 1, 2, 3, 4, 5 — numbering of the metatarsals from medial to lateral.

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9: SKELETAL JOINTS (ARTICULATIONS)

Chapter Overview



Figure 9.1: Person paddling a kayak through choppy water. (CC BY 4.0; via Wikimedia Commons).

Structural and Functional Classification of Joints

The adult body has 206 bones; except for the hyoid, each connects to at least one other bone. Joints (articulations) are where bones (or bone and cartilage) meet to connect the skeleton, transmit forces, and permit movement. Several joints are designed for stability and provide for little or no movement. Importantly, joint stability and movement are related to each other. This means that stable joints allow for little or no mobility between the adjacent bones. Conversely, joints that provide the most movement between bones are the least stable.

Structural classification of joints is based on the type of connecting tissue and presence or absence of a joint cavity (fibrous, cartilaginous, synovial), while functional classification describes the degree of movement permitted (synarthrosis, amphiarthrosis, diarthrosis).

Fibrous Joints: Sutures, Gomphoses, and Syndesmoses

Fibrous joints unite bones with fibrous connective tissue and lack a joint cavity; they include immobile sutures between skull bones, gomphoses anchoring teeth in their sockets, and slightly movable syndesmoses linking parallel bones via ligaments or an interosseous membrane.

Cartilaginous Joints: Synchondroses and Symphyses

Cartilaginous joints join bones with cartilage and have no joint cavity; synchondroses use hyaline cartilage and are typically immobile, whereas symphyses use fibrocartilage to allow limited movement, as seen in the pubic symphysis and intvertebral discs.

Functional Joint Types: Synarthrosis, Amphiarthrosis, Diarthrosis

Functionally, joints are classified as synarthroses (essentially immovable), amphiarthroses (slightly movable), or diarthroses (freely movable), with all synovial joints falling into the diarthrotic category and varying by the number of movement axes (uniaxial, biaxial,

multiaxial).

Core Structural Features of Synovial Joints

Synovial joints share key components—articular hyaline cartilage, a fluid-filled joint cavity, and a multi-layered articular capsule—and are stabilized by ligaments, muscles, tendons, and sometimes articular discs or menisci, while bursae and tendon sheaths reduce friction.

Types of Synovial Joints and Their Motions

Synovial joints are categorized by shape and permitted movements into pivot, hinge, condyloid, saddle, plane, and ball-and-socket types, each allowing specific patterns of motion such as rotation, flexion–extension, abduction–adduction, circumduction, and multiaxial movement.

Region-Specific Joint Movements

Named movements at particular joints and regions include head and neck flexion, extension, and rotation; forearm pronation and supination; ankle and foot dorsiflexion, plantarflexion, inversion, and eversion; and combined flexion, extension, lateral flexion, and rotation across the vertebral column.

Temporomandibular Joint Structure and Movements

The temporomandibular joint, between the mandibular condyle and temporal bone, contains an articular disc and functions as a combined hinge and gliding joint, allowing elevation, depression, protraction, retraction, and lateral excursion of the mandible.

Shoulder and Elbow Synovial Joints

The shoulder (glenohumeral) joint is a multiaxial ball-and-socket joint with a shallow glenoid cavity deepened by a labrum and stabilized mainly by rotator cuff muscles and supporting ligaments and bursae, while the elbow combines hinge and pivot components stabilized by collateral and annular ligaments.

Hip and Knee Synovial Joints

The hip is a deep, stable ball-and-socket joint with strong capsular ligaments and an acetabular labrum, whereas the knee is a modified hinge joint with cruciate and collateral ligaments, menisci, and a locking mechanism that together guide and stabilize its complex rolling and gliding motions.

Ankle Joint and Ligamentous Support

The ankle (talocrural) joint operates as a hinge between the tibia–fibula mortise and the talus, with medial (deltoid) and lateral ligament complexes providing stability and limiting excessive eversion and inversion, common sites of ankle sprain.

Embryonic Development of Joints and Epiphyseal Plates

Joints develop from mesenchyme that differentiates into bone, cartilage, and fibrous tissue; limb joints arise from cartilage models separated by a joint interzone that cavitates to form synovial cavities, while temporary synchondroses at epiphyseal plates later ossify into synostoses at skeletal maturity

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own.

By the end of this chapter, students should be able to:

- Define a skeletal joint (articulation) and distinguish structural versus functional classifications.
- Classify any joint by structure (fibrous, cartilaginous—synchondroses/symphyses, synovial) and by function (synarthrosis, amphiarthrosis, diarthrosis), citing representative examples of each.
- Describe and identify the hallmark tissues and features of fibrous joints (sutures, gomphoses, syndesmoses) and cartilaginous joints, with locations in the body.
- Describe core components of synovial joints—articular cartilage, joint cavity, synovial fluid, articular capsule (fibrous layer and synovial membrane)—and friction-reducing/support structures (ligaments: extrinsic/intrinsic/intracapsular; bursae; tendon sheaths; articular discs/menisci).
- Distinguish the six synovial joint types by surface shape and axes of motion (pivot, hinge, condyloid, saddle, plane, ball-and-socket) and match each to key examples.
- Define and recognize named body movements, including flexion/extension, abduction/adduction, circumduction, medial/lateral rotation, pronation/supination, dorsiflexion/plantarflexion, inversion/eversion, elevation/depression, protraction/retraction, opposition/reposition, and lateral flexion.
- Describe the anatomy, stabilizers, and motions of selected joints: temporomandibular; atlanto-occipital and atlanto-axial; shoulder (glenohumeral); elbow and proximal radioulnar; wrist; hip; knee; ankle (talocrural) and subtalar; vertebral facet and intervertebral symphysis joints.
- Explain how specific ligaments and soft tissues contribute to stability and motion (example: rotator cuff; ACL, PCL, MCL, LCL, and menisci at the knee; annular ligament at the proximal radioulnar joint; deltoid and lateral collateral ligaments at the ankle; acetabular and glenoid labra).
- Compare motion capabilities across cervical, thoracic, and lumbar regions and relate them to joint orientation and type.
- Apply anatomical terminology to communicate joint structure, function, movement, and common clinical correlations (example: ankle sprain, ACL injury, rotator cuff pathology, TMJ dysfunction

9.1: Classification of Joints

9.2: Fibrous Joints

9.3: Cartilaginous Joints

9.4: Synovial Joints

9.5: Types of Body Movements

9.6: Anatomy of Selected Synovial Joints

9.7: Terms and Definitions

9.8: Chapter Review Questions

9.9: Applied Thinking Self-Check

9.10: Alternate Text Descriptions

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9.1: Classification of Joints

Structural Classification of Joints

A joint, also called an articulation, is any place where adjacent bones or bone and cartilage come together (articulate with each other) to form a connection. Joints are classified both structurally and functionally. Structural classifications of joints take into account whether the adjacent bones are strongly anchored to each other by fibrous connective tissue or cartilage, or whether the adjacent bones articulate with each other within a fluid-filled space called a joint cavity. Functional classifications describe the degree of movement available between the bones, ranging from immobile, to slightly mobile, to freely moveable joints. The amount of movement available at a particular joint of the body is related to the functional requirements for that joint. Thus immobile or slightly moveable joints serve to protect internal organs, give stability to the body, and allow for limited body movement. In contrast, freely moveable joints allow for much more extensive movements of the body and limbs.

The structural classification of joints is based on whether the articulating surfaces of the adjacent bones are directly connected by fibrous connective tissue or cartilage, or whether the articulating surfaces contact each other within a fluid-filled joint cavity. These differences serve to divide the joints of the body into three structural classifications. A fibrous joint is where the adjacent bones are united by fibrous connective tissue. At a cartilaginous joint, the bones are joined by hyaline cartilage or fibrocartilage. At a synovial joint, the articulating surfaces of the bones are not directly connected, but instead come into contact with each other within a joint cavity that is filled with a lubricating fluid. Synovial joints allow for free movement between the bones and are the most common joints of the body.

Functional Classification of Joints

The functional classification of joints is determined by the amount of mobility found between the adjacent bones. Joints are thus functionally classified as a synarthrosis or immobile joint, an amphiarthrosis or slightly moveable joint, or as a diarthrosis, which is a freely moveable joint (arthroun = “to fasten by a joint”). Depending on their location, fibrous joints may be functionally classified as a synarthrosis (immobile joint) or an amphiarthrosis (slightly mobile joint). Cartilaginous joints are also functionally classified as either a synarthrosis or an amphiarthrosis joint. All synovial joints are functionally classified as a diarthrosis joint.

Synarthrosis

An immobile or nearly immobile joint is called a synarthrosis. The immobile nature of these joints provide for a strong union between the articulating bones. This is important at locations where the bones provide protection for internal organs. Examples include sutures, the fibrous joints between the bones of the skull that surround and protect the brain (Figure $9.1.1$), and the manubriosternal joint, the cartilaginous joint that unites the manubrium and body of the sternum for protection of the heart.

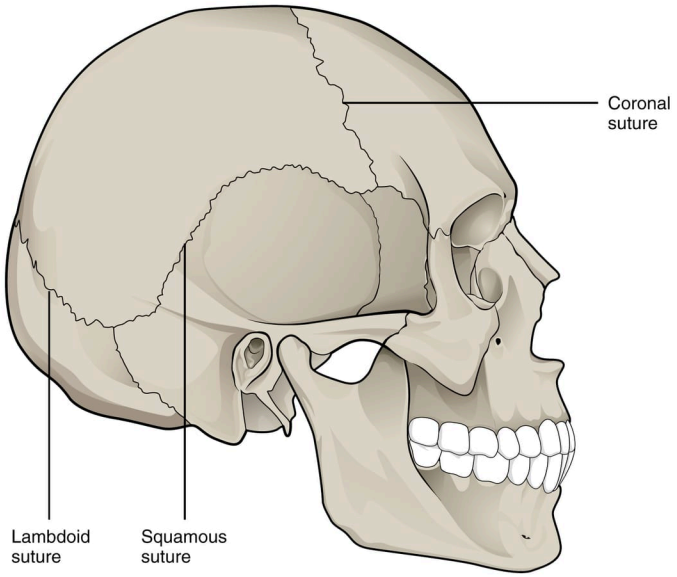


Figure 9.1.1: The suture joints of the skull are an example of a synarthrosis, an immobile or essentially immobile joint. (CC BY 4.0; via Classifications of Joints). Alternate text description of the Figure 9.1.1.

Amphiarthrosis

amphiarthrosis is a joint that has limited mobility. An example of this type of joint is the cartilaginous joint that unites the bodies of adjacent vertebrae. Filling the gap between the vertebrae is a thick pad of fibrocartilage called an intervertebral disc (Figure 9.1.2). Each intervertebral disc strongly unites the vertebrae but still allows for a limited amount of movement between them. However, the small movements available between adjacent vertebrae can sum together along the length of the vertebral column to provide for large ranges of body movements.

Another example of an amphiarthrosis is the pubic symphysis of the pelvis. This is a cartilaginous joint in which the pubic regions of the right and left hip bones are strongly anchored to each other by fibrocartilage. This joint normally has very little mobility. The strength of the pubic symphysis is important in conferring weight-bearing stability to the pelvis.

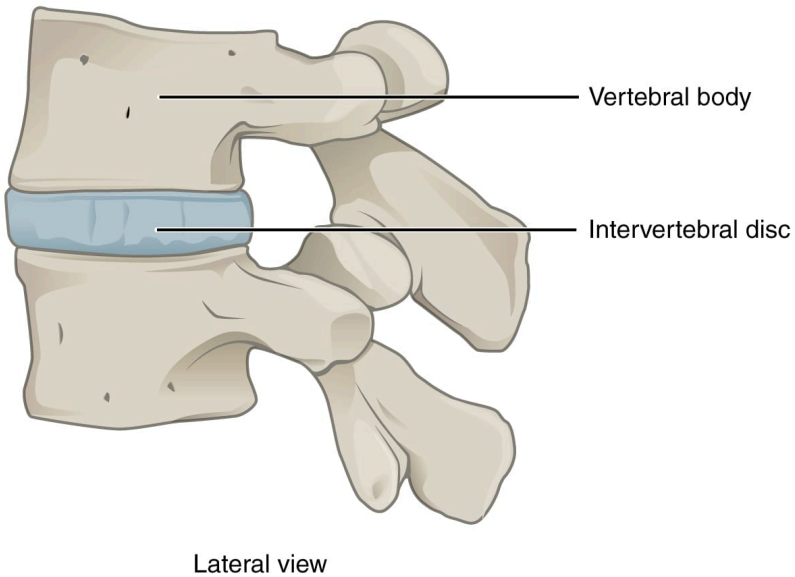


Figure 9.1.2: An intervertebral disc unites the bodies of adjacent vertebrae within the vertebral column. Each disc allows for limited movement between the vertebrae and thus functionally forms an amphiarthrosis type of joint. Intervertebral discs are made of fibrocartilage and thereby structurally form a symphysis type of cartilaginous joint. (CC BY 4.0; via Classifications of Joints). Alternate text description of the Figure 9.1.2.

Diarthrosis

A freely mobile joint is classified as a diarthrosis. These types of joints include all synovial joints of the body, which provide the majority of body movements. Most diarthrotic joints are found in the appendicular skeleton and thus give the limbs a wide range of motion. These joints are divided into three categories, based on the number of axes of motion provided by each. An axis in anatomy is described as the movements in reference to the three anatomical planes: transverse, frontal, and sagittal. Thus, diarthroses are classified as uniaxial (for movement in one plane), biaxial (for movement in two planes), or multiaxial joints (for movement in all three anatomical planes).

A uniaxial joint only allows for a motion in a single plane (around a single axis). The elbow joint, which only allows for bending or straightening, is an example of a uniaxial joint. A biaxial joint allows for motions within two planes. An example of a biaxial joint is a metacarpophalangeal joint (knuckle joint) of the hand. The joint allows for movement along one axis to produce bending or straightening of the finger, and movement along a second axis, which allows for spreading of the fingers away from each other and bringing them together. A joint that allows for the several directions of movement is called a multiaxial joint (polyaxial or triaxial joint). This type of diarthrotic joint allows for movement along three axes (Figure 9.1.3). The shoulder and hip joints are multiaxial joints. They allow the upper or lower limb to move in an anterior-posterior direction and a medial-lateral direction. In addition, the limb can also be rotated around its long axis. This third movement results in rotation of the limb so that its anterior surface is moved either toward or away from the midline of the body.

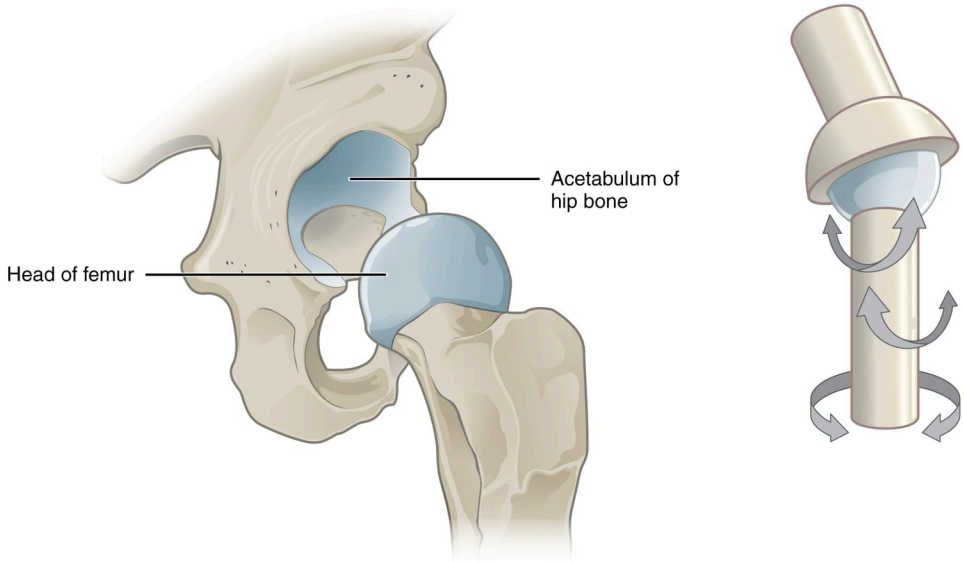


Figure 9.1.3: A multiaxial joint, such as the hip joint, allows for three types of movement: anterior-posterior, medial-lateral, and rotational. (CC BY 4.0; via Classifications of Joints). Alternate text description of the Figure 9.1.3.

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9.2: Fibrous Joints

Structure and Function of Fibrous Joints

At a fibrous joint, the adjacent bones are directly connected to each other by fibrous connective tissue, and thus the bones do not have a joint cavity between them (Figure 9.2.1). The gap between the bones may be narrow or wide. There are three types of fibrous joints. A suture is the narrow fibrous joint found between most bones of the skull. At a syndesmosis joint, the bones are more widely separated but are held together by a narrow band of fibrous connective tissue called a ligament or a wide sheet of connective tissue called an interosseous membrane. This type of fibrous joint is found between the shaft regions of the long bones in the forearm and in the leg. Lastly, a gomphosis is the narrow fibrous joint between the roots of a tooth and the bony socket in the jaw into which the tooth fits.

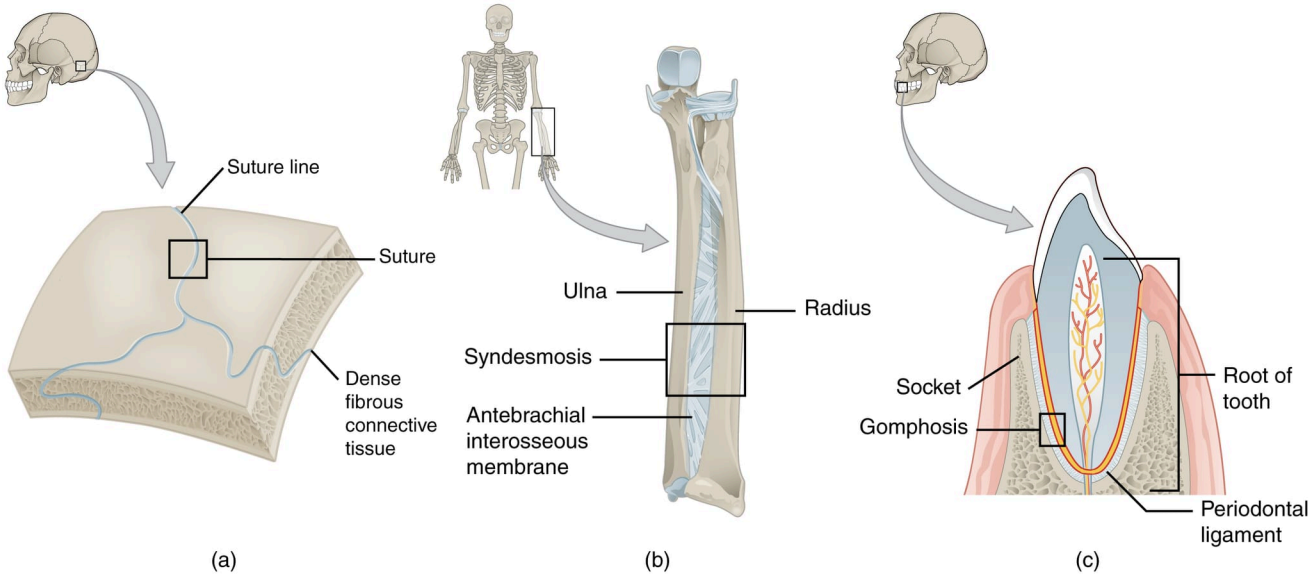


Figure 9.2.1: Fibrous joints form strong connections between bones. (a) Sutures join most bones of the skull. (b) An interosseous membrane forms a syndesmosis between the radius and ulna bones of the forearm. (c) A gomphosis is a specialized fibrous joint that anchors a tooth to its socket in the jaw. (CC BY 4.0; via Fibrous Joints). Alternate text description of the Figure 9.2.1.

Suture

All the bones of the skull, except for the mandible, are joined to each other by a fibrous joint called a suture. The fibrous connective tissue found at a suture ("to bind or sew") strongly unites the adjacent skull bones and thus helps to protect the brain and form the face. In adults, the skull bones are closely opposed and fibrous connective tissue fills the narrow gap between the bones. The suture is frequently convoluted, forming a tight union that prevents most movement between the bones. Thus, skull sutures are functionally classified as a synarthrosis, although some sutures may allow for slight movements between the cranial bones.

In newborns and infants, the areas of connective tissue between the bones are much wider, especially in those areas on the top and sides of the skull that will become the sagittal, coronal, squamous, and lambdoid sutures. These broad areas of connective tissue are called fontanelles (Figure 9.2.2). During birth, the fontanelles provide flexibility to the skull, allowing the bones to push closer together or to overlap slightly, thus aiding movement of the infant's head through the birth canal. After birth, these expanded regions of connective tissue allow for rapid growth of the skull and enlargement of the brain. The fontanelles greatly decrease in width during the first year after birth as the skull bones enlarge. When the connective tissue between the adjacent bones is reduced to a narrow layer, these fibrous joints are now called sutures. At some sutures, the connective tissue will ossify and be converted into bone, causing the adjacent bones to fuse to each other. This fusion between bones is called a synostosis ("joined by bone"). Examples of synostosis fusions between cranial bones are found both early and late in life. At the time of birth, the frontal and maxillary bones consist of right and left halves joined together by sutures, which disappear by the eighth year as

the halves fuse together to form a single bone. Late in life, the sagittal, coronal, and lambdoid sutures of the skull will begin to ossify and fuse, causing the suture line to gradually disappear.

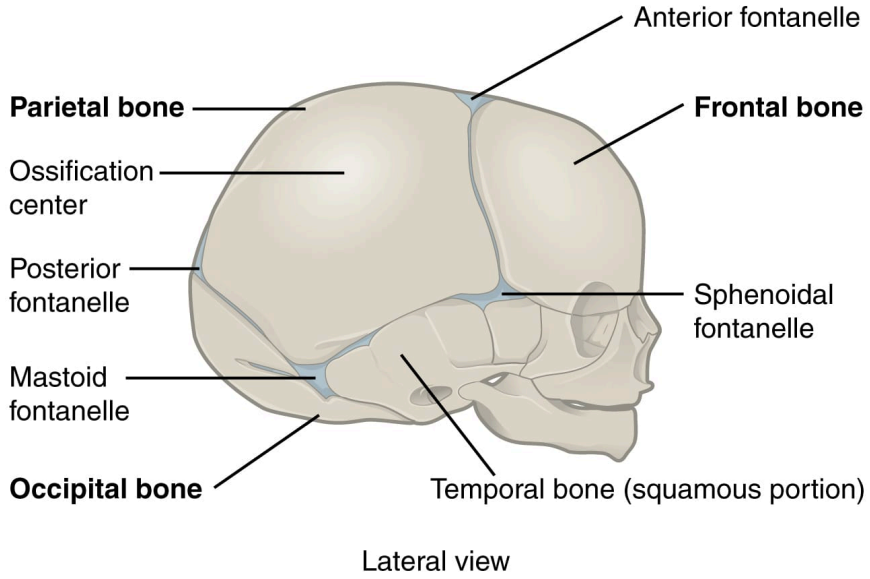


Figure 9.2.2: The fontanelles of a newborn's skull are broad areas of fibrous connective tissue that form fibrous joints between the bones of the skull. (CC BY 4.0; via Fibrous Joints). Alternate text description of the Figure 9.2.2.

Syndesmosis

A syndesmosis ("fastened with a band") is a type of fibrous joint in which two parallel bones are united to each other by fibrous connective tissue. The gap between the bones may be narrow, with the bones joined by ligaments, or the gap may be wide and filled in by a broad sheet of connective tissue called an interosseous membrane.

In the forearm, the wide gap between the shaft portions of the radius and ulna bones are strongly united by an interosseous membrane. Similarly, in the leg, the shafts of the tibia and fibula are also united by an interosseous membrane. In addition, at the distal tibiofibular joint, the articulating surfaces of the bones lack cartilage and the narrow gap between the bones is anchored by fibrous connective tissue and ligaments on both the anterior and posterior aspects of the joint. Together, the interosseous membrane and these ligaments form the tibiofibular syndesmosis.

The syndesmoses found in the forearm and leg serve to unite parallel bones and prevent their separation. However, a syndesmosis does not prevent all movement between the bones, and thus this type of fibrous joint is functionally classified as an amphiarthrosis. In the leg, the syndesmosis between the tibia and fibula strongly unites the bones, allows for little movement, and firmly locks the talus bone in place between the tibia and fibula at the ankle joint. This provides strength and stability to the leg and ankle, which are important during weight bearing. In the forearm, the interosseous membrane is flexible enough to allow for rotation of the radius bone during forearm movements. Thus in contrast to the stability provided by the tibiofibular syndesmosis, the flexibility of the antebrachial interosseous membrane allows for the much greater mobility of the forearm.

The interosseous membranes of the leg and forearm also provide areas for muscle attachment. Damage to a syndesmotic joint, which usually results from a fracture of the bone with an accompanying tear of the interosseous membrane, will produce pain, loss of stability of the bones, and may damage the muscles attached to the interosseous membrane. If the fracture site is not properly immobilized with a cast or splint, contractile activity by these muscles can cause improper alignment of the broken bones during healing.

Gomphosis

A gomphosis ("fastened with bolts") is the specialized fibrous joint that anchors the root of a tooth into its bony socket within the maxillary bone (upper jaw) or mandible bone (lower jaw) of the skull. A gomphosis is also known as a peg-and-socket joint. Spanning between the bony walls of the socket and the root of the tooth are numerous short bands of dense connective tissue, each of which is called a periodontal ligament. Due to the immobility of a gomphosis, this type of joint is functionally classified as a synarthrosis.

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9.3: Cartilaginous Joints

Synchondroses and Symphyses

As the name indicates, at a cartilaginous joint, the adjacent bones are united by cartilage, a tough but flexible type of connective tissue. These types of joints lack a joint cavity and involve bones that are joined together by either hyaline cartilage or fibrocartilage (Figure 9.3.1). There are two types of cartilaginous joints. A synchondrosis is a cartilaginous joint where the bones are joined by hyaline cartilage. Also classified as a synchondrosis are places where bone is united to a cartilage structure, such as between the anterior end of a rib and the costal cartilage of the thoracic cage. The second type of cartilaginous joint is a symphysis, where the bones are joined by fibrocartilage.

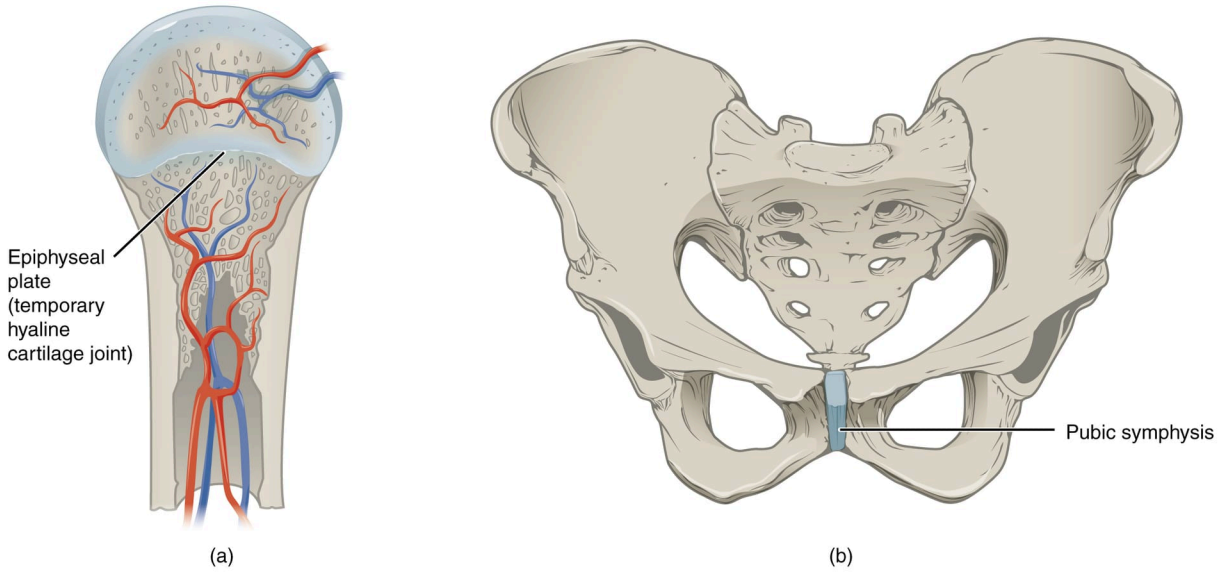


Figure 9.3.1: Illustration showing an epiphyseal plate in a long bone and the pubic symphysis of the pelvis as examples of cartilaginous joints. (CC BY 4.0; via Cartilaginous Joints). Alternate text description of the Figure 9.3.1.

Synchondrosis

A synchondrosis ("joined by cartilage") is a cartilaginous joint where bones are joined together by hyaline cartilage, or where bone is united to hyaline cartilage. A synchondrosis may be temporary or permanent. A temporary synchondrosis is the epiphyseal plate (growth plate) of a growing long bone. The epiphyseal plate is the region of growing hyaline cartilage that unites the diaphysis (shaft) of the bone to the epiphysis (end of the bone). Bone lengthening involves growth of the epiphyseal plate cartilage and its replacement by bone, which adds to the diaphysis. For many years during childhood growth, the rates of cartilage growth and bone formation are equal and thus the epiphyseal plate does not change in overall thickness as the bone lengthens. During the late teens and early 20s, growth of the cartilage slows and eventually stops. The epiphyseal plate is then completely replaced by bone, and the diaphysis and epiphysis portions of the bone fuse together to form a single adult bone. This fusion of the diaphysis and epiphysis is a synostosis. Once this occurs, bone lengthening ceases. For this reason, the epiphyseal plate is considered to be a temporary synchondrosis. Because cartilage is softer than bone tissue, injury to a growing long bone can damage the epiphyseal plate cartilage, thus stopping bone growth and preventing additional bone lengthening.

Growing layers of cartilage also form synchondroses that join together the ilium, ischium, and pubic portions of the hip bone during childhood and adolescence. When body growth stops, the cartilage disappears and is replaced by bone, forming synostoses and fusing the bony components together into the single hip bone of the adult. Similarly, synostoses unite the sacral vertebrae that fuse together to form the adult sacrum.

Examples of permanent synchondroses are found in the thoracic cage. One example is the first sternocostal joint, where the first rib is anchored to the manubrium by its costal cartilage. (The articulations of the remaining costal cartilages to the sternum are

all synovial joints.) Additional synchondroses are formed where the anterior end of the other 11 ribs is joined to its costal cartilage. Unlike the temporary synchondroses of the epiphyseal plate, these permanent synchondroses retain their hyaline cartilage and thus do not ossify with age. Due to the lack of movement between the bone and cartilage, both temporary and permanent synchondroses are functionally classified as a synarthrosis.

Symphyses

A cartilaginous joint where the bones are joined by fibrocartilage is called a symphysis (“growing together”). Fibrocartilage is very strong because it contains numerous bundles of thick collagen fibers, thus giving it a much greater ability to resist pulling and bending forces when compared with hyaline cartilage. This gives symphyses the ability to strongly unite the adjacent bones, but can still allow for limited movement to occur. Thus, a symphysis is functionally classified as an amphiarthrosis.

The gap separating the bones at a symphysis may be narrow or wide. Examples in which the gap between the bones is narrow include the pubic symphysis and the manubriosternal joint. At the pubic symphysis, the pubic portions of the right and left hip bones of the pelvis are joined together by fibrocartilage across a narrow gap. Similarly, at the manubriosternal joint, fibrocartilage unites the manubrium and body portions of the sternum.

The intervertebral symphysis is a wide symphysis located between the bodies of adjacent vertebrae of the vertebral column. Here a thick pad of fibrocartilage called an intervertebral disc strongly unites the adjacent vertebrae by filling the gap between them. The width of the intervertebral symphysis is important because it allows for small movements between the adjacent vertebrae. In addition, the thick intervertebral disc provides cushioning between the vertebrae, which is important when carrying heavy objects or during high-impact activities such as running or jumping.

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9.4: Synovial Joints

Structure and Features of Synovial Joints

Synovial joints are the most common type of joint in the body (Figure 9.4.1). A key structural characteristic for a synovial joint that is not seen at fibrous or cartilaginous joints is the presence of a joint cavity. This fluid-filled space is the site at which the articulating surfaces of the bones contact each other. Also unlike fibrous or cartilaginous joints, the articulating bone surfaces at a synovial joint are not directly connected to each other with fibrous connective tissue or cartilage. This gives the bones of a synovial joint the ability to move smoothly against each other, allowing for increased joint mobility.

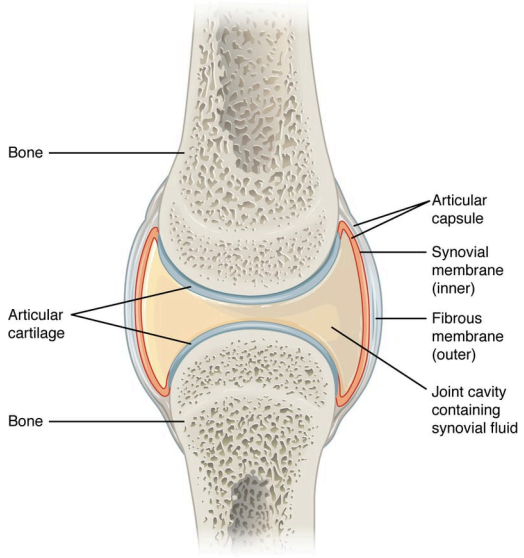


Figure 9.4.1: Synovial joints allow for smooth movements between the adjacent bones. The joint is surrounded by an articular capsule that defines a joint cavity filled with synovial fluid. The articulating surfaces of the bones are covered by a thin layer of articular cartilage. Ligaments support the joint by holding the bones together and resisting excess or abnormal joint motions. (CC BY 4.0; via Synovial Joints).
Alternate text description of the Figure 9.4.1.

The two bones form the framework of the joint. Each bone end contains spongy, or trabecular, bone internally and a more solid outer layer. Their functions are to provide the structural framework for movement and to transmit forces across the joint.

The articular cartilage forms smooth layers covering the ends of both bones where they meet. Its functions are to reduce friction during movement, absorb shock, and provide a smooth surface for joint motion.

The joint cavity is the space between the articular cartilage of the two bones. Its functions are to allow free movement of the joint and contain synovial fluid.

The synovial fluid is the fluid within the joint cavity. Its functions are to lubricate the joint, reduce friction between the articular surfaces, and provide nutrients to the articular cartilage.

The articular capsule surrounds and encloses the joint. It is made of two layers. The fibrous membrane is the tough outer layer. Its functions are to provide mechanical support and protection and help stabilize the joint. The synovial membrane is the thin inner lining. Its functions are to produce synovial fluid and maintain the internal environment of the joint.

Friction between the bones at a synovial joint is prevented by the presence of the articular cartilage, a thin layer of hyaline cartilage that covers the entire articulating surface of each bone. However, unlike at a cartilaginous joint, the articular cartilages of each bone are not continuous with each other. Instead, the articular cartilage acts like a Teflon® coating over the bone surface, allowing the articulating bones to move smoothly against each other without damaging the underlying bone tissue. Lining the inner surface of the articular capsule is a thin synovial membrane. The cells of this membrane secrete synovial fluid (synovia = “a

thick fluid"), a thick, slimy fluid that provides lubrication to further reduce friction between the bones of the joint. This fluid also provides nourishment to the articular cartilage, which does not contain blood vessels. The ability of the bones to move smoothly against each other within the joint cavity, and the freedom of joint movement this provides, means that each synovial joint is functionally classified as a diarthrosis.

Outside of their articulating surfaces, the bones are connected together by ligaments, which are strong bands of fibrous connective tissue. These strengthen and support the joint by anchoring the bones together and preventing their separation. Ligaments allow for normal movements at a joint, but limit the range of these motions, thus preventing excessive or abnormal joint movements. Ligaments are classified based on their relationship to the fibrous articular capsule. An extrinsic ligament is located outside of the articular capsule, an intrinsic ligament is fused to or incorporated into the wall of the articular capsule, and an intracapsular ligament is located inside of the articular capsule.

At many synovial joints, additional support is provided by the muscles and their tendons that act across the joint. A tendon is the dense connective tissue structure that attaches a muscle to bone. As forces acting on a joint increase, the body will automatically increase the overall strength of contraction of the muscles crossing that joint, thus allowing the muscle and its tendon to serve as a "dynamic ligament" to resist forces and support the joint. This type of indirect support by muscles is very important at the shoulder joint, for example, where the ligaments are relatively weak.

Additional Structures Associated with Synovial Joints

A few synovial joints of the body have a fibrocartilage structure located between the articulating bones. This is called an articular disc, which is generally small and oval-shaped, or a meniscus, which is larger and C-shaped. These structures can serve several functions, depending on the specific joint. In some places, an articular disc may act to strongly unite the bones of the joint to each other. Examples of this include the articular discs found at the sternoclavicular joint or between the distal ends of the radius and ulna bones. At other synovial joints, the disc can provide shock absorption and cushioning between the bones, which is the function of each meniscus within the knee joint. Finally, an articular disc can serve to smooth the movements between the articulating bones, as seen at the temporomandibular joint. Some synovial joints also have a fat pad, which can serve as a cushion between the bones.

Additional structures located outside of a synovial joint serve to prevent friction between the bones of the joint and the overlying muscle tendons or skin. A bursa (plural = bursae) is a thin connective tissue sac filled with lubricating liquid. They are located in regions where skin, ligaments, muscles, or muscle tendons can rub against each other, usually near a body joint (Figure $9.4.2$). Bursae reduce friction by separating the adjacent structures, preventing them from rubbing directly against each other. Bursae are classified by their location. A subcutaneous bursa is located between the skin and an underlying bone. It allows skin to move smoothly over the bone. Examples include the prepatellar bursa located over the kneecap and the olecranon bursa at the tip of the elbow. A submuscular bursa is found between a muscle and an underlying bone, or between adjacent muscles. These prevent rubbing of the muscle during movements. A large submuscular bursa, the trochanteric bursa, is found at the lateral hip, between the greater trochanter of the femur and the overlying gluteus maximus muscle. A subtendinous bursa is found between a tendon and a bone. Examples include the subacromial bursa that protects the tendon of shoulder muscle as it passes under the acromion of the scapula, and the suprapatellar bursa that separates the tendon of the large anterior thigh muscle from the distal femur just above the knee.

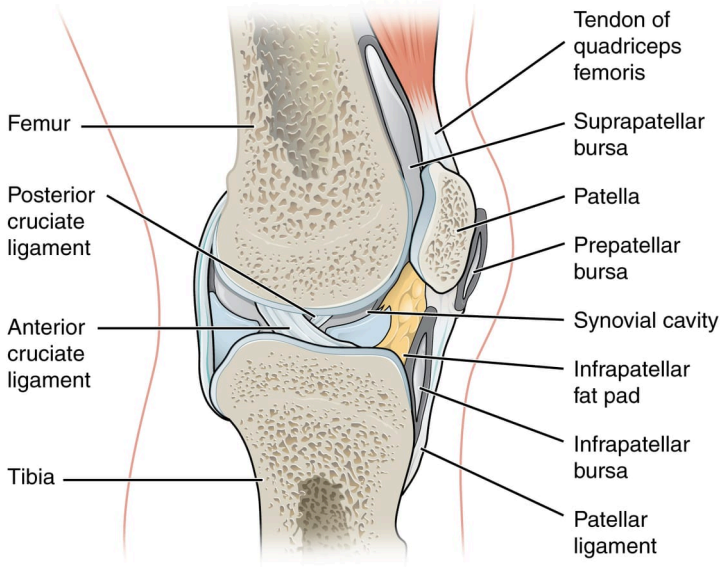


Figure 9.4.2: Bursae are fluid-filled sacs that serve to prevent friction between skin, muscle, or tendon and an underlying bone. Three major bursae and a fat pad are part of the complex joint that unites the femur and tibia of the leg. (CC BY 4.0; via Synovial Joints). Alternate text description of the Figure 9.4.2.

The femur forms the superior part of the joint. Its functions are to transfer body weight downward and form the upper articulation of the knee. The tibia forms the inferior part of the joint. Its functions are to support body weight from the femur and provide the base for movement at the knee. The patella is a small bone located in front of the joint. Its functions are to protect the knee joint and improve the mechanical efficiency of the quadriceps muscle during extension.

The stabilizing ligaments include the ACL, PCL, and patellar ligament. The anterior cruciate ligament lies within the joint between the femur and tibia. Its functions are to prevent forward movement of the tibia relative to the femur and stabilize the knee during motion. The posterior cruciate ligament lies behind the ACL. Its functions are to prevent backward movement of the tibia relative to the femur and provide additional joint stability. The patellar ligament extends from the patella to the tibia. Its functions are to transfer force from the quadriceps muscle to the lower leg and enable extension of the knee.

The tendon of the quadriceps femoris connects the quadriceps muscle to the patella. Its functions are to transmit the pull of the quadriceps and allow the muscle to extend the knee and control leg movement.

The synovial cavity is the space between the articulating surfaces of the joint. Its functions are to allow free movement of the joint and contain synovial fluid for lubrication. The articular cartilage, inferred from the joint surfaces, is the smooth covering on the ends of the bones. Its functions are to reduce friction and absorb shock.

The figure also shows several bursae, which are fluid-filled sacs that reduce friction between moving structures. The suprapatellar bursa is located above the patella and reduces friction between the femur and the overlying tendon. The prepatellar bursa lies in front of the patella and reduces friction between the patella and the skin. The infrapatellar bursa lies below the patella and reduces friction between the patellar ligament and surrounding tissues. The infrapatellar fat pad is a pad of tissue below the patella that cushions the joint and helps absorb mechanical forces.

Homeostatic Imbalances

Bursitis

Bursitis is the inflammation of a bursa near a joint. This will cause pain, swelling, or tenderness of the bursa and surrounding area, and may also result in joint stiffness. Bursitis is most commonly associated with the bursae found at or near the shoulder, hip, knee, or elbow joints. At the shoulder, subacromial bursitis may occur in the bursa that separates the acromion of the scapula from the tendon of a shoulder muscle as it passes deep to the acromion. In the hip region, trochanteric bursitis can occur in the bursa that overlies the greater trochanter of the femur, just below the lateral side of the hip. Ischial bursitis occurs in the bursa that separates the skin from the ischial tuberosity of the pelvis, the bony structure that is weight bearing

when sitting. At the knee, inflammation and swelling of the bursa located between the skin and patella bone is prepatellar bursitis (“housemaid’s knee”), a condition more commonly seen today in roofers or floor and carpet installers who do not use knee pads. At the elbow, olecranon bursitis is inflammation of the bursa between the skin and olecranon process of the ulna. The olecranon forms the bony tip of the elbow, and bursitis here is also known as “student’s elbow.”

Bursitis can be either acute (lasting only a few days) or chronic. It can arise from muscle overuse, trauma, excessive or prolonged pressure on the skin, rheumatoid arthritis, gout, or infection of the joint. Repeated acute episodes of bursitis can result in a chronic condition. Treatments for the disorder include antibiotics if the bursitis is caused by an infection, or anti-inflammatory agents, such as nonsteroidal anti-inflammatory drugs (NSAIDs) or corticosteroids if the bursitis is due to trauma or overuse. Chronic bursitis may require that fluid be drained, but additional surgery is usually not required.

Types of Synovial Joints

Synovial joints are subdivided based on the shapes of the articulating surfaces of the bones that form each joint. The six types of synovial joints are pivot, hinge, condyloid, saddle, plane, and ball-and socket-joints (Figure $9.4.3$).

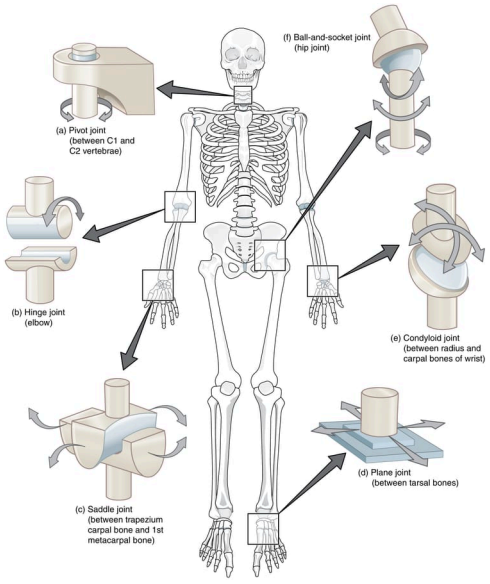


Figure $9.4.3$: The six types of synovial joints allow the body to move in a variety of ways. (CC BY 4.0; via Synovial Joints). Alternate text description of the Figure $9.4.3$.

Pivot Joint

At a pivot joint, a rounded portion of a bone is enclosed within a ring formed partially by the articulation with another bone and partially by a ligament (Figure $9.4.3a$). The bone rotates within this ring. Since the rotation is around a single axis, pivot joints are functionally classified as a uniaxial diarthrosis type of joint. An example of a pivot joint is the atlantoaxial joint, found between the C1 (atlas) and C2 (axis) vertebrae. Here, the upward projecting dens of the axis articulates with the inner aspect of the atlas, where it is held in place by a ligament. Rotation at this joint allows you to turn your head from side to side. A second pivot joint is found at the proximal radioulnar joint. Here, the head of the radius is largely encircled by a ligament that holds it in place as it articulates with the radial notch of the ulna. Rotation of the radius allows for forearm movements.

Hinge Joint

In a hinge joint, the convex end of one bone articulates with the concave end of the adjoining bone (Figure $9.4.3b$). This type of joint allows only for bending and straightening motions along a single axis, and thus hinge joints are functionally classified as uniaxial joints. A good example is the elbow joint, with the articulation between the trochlea of the humerus and the trochlear notch of the ulna. Other hinge joints of the body include the knee, ankle, and interphalangeal joints between the phalanx bones of the fingers and toes.

Condyloid Joint

At a condyloid joint (ellipsoid joint), the shallow depression at the end of one bone articulates with a rounded structure from an adjacent bone or bones (Figure $9.4.3e$). The knuckle (metacarpophalangeal) joints of the hand between the distal end of a metacarpal bone and the proximal phalanx bone are condyloid joints. Another example is the radiocarpal joint of the wrist, between the shallow depression at the distal end of the radius bone and the rounded scaphoid, lunate, and triquetrum carpal bones. In this case, the articulation area has a more oval (elliptical) shape. Functionally, condyloid joints are biaxial joints that allow for two planes of movement. One movement involves the bending and straightening of the fingers or the anterior-posterior movements of the hand. The second movement is a side-to-side movement, which allows you to spread your fingers apart and bring them together, or to move your hand in a medial-going or lateral-going direction.

Saddle Joint

At a saddle joint, both of the articulating surfaces for the bones have a saddle shape, which is concave in one direction and convex in the other (Figure $9.4.3c$). This allows the two bones to fit together like a rider sitting on a saddle. Saddle joints are functionally classified as biaxial joints. The primary example is the first carpometacarpal joint, between the trapezium (a carpal bone) and the first metacarpal bone at the base of the thumb. This joint provides the thumb the ability to move away from the palm of the hand along two planes. Thus, the thumb can move within the same plane as the palm of the hand, or it can jut out anteriorly, perpendicular to the palm. This movement of the first carpometacarpal joint is what gives humans their distinctive “opposable” thumbs. The sternoclavicular joint is also classified as a saddle joint.

Plane Joint

At a plane joint (gliding joint), the articulating surfaces of the bones are flat or slightly curved and of approximately the same size, which allows the bones to slide against each other (Figure $9.4.3d$). The motion at this type of joint is usually small and tightly constrained by surrounding ligaments. Based only on their shape, plane joints can allow multiple movements, including rotation. Thus plane joints can be functionally classified as a multiaxial joint. However, not all of these movements are available to every plane joint due to limitations placed on it by ligaments or neighboring bones. Thus, depending upon the specific joint of the body, a plane joint may exhibit only a single type of movement or several movements. Plane joints are found between the carpal bones (intercarpal joints) of the wrist or tarsal bones (intertarsal joints) of the foot, between the clavicle and acromion of the scapula (acromioclavicular joint), and between the superior and inferior articular processes of adjacent vertebrae (zygapophysial joints).

Ball-and-Socket Joint

The joint with the greatest range of motion is the ball-and-socket joint. At these joints, the rounded head of one bone (the ball) fits into the concave articulation (the socket) of the adjacent bone (Figure $9.4.3f$). The hip joint and the glenohumeral (shoulder) joint are the only ball-and-socket joints of the body. At the hip joint, the head of the femur articulates with the acetabulum of the hip bone, and at the shoulder joint, the head of the humerus articulates with the glenoid cavity of the scapula.

Ball-and-socket joints are classified functionally as multiaxial joints. The femur and the humerus are able to move in both anterior-posterior and medial-lateral directions and they can also rotate around their long axis. The shallow socket formed by the glenoid cavity allows the shoulder joint an extensive range of motion. In contrast, the deep socket of the acetabulum and the strong supporting ligaments of the hip joint serve to constrain movements of the femur, reflecting the need for stability and weight-bearing ability at the hip.

Aging and the...

Joints

Arthritis is a common disorder of synovial joints that involves inflammation of the joint. This often results in significant joint pain, along with swelling, stiffness, and reduced joint mobility. There are more than 100 different forms of arthritis. Arthritis may arise from aging, damage to the articular cartilage, autoimmune diseases, bacterial or viral infections, or unknown (probably genetic) causes.

The most common type of arthritis is osteoarthritis, which is associated with aging and “wear and tear” of the articular cartilage (Figure 9.4.4). Risk factors that may lead to osteoarthritis later in life include injury to a joint; jobs that involve physical labor; sports with running, twisting, or throwing actions; and being overweight. These factors put stress on the articular cartilage that covers the surfaces of bones at synovial joints, causing the cartilage to gradually become thinner. As the articular cartilage layer wears down, more pressure is placed on the bones. The joint responds by increasing production of the lubricating synovial fluid, but this can lead to swelling of the joint cavity, causing pain and joint stiffness as the articular capsule is stretched. The bone tissue underlying the damaged articular cartilage also responds by thickening, producing irregularities and causing the articulating surface of the bone to become rough or bumpy. Joint movement then results in pain and inflammation. In its early stages, symptoms of osteoarthritis may be reduced by mild activity that “warms up” the joint, but the symptoms may worsen following exercise. In individuals with more advanced osteoarthritis, the affected joints can become more painful and therefore are difficult to use effectively, resulting in increased immobility. There is no cure for osteoarthritis, but several treatments can help alleviate the pain. Treatments may include lifestyle changes, such as weight loss and low-impact exercise, and over-the-counter or prescription medications that help to alleviate the pain and inflammation. For severe cases, joint replacement surgery (arthroplasty) may be required.

Joint replacement is a very invasive procedure, so other treatments are always tried before surgery. However arthroplasty can provide relief from chronic pain and can enhance mobility within a few months following the surgery. This type of surgery involves replacing the articular surfaces of the bones with prosthesis (artificial components). For example, in hip arthroplasty, the worn or damaged parts of the hip joint, including the head and neck of the femur and the acetabulum of the pelvis, are removed and replaced with artificial joint components. The replacement head for the femur consists of a rounded ball attached to the end of a shaft that is inserted inside the diaphysis of the femur. The acetabulum of the pelvis is reshaped and a replacement socket is fitted into its place. The parts, which are always built in advance of the surgery, are sometimes custom made to produce the best possible fit for a patient.

Gout is a form of arthritis that results from the deposition of uric acid crystals within a body joint. Usually only one or a few joints are affected, such as the big toe, knee, or ankle. The attack may only last a few days, but may return to the same or another joint. Gout occurs when the body makes too much uric acid or the kidneys do not properly excrete it. A diet with excessive fructose has been implicated in raising the chances of a susceptible individual developing gout.

Other forms of arthritis are associated with various autoimmune diseases, bacterial infections of the joint, or unknown genetic causes. Autoimmune diseases, including rheumatoid arthritis, scleroderma, or systemic lupus erythematosus, produce arthritis because the immune system of the body attacks the body joints. In rheumatoid arthritis, the joint capsule and synovial membrane become inflamed. As the disease progresses, the articular cartilage is severely damaged or destroyed, resulting in joint deformation, loss of movement, and severe disability. The most commonly involved joints are the hands, feet, and cervical spine, with corresponding joints on both sides of the body usually affected, though not always to the same extent. Rheumatoid arthritis is also associated with lung fibrosis, vasculitis (inflammation of blood vessels), coronary heart disease, and premature mortality. With no known cure, treatments are aimed at alleviating symptoms. Exercise, anti-inflammatory and pain medications, various specific disease-modifying anti-rheumatic drugs, or surgery are used to treat rheumatoid arthritis.

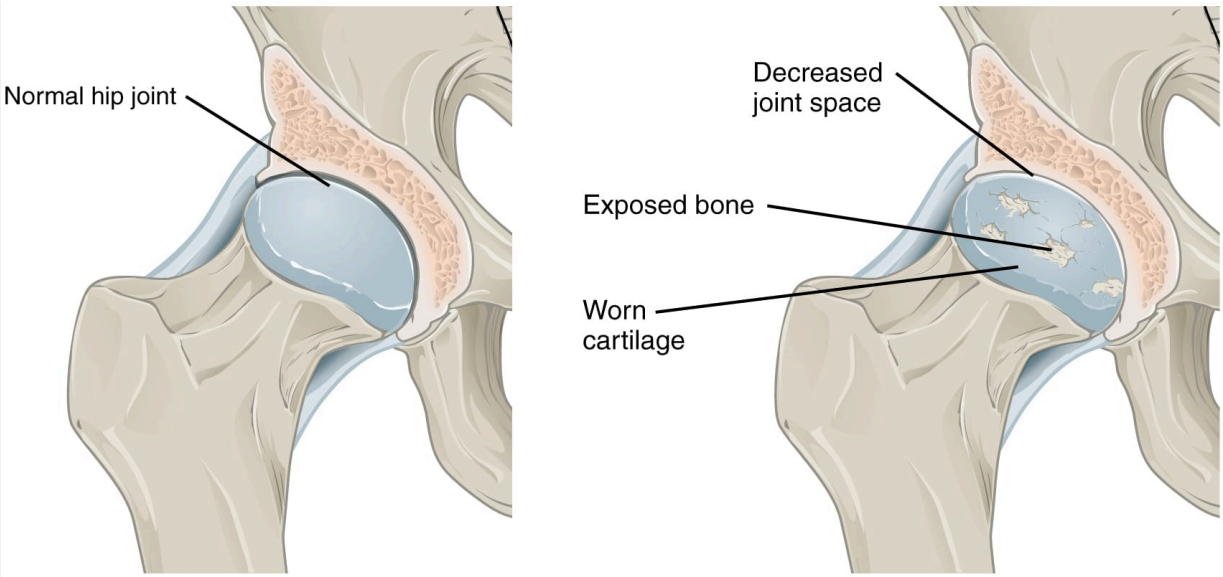


Figure 9.4.4: Osteoarthritis of a synovial joint results from aging or prolonged joint wear and tear. These cause erosion and loss of the articular cartilage covering the surfaces of the bones, resulting in inflammation that causes joint stiffness and pain. (CC BY 4.0; via Synovial Joints). Alternate text description of the Figure 9.4.4.

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9.5: Types of Body Movements

Movements at Synovial Joints

Synovial joints allow the body a tremendous range of movements. Each movement at a synovial joint results from the contraction or relaxation of the muscles that are attached to the bones on either side of the articulation. The type of movement that can be produced at a synovial joint is determined by its structural type. While the ball-and-socket joint gives the greatest range of movement at an individual joint, in other regions of the body, several joints may work together to produce a particular movement. Overall, each type of synovial joint is necessary to provide the body with its great flexibility and mobility. There are many types of movement that can occur at synovial joints. Movement types are generally paired, with one being the opposite of the other. Body movements are always described in relation to the anatomical position of the body, upright stance, with upper limbs to the side of body and palms facing forward. Refer to Figure 9.5.1 as you go through this section.

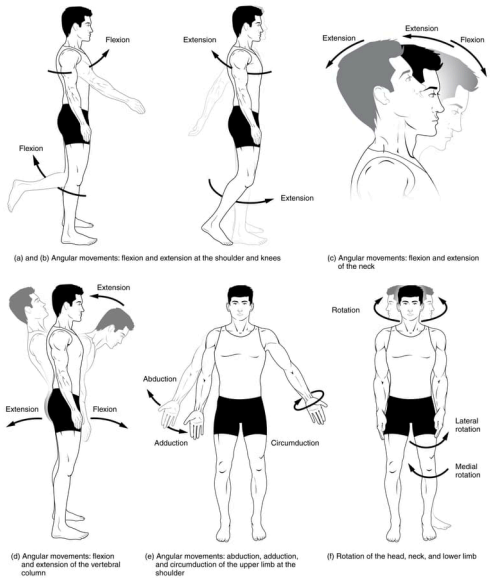


Figure 9.5.1: Illustrating major angular movements including flexion, extension, abduction, adduction, rotation, and circumduction, using multiple body diagrams. (CC BY 4.0; via Types of Body Movements). Alternate text description of the Figure 9.5.1.

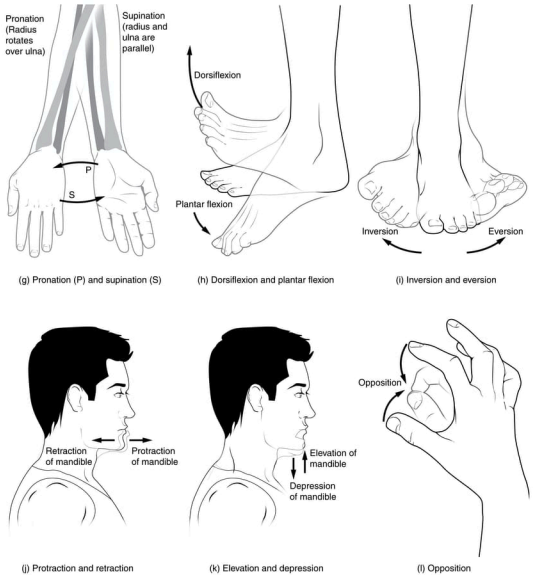


Figure 9.5.2: Illustrating several specialized body movements, including pronation and supination of the forearm, dorsiflexion and plantar flexion of the foot, inversion and eversion, protraction and retraction of the mandible, elevation and depression of the jaw, and thumb opposition. (CC BY 4.0; via Types of Body Movements). Alternate text description of the Figure 9.5.2.

Flexion and Extension

Flexion and extension are typically movements that take place within the sagittal plane and involve anterior or posterior movements of the neck, trunk, or limbs.

For the vertebral column, flexion (anterior flexion) is an anterior (forward) bending of the neck or trunk, while extension involves a posterior-directed motion, such as straightening from a flexed position or bending backward. Lateral flexion of the vertebral column occurs in the coronal plane and is defined as the bending of the neck or trunk toward the right or left side. Spinal movement happens at the disc joints and at the small gliding joints between the bony projections of neighboring vertebrae.

Flexion bends a joint by decreasing the angle between the bones; extension straightens a joint by increasing that angle. In the upper limb, movements toward the front of the body (forward) are flexion and movements toward the back (backward) are extension. This applies at the shoulder (arm), elbow (forearm), wrist (hand), and finger joints. For the thumb, extension moves the thumb away from the palm in the same plane as the palm, and flexion brings the thumb toward the index finger or into the palm at the first carpometacarpal joint. In the lower limb, lifting the thigh forward/up is hip flexion, and moving it backward is hip extension; going past the standing position is limited by strong hip ligaments. Bending the knee to bring the heel toward the back of the thigh is knee flexion; straightening the knee is extension. Flexion and extension occur at hinge, condyloid, saddle, and ball-and-socket joints (Figure 9.5.1).

Hyperextension is the abnormal or excessive extension of a joint beyond its normal range of motion, thus resulting in injury. Similarly, hyperflexion is excessive flexion at a joint. Hyperextension injuries are common at hinge joints such as the knee or elbow. In cases of “whiplash” in which the head is suddenly moved backward and then forward, a patient may experience both hyperextension and hyperflexion of the cervical region.

Abduction and Adduction

Abduction and adduction motions occur within the coronal plane and involve medial-lateral motions of the limbs, fingers, toes, or thumb. Abduction moves the limb laterally away from the midline of the body, while adduction is the opposing movement that brings the limb toward the body or across the midline. For example, abduction is raising the arm at the shoulder joint, moving it laterally away from the body, while adduction brings the arm down to the side of the body. Similarly, abduction and adduction at the wrist moves the hand away from or toward the midline of the body. Spreading the fingers or toes apart is also abduction, while bringing the fingers or toes together is adduction. For the thumb, abduction is the anterior movement that brings the thumb to a 90° perpendicular position, pointing straight out from the palm. Adduction moves the thumb back to the anatomical position, next to the index finger. Abduction and adduction movements are seen at condyloid, saddle, and ball-and-socket joints (Figure

9.5.1).

Circumduction

Circumduction is the movement of a body region in a circular manner, in which one end of the body region being moved stays relatively stationary while the other end describes a circle. It involves the sequential combination of flexion, adduction, extension, and abduction at a joint. This type of motion is found at biaxial condyloid and saddle joints, and at multiaxial ball-and-sockets joints (Figure 9.5.1*e*).

Rotation

Rotation can occur within the vertebral column, at a pivot joint, or at a ball-and-socket joint. Rotation of the neck or body is the twisting movement produced by the summation of the small rotational movements available between adjacent vertebrae. At a pivot joint, one bone rotates in relation to another bone. This is a uniaxial joint, and thus rotation is the only motion allowed at a pivot joint. For example, at the atlantoaxial joint, the first cervical (C1) vertebra (atlas) rotates around the dens, the upward projection from the second cervical (C2) vertebra (axis). This allows the head to rotate from side to side as when shaking the head "no." The proximal radioulnar joint is a pivot joint formed by the head of the radius and its articulation with the ulna. This joint allows for the radius to rotate along its length during pronation and supination movements of the forearm.

Rotation can also occur at the ball-and-socket joints of the shoulder and hip. Here, the humerus and femur rotate around their long axis, which moves the anterior surface of the arm or thigh either toward or away from the midline of the body. Movement that brings the anterior surface of the limb toward the midline of the body is called medial (internal) rotation. Conversely, rotation of the limb so that the anterior surface moves away from the midline is lateral (external) rotation (Figure 9.5.1*f*). Be sure to distinguish medial and lateral rotation, which can only occur at the multiaxial shoulder and hip joints, from circumduction, which can occur at either biaxial or multiaxial joints.

Supination and Pronation

Supination and pronation are movements of the forearm. In the anatomical position, the upper limb is held next to the body with the palm facing forward. This is the supinated position of the forearm. In this position, the radius and ulna are parallel to each other. When the palm of the hand faces backward, the forearm is in the pronated position, and the radius and ulna form an X-shape.

Supination and pronation are the movements of the forearm that go between these two positions. Pronation is the motion that moves the forearm from the supinated (anatomical) position to the pronated (palm backward) position. This motion is produced by rotation of the radius at the proximal radioulnar joint, accompanied by movement of the radius at the distal radioulnar joint. The proximal radioulnar joint is a pivot joint that allows for rotation of the head of the radius. Because of the slight curvature of the shaft of the radius, this rotation causes the distal end of the radius to cross over the distal ulna at the distal radioulnar joint. This crossing over brings the radius and ulna into an X-shape position. Supination is the opposite motion, in which rotation of the radius returns the bones to their parallel positions and moves the palm to the anterior facing (supinated) position. It helps to remember that supination is the motion you use when scooping up soup with a spoon (Figure 9.5.2*g*).

Dorsiflexion and Plantar Flexion

Dorsiflexion and plantar flexion are movements at the ankle joint, which is a hinge joint. Lifting the front of the foot, so that the top of the foot moves toward the anterior leg is dorsiflexion, while lifting the heel of the foot from the ground or pointing the toes downward is plantar flexion. These are the only movements available at the ankle joint (Figure 9.5.2*h*).

Inversion and Eversion

Inversion and eversion are complex movements that involve the multiple plane joints among the tarsal bones of the posterior foot (intertarsal joints) and thus are not motions that take place at the ankle joint. Inversion is the turning of the foot to angle the bottom of the foot toward the midline, while eversion turns the bottom of the foot away from the midline. The foot has a greater range of inversion than eversion motion. These are important motions that help to stabilize the foot when walking or running on an uneven surface and aid in the quick side-to-side changes in direction used during active sports such as basketball, racquetball, or soccer (Figure 9.5.2*i*).

Protraction and Retraction

Protraction and retraction are anterior-posterior movements of the scapula or mandible. Protraction of the scapula occurs when the shoulder is moved forward, as when pushing against something or throwing a ball. Retraction is the opposite motion, with the scapula being pulled posteriorly and medially, toward the vertebral column. For the mandible, protraction occurs when the lower jaw is pushed forward, to stick out the chin, while retraction pulls the lower jaw backward. (Figure $9.5.2j$)

Depression and Elevation

Depression and elevation are downward and upward movements of the scapula or mandible. The upward movement of the scapula and shoulder is elevation, while a downward movement is depression. These movements are used to shrug your shoulders. Similarly, elevation of the mandible is the upward movement of the lower jaw used to close the mouth or bite on something, and depression is the downward movement that produces opening of the mouth (Figure $9.5.2k$).

Excursion

Excursion is the side to side movement of the mandible. Lateral excursion moves the mandible away from the midline, toward either the right or left side. Medial excursion returns the mandible to its resting position at the midline.

Superior Rotation and Inferior Rotation

Superior and inferior rotation are movements of the scapula and are defined by the direction of movement of the glenoid cavity. These motions involve rotation of the scapula around a point inferior to the scapular spine and are produced by combinations of muscles acting on the scapula. During superior rotation, the glenoid cavity moves upward as the medial end of the scapular spine moves downward. This is a very important motion that contributes to upper limb abduction. Without superior rotation of the scapula, the greater tubercle of the humerus would hit the acromion of the scapula, thus preventing any abduction of the arm above shoulder height. Superior rotation of the scapula is thus required for full abduction of the upper limb. Superior rotation is also used without arm abduction when carrying a heavy load with your hand or on your shoulder. You can feel this rotation when you pick up a load, such as a heavy book bag and carry it on only one shoulder. To increase its weight-bearing support for the bag, the shoulder lifts as the scapula superiorly rotates. Inferior rotation occurs during limb adduction and involves the downward motion of the glenoid cavity with upward movement of the medial end of the scapular spine.

Opposition and Reposition

Opposition is the thumb movement that brings the tip of the thumb in contact with the tip of a finger. This movement is produced at the first carpometacarpal joint, which is a saddle joint formed between the trapezium carpal bone and the first metacarpal bone. Thumb opposition is produced by a combination of flexion and abduction of the thumb at this joint. Returning the thumb to its anatomical position next to the index finger is called reposition (Figure $9.5.2l$).

Table $9.5.1$: Movements of the Joints

Type of Joint	Movement	Example
Pivot	Uniaxial joint; allows rotational movement	Atlantoaxial joint (C1–C2 vertebrae articulation); proximal radioulnar joint
Hinge	Uniaxial joint; allows flexion/extension movements	Knee; elbow; ankle; interphalangeal joints of fingers and toes
Condyloid	Biaxial joint; allows flexion/extension, abduction/adduction, and circumduction movements	Metacarpophalangeal (knuckle) joints of fingers; radiocarpal joint of wrist; metatarsophalangeal joints for toes
Saddle	Biaxial joint; allows flexion/extension, abduction/adduction, and circumduction movements	First carpometacarpal joint of the thumb; sternoclavicular joint

Type of Joint	Movement	Example
Plane	Multiaxial joint; allows inversion and eversion of foot, or flexion, extension, and lateral flexion of the vertebral column	Intertarsal joints of foot; superior-inferior articular process articulations between vertebrae
Ball-and-socket	Multiaxial joint; allows flexion/extension, abduction/adduction, circumduction, and medial/lateral rotation movements	Shoulder and hip joints

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9.6: Anatomy of Selected Synovial Joints

Articulations of the Vertebral Column

Each synovial joint of the body is specialized to perform certain movements. The movements that are allowed are determined by the structural classification for each joint. For example, a multiaxial ball-and-socket joint has much more mobility than a uniaxial hinge joint. However, the ligaments and muscles that support a joint may place restrictions on the total range of motion available. Thus, the ball-and-socket joint of the shoulder has little in the way of ligament support, which gives the shoulder a very large range of motion. In contrast, movements at the hip joint are restricted by strong ligaments, which reduce its range of motion but confer stability during standing and weight bearing.

This section will examine the anatomy of selected synovial joints of the body. Anatomical names for most joints are derived from the names of the bones that articulate at that joint, although some joints, such as the elbow, hip, and knee joints are exceptions to this general naming scheme.

In addition to being held together by the intervertebral discs, adjacent vertebrae also articulate with each other at synovial joints formed between the superior and inferior articular processes. These are plane joints that provide for only limited motions between the vertebrae. The orientation of the articular processes at these joints varies in different regions of the vertebral column and serves to determine the types of motions available in each vertebral region. The cervical and lumbar regions have the greatest ranges of motions.

In the neck, the articular processes of cervical vertebrae are flattened and generally face upward or downward. This orientation provides the cervical vertebral column with extensive ranges of motion for flexion, extension, lateral flexion, and rotation. In the thoracic region, the downward projecting and overlapping spinous processes, along with the attached thoracic cage, greatly limit flexion, extension, and lateral flexion. The lumbar region allows for considerable extension, flexion, and lateral flexion, but the orientation of the articular processes largely prohibits rotation.

The articulations formed between the skull, the atlas (C1 vertebra), and the axis (C2 vertebra) differ from the articulations in other vertebral areas and play important roles in movement of the head. The atlanto-occipital joint is formed by the articulations between the superior articular processes of the atlas and the occipital condyles on the base of the skull. This articulation has a pronounced U-shaped curvature, oriented along the anterior-posterior axis. This allows the skull to rock forward and backward, producing flexion and extension of the head. This moves the head up and down, as when shaking your head “yes.”

The atlantoaxial joint, between the atlas and axis, consists of three articulations. The paired superior articular processes of the axis articulate with the inferior articular processes of the atlas. These articulating surfaces are relatively flat and oriented horizontally. The third articulation is the pivot joint formed between the dens, which projects upward from the body of the axis, and the inner aspect of the anterior arch of the atlas (Figure 9.6.1). A strong ligament passes posterior to the dens to hold it in position against the anterior arch. These articulations allow the atlas to rotate on top of the axis, moving the head toward the right or left, as when shaking your head “no.”

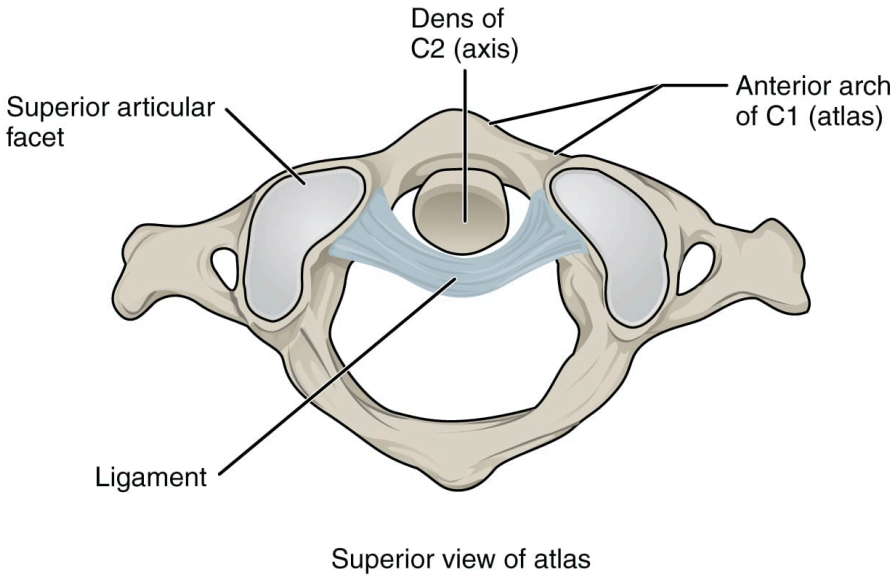


Figure 9.6.1: The atlantoaxial joint is a pivot type of joint between the dens portion of the axis (C2 vertebra) and the anterior arch of the atlas (C1 vertebra), with the dens held in place by a ligament. (CC BY 4.0; via Anatomy of Selected Synovial Joints). Alternate text description of the Figure 9.6.1.

Temporomandibular Joint

The temporomandibular joint (TMJ) is the joint that allows for opening (mandibular depression) and closing (mandibular elevation) of the mouth, as well as side-to-side and protraction/retraction motions of the lower jaw. This joint involves the articulation between the mandibular fossa and articular tubercle of the temporal bone, with the condyle (head) of the mandible. Located between these bony structures, filling the gap between the skull and mandible, is a flexible articular disc (Figure 9.6.2). This disc serves to smooth the movements between the temporal bone and mandibular condyle.

Movement at the TMJ during opening and closing of the mouth involves both gliding and hinge motions of the mandible. With the mouth closed, the mandibular condyle and articular disc are located within the mandibular fossa of the temporal bone. During opening of the mouth, the mandible hinges downward and at the same time is pulled anteriorly, causing both the condyle and the articular disc to glide forward from the mandibular fossa onto the downward projecting articular tubercle. The net result is a forward and downward motion of the condyle and mandibular depression. The temporomandibular joint is supported by an extrinsic ligament that anchors the mandible to the skull. This ligament spans the distance between the base of the skull and the lingula on the medial side of the mandibular ramus.

Dislocation of the TMJ may occur when opening the mouth too wide (such as when taking a large bite) or following a blow to the jaw, resulting in the mandibular condyle moving beyond (anterior to) the articular tubercle. In this case, the individual would not be able to close their mouth. Temporomandibular joint disorder is a painful condition that may arise due to arthritis, wearing of the articular cartilage covering the bony surfaces of the joint, muscle fatigue from overuse or grinding of the teeth, damage to the articular disc within the joint, or jaw injury. Temporomandibular joint disorders can also cause headache, difficulty chewing, or even the inability to move the jaw (lock jaw). Lockjaw refers to difficulty opening or closing your mouth fully. Common triggers include jaw injury, teeth grinding or clenching, stress, misaligned bite, arthritis, and joint misalignment. Muscle and joint inflammation typically accompanies the condition. Common symptoms of lockjaw includes

- Difficulty opening or closing your mouth fully.
- Clicking, popping, or grinding sounds when moving your jaw.
- Pain or tenderness in the jaw, ear area, or facial muscles.

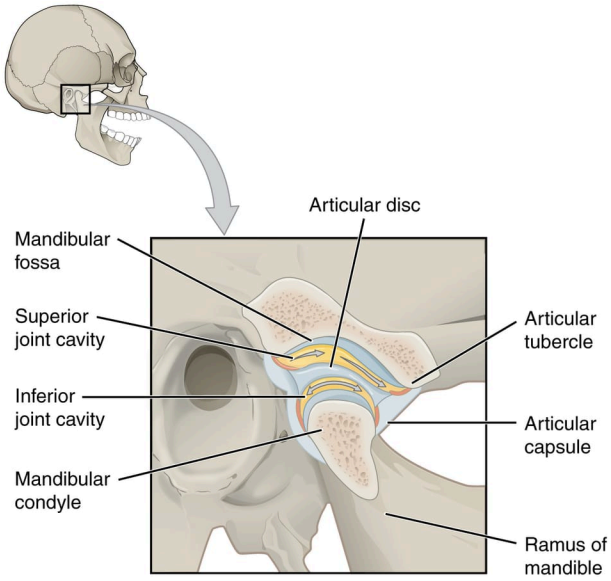


Figure 9.6.2: Figure illustrating the temporomandibular joint with labeled structures, including the mandibular fossa, articular disc, joint cavities, mandibular condyle, articular tubercle, and joint capsule. (CC BY 4.0; via Anatomy of Selected Synovial Joints). Alternate text description of the Figure 9.6.2.

Shoulder Joint

The shoulder joint is called the glenohumeral joint. This is a ball-and-socket joint formed by the articulation between the head of the humerus and the glenoid cavity of the scapula (Figure 9.6.3). This joint has the largest range of motion of any joint in the body. However, this freedom of movement is due to the lack of structural support and thus the enhanced mobility is offset by a loss of stability.

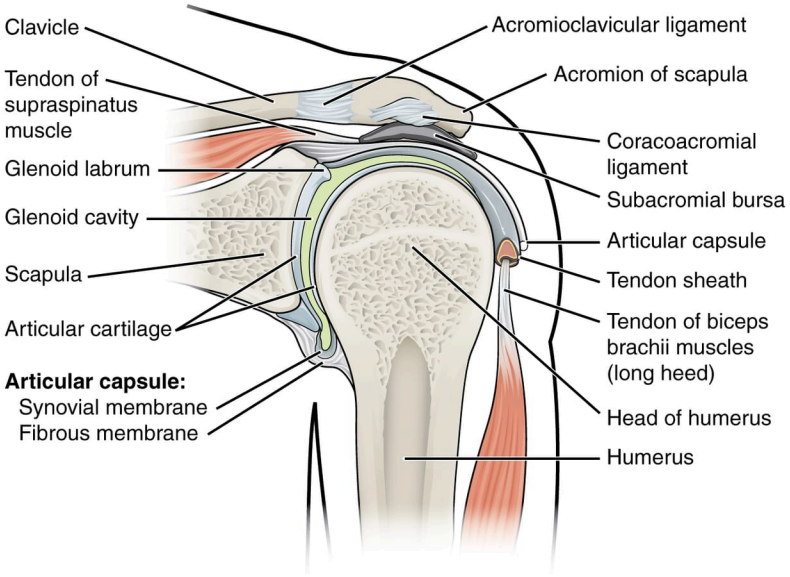


Figure 9.6.3: The glenohumeral (shoulder) joint is a ball-and-socket joint that provides the widest range of motions. It has a loose articular capsule and is supported by ligaments and the rotator cuff muscles. (CC BY 4.0; via Anatomy of Selected Synovial Joints). Alternate text description of the Figure 9.6.3.

Shoulder Joint Mobility and Stability

Why it moves so much? The socket is shallow; a fibrocartilage rim called the labrum slightly deepens it. A loose joint capsule

allows wide motion. Movement of the scapula on the thorax adds extra range (scapulohumeral rhythm).

The large range of motions at the shoulder joint is provided by the articulation of the large, rounded humeral head with the small and shallow glenoid cavity, which is only about one third of the size of the humeral head. The socket formed by the glenoid cavity is deepened slightly by a small lip of fibrocartilage called the glenoid labrum, which extends around the outer margin of the cavity. The articular capsule that surrounds the glenohumeral joint is relatively thin and loose to allow for large motions of the upper limb. Some structural support for the joint is provided by thickenings of the articular capsule wall that form weak intrinsic ligaments. These include the coracohumeral ligament, running from the coracoid process of the scapula to the anterior humerus, and three ligaments, each called a glenohumeral ligament, located on the anterior side of the articular capsule. These ligaments help to strengthen the superior and anterior capsule walls.

What stabilizes it? Static supports: labrum; capsule; glenohumeral ligaments (superior, middle, inferior) and the coracohumeral ligament; negative intra-articular pressure. Dynamic supports: rotator cuff muscles (SITS—supraspinatus, infraspinatus, teres minor, subscapularis) that compress the humeral head into the socket; other movers like deltoid, pectoralis major, latissimus dorsi, and trapezius/serratus anterior (scapular control). • Bursae (especially the subacromial/subdeltoid bursa) reduce friction under the acromion.

Two bursae, the subacromial bursa and the subscapular bursa, help to prevent friction between the rotator cuff muscle tendons and the scapula as these tendons cross the glenohumeral joint.

Injuries to the shoulder joint are common. Repetitive use of the upper limb, particularly in abduction such as during throwing, swimming, or racquet sports, may lead to acute or chronic inflammation of the bursa or muscle tendons, a tear of the glenoid labrum, or degeneration or tears of the rotator cuff. Because the humeral head is strongly supported by muscles and ligaments around its anterior, superior, and posterior aspects, most dislocations of the humerus occur in an inferior direction. This can occur when force is applied to the humerus when the upper limb is fully abducted, as when diving to catch a baseball and landing on your hand or elbow. Inflammatory responses to any shoulder injury can lead to the formation of scar tissue between the articular capsule and surrounding structures, thus reducing shoulder mobility, a condition called adhesive capsulitis (“frozen shoulder”).

Elbow Joint

The elbow is formed where the upper arm bone (humerus) meets the two bones of the forearm, the ulna and the radius. Although we refer to it as one joint, it actually has three functional parts within a single joint capsule. The humeroulnar joint acts as the main hinge that allows bending and straightening. The humeroradial joint also participates in flexion and extension while contributing to rotational movement. The proximal radioulnar joint functions as a pivot, allowing the forearm to rotate. All three joints operate together inside one continuous articular capsule.

Main movements: Flexion: bend the elbow to bring the hand toward the face. Extension: straighten the elbow. Pronation: turn the palm down (radius crosses over the ulna). Supination: turn the palm up (radius and ulna are parallel). Everyday examples: lift a cup (flexion), push a door (extension), use a screwdriver (pronation/supination).

The articular capsule of the elbow is thin on its anterior and posterior aspects, but is thickened along its outside margins by strong intrinsic ligaments. These ligaments prevent side-to-side movements and hyperextension. On the medial side is the triangular ulnar collateral ligament. This arises from the medial epicondyle of the humerus and attaches to the medial side of the proximal ulna. The strongest part of this ligament is the anterior portion, which resists hyperextension of the elbow. The ulnar collateral ligament may be injured by frequent, forceful extensions of the forearm, as is seen in baseball pitchers. Reconstructive surgical repair of this ligament is referred to as Tommy John surgery, named for the former major league pitcher who was the first person to have this treatment.

The lateral side of the elbow is supported by the radial collateral ligament. This arises from the lateral epicondyle of the humerus and then blends into the lateral side of the annular ligament. The annular ligament encircles the head of the radius. This ligament supports the head of the radius as it articulates with the radial notch of the ulna at the proximal radioulnar joint. This is a pivot joint that allows for rotation of the radius during supination and pronation of the forearm.

Common problems (simple notes):

- Tennis elbow (lateral epicondylitis): pain on the outside from overuse of wrist extensors.
- Golfer’s elbow (medial epicondylitis): pain on the inside from overuse of wrist flexors.
- Olecranon bursitis: swelling over the elbow tip from pressure or injury.

- Dislocation or fracture: usually after a fall on an outstretched hand.

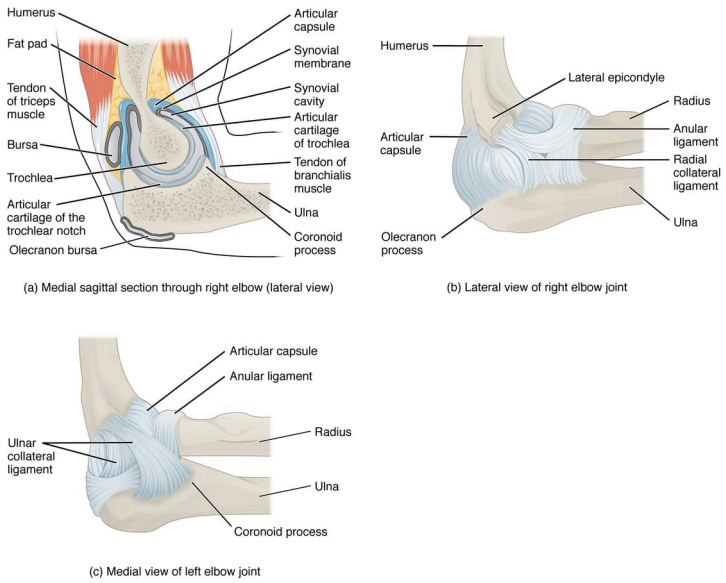


Figure 9.6.4: Figure showing sagittal, lateral, and medial views of the elbow joint, highlighting the articular capsule, synovial membrane, bursae, ligaments, tendons, and articulations among the humerus, ulna, and radius. (CC BY 4.0; via Anatomy of Selected Synovial Joints). Alternate text description of the Figure 9.6.4.

Hip Joint

The hip is where the thigh bone (femur) meets the pelvis. The round femoral head fits into the acetabulum (a cup in the pelvis). It is a synovial ball-and-socket joint built for strength and movement (Figure 9.6.5). The hip carries the weight of the body and thus requires strength and stability during standing and walking. For these reasons, its range of motion is more limited than at the shoulder joint.

The acetabulum forms the socket portion of the hip joint. It is deep and provides a broad surface for articulation with the femoral head, which contributes significantly to the joint's stability and weight-bearing ability. The acetabular labrum, a fibrocartilage rim attached to the outer edge of the acetabulum, further deepens the socket. The surrounding articular capsule is strong and reinforced by several intrinsic ligaments. The iliofemoral ligament, located anteriorly, is extremely strong and limits hyperextension. The pubofemoral ligament, positioned anteromedially, restricts abduction and extension. The ischiofemoral ligament, found posteriorly, limits internal rotation and extension.

- Main movements (with simple examples)
- Flexion: lift the knee up (sit down, tie shoes).
- Extension: move the thigh back (stand up, push off when walking).
- Abduction: move the leg out to the side (side step).
- Adduction: bring the leg back toward the midline (cross legs).
- Internal rotation: turn the knee inward (pivot feet in).
- External rotation: turn the knee outward (sit cross-legged).
- Key muscles (just the main ones)
- Flexion: iliopsoas, rectus femoris.
- Extension: gluteus maximus, hamstrings.
- Abduction: gluteus medius and minimus.
- Adduction: adductor group (longus, brevis, magnus).
- Rotation: deep rotators (piriformis etc.), gluteals.

The hip is prone to osteoarthritis (cartilage wear → pain and stiffness), and thus was the first joint for which a replacement prosthesis was developed. A common injury in elderly individuals, particularly those with weakened bones due to osteoporosis,

is a “broken hip,” which is actually a fracture of the femoral neck. This may result from a fall, or it may cause the fall. This can happen as one lower limb is taking a step and all of the body weight is placed on the other limb, causing the femoral neck to break and producing a fall. Any accompanying disruption of the blood supply to the femoral neck or head can lead to necrosis of these areas, resulting in bone and cartilage death. Femoral fractures usually require surgical treatment, after which the patient will need mobility assistance for a prolonged period, either from family members or in a long-term care facility. Consequentially, the associated health care costs of “broken hips” are substantial. In addition, hip fractures are associated with increased rates of morbidity (incidences of disease) and mortality (death). Surgery for a hip fracture followed by prolonged bed rest may lead to life-threatening complications, including pneumonia, infection of pressure ulcers (bedsores), and thrombophlebitis (deep vein thrombosis; blood clot formation) that can result in a pulmonary embolism (blood clot within the lung). Greater trochanteric pain (bursitis/tendon irritation): pain on the outer hip.

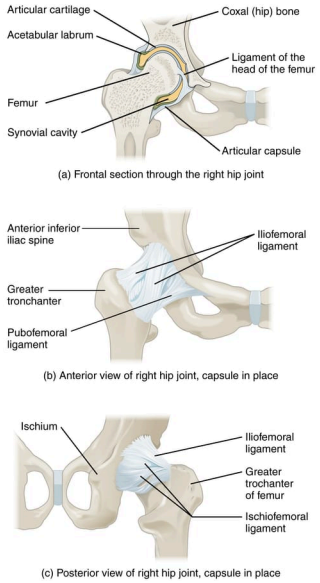


Figure 9.6.5: Frontal, anterior, and posterior views of the right hip joint, highlighting the acetabulum, femur, articular capsule, and major intrinsic ligaments including the iliofemoral, pubofemoral, and ischiofemoral ligaments. (CC BY 4.0; via Anatomy of Selected Synovial Joints).
Alternate text description of the Figure 9.6.5.

Knee Joint

The knee joint is the largest joint of the body (Figure 9.6.6). All of these articulations are enclosed within a single articular capsule. It has three articulations inside one joint capsule (one “bag” of tissue that surrounds the joint):

- Femoropatellar joint: between the patella (kneecap) and the distal femur.
- Medial tibiofemoral joint: medial femoral condyle with medial tibial condyle.
- Lateral tibiofemoral joint: lateral femoral condyle with lateral tibial condyle.

Main movements and how they happen

- The knee works mainly as a hinge.
- Flexion = bending the knee.
- Extension = straightening the knee.
- Movement is a mix of rolling and gliding of the femur on the tibia. Rolling changes the angle (bends or straightens). Gliding keeps the femoral condyles centered on the tibial condyles for stable weight bearing.
- A small rotation happens only when the knee is flexed (bent), not when fully extended (straight).
- Locking - As the knee reaches full extension, the femur turns slightly inward (medial rotation). This “locks” the knee for stability.
- Unlocking - The popliteus muscle starts flexion by turning the femur slightly outward (lateral rotation). This “unlocks” the knee.

The knee is well constructed for weight bearing in its extended position, but is vulnerable to injuries associated with

hyperextension, twisting, or blows to the medial or lateral side of the joint, particularly while weight bearing.

Patella and extensor mechanism

The patella is a sesamoid bone inside the quadriceps tendon. It slides up and down in a groove on the femur (femoropatellar joint). The patellar ligament continues from the patella to the tibia. The quadriceps muscle group extends (straightens) the knee and acts like a “dynamic ligament” to help stabilize the joint.

Menisci (shock absorbers and fitters)

Two C-shaped fibrocartilage pads sit between femur and tibia: Medial meniscus and lateral meniscus. Thin on the inner edge, thick on the outer edge; attached to the tibia (not to the femur). They improve fit, spread load, and add cushioning. The medial meniscus moves less because it is attached to the joint capsule and the medial (tibial) collateral ligament. Some areas have poor blood supply, so healing can be slow or incomplete.

Ligaments and stability

- Collateral ligaments (outside the capsule on the sides): Both are tight in full extension, preventing side-to-side and unwanted rotation.
  - Fibular (lateral) collateral ligament (LCL): from lateral femur to fibular head; limits varus (inward) stress.
  - Tibial (medial) collateral ligament (MCL): from medial femur to medial tibia; attached to capsule and medial meniscus; limits outward stress.
- Cruciate ligaments (inside the joint capsule): The cruciate ligaments are named for the X-shape formed as they pass each other (cruciate means “cross”).
  - Anterior cruciate ligament (ACL): tight in extension; resists hyperextension and limits forward slide of the tibia under the femur.
  - Posterior cruciate ligament (PCL): stronger; supports the flexed, weight-bearing knee and prevents the femur from sliding forward on the tibia (or tibia sliding backward).
- Posterior capsule
- Thickened areas help resist hyperextension.

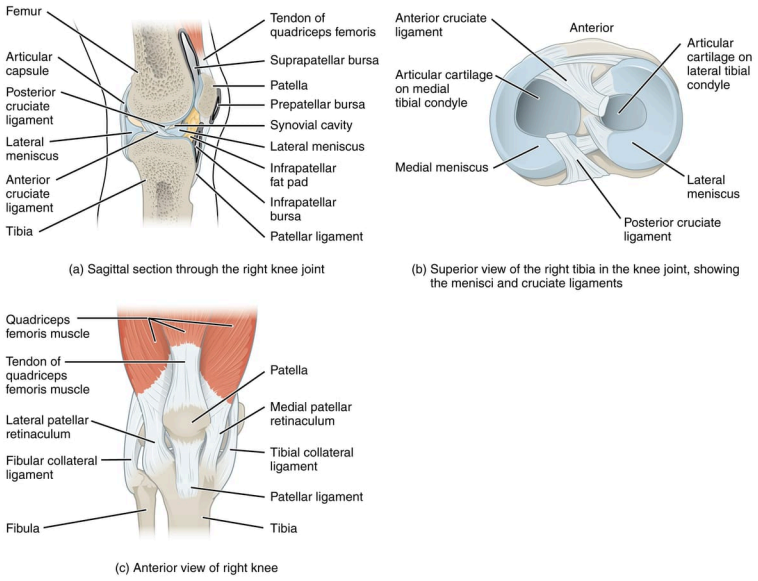


Figure 9.6.6: Sagittal, superior, and anterior views of the right knee joint, highlighting the menisci, cruciate ligaments, collateral ligaments, bursae, patella, and articular structures. (CC BY 4.0; via Anatomy of Selected Synovial Joints). Alternate text description of the Figure 9.6.6.

Joints

Injuries to the knee are common. Since this joint is primarily supported by muscles and ligaments, injuries to any of these structures will result in pain or knee instability. Injury to the posterior cruciate ligament occurs when the knee is flexed and the tibia is driven posteriorly, such as falling and landing on the tibial tuberosity or hitting the tibia on the dashboard when not wearing a seatbelt during an automobile accident. More commonly, injuries occur when forces are applied to the extended knee, particularly when the foot is planted and unable to move. Anterior cruciate ligament injuries can result with a forceful blow to the anterior knee, producing hyperextension, or when a runner makes a quick change of direction that produces both twisting and hyperextension of the knee.

A worse combination of injuries can occur with a hit to the lateral side of the extended knee (Figure 9.6.7). A moderate blow to the lateral knee will cause the medial side of the joint to open, resulting in stretching or damage to the tibial collateral ligament. Because the medial meniscus is attached to the tibial collateral ligament, a stronger blow can tear the ligament and also damage the medial meniscus. This is one reason that the medial meniscus is 20 times more likely to be injured than the lateral meniscus. A powerful blow to the lateral knee produces a “terrible triad” injury, in which there is a sequential injury to the tibial collateral ligament, medial meniscus, and anterior cruciate ligament.

Arthroscopic surgery has greatly improved the surgical treatment of knee injuries and reduced subsequent recovery times. This procedure involves a small incision and the insertion into the joint of an arthroscope, a pencil-thin instrument that allows for visualization of the joint interior. Small surgical instruments are also inserted via additional incisions. These tools allow a surgeon to remove or repair a torn meniscus or to reconstruct a ruptured cruciate ligament. The current method for anterior cruciate ligament replacement involves using a portion of the patellar ligament. Holes are drilled into the cruciate ligament attachment points on the tibia and femur, and the patellar ligament graft, with small areas of attached bone still intact at each end, is inserted into these holes. The bone-to-bone sites at each end of the graft heal rapidly and strongly, thus enabling a rapid recovery.

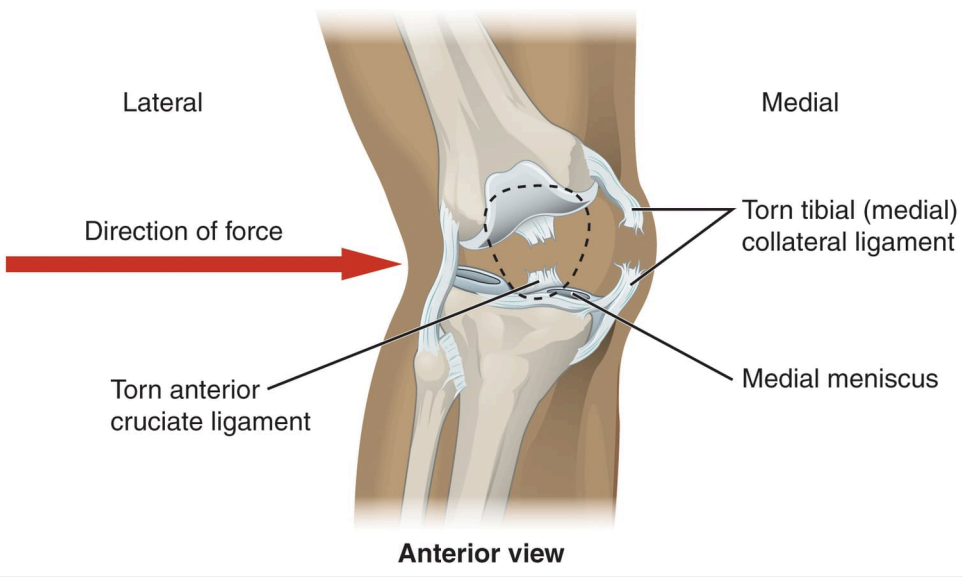


Figure 9.6.7: A strong blow to the lateral side of the extended knee will cause three injuries, in sequence: tearing of the tibial collateral ligament, damage to the medial meniscus, and rupture of the anterior cruciate ligament. (CC BY 4.0; via Anatomy of Selected Synovial Joints). Alternate text description of the Figure 9.6.7.

Ankle and Foot Joints

The ankle is not one joint but two main joints working together:

- **Talocrural joint** (true ankle): where the tibia and fibula (lower leg bones) meet the talus (foot bone) (Figure 9.6.8).

- **Subtalar joint**: where the talus meets the calcaneus (heel bone).

Together, these joints allow the foot to move in multiple directions and help absorb shock when walking.

The bones

- **Tibia**: the larger shin bone on the inside of the ankle; its lower end is called the medial malleolus (inside ankle bump).
- **Fibula**: the smaller bone on the outside of the lower leg; its lower end is called the lateral malleolus (outside ankle bump).
- **Talus**: a small bone that sits between the tibia and fibula; it has a pulley-shaped top surface (trochlea) that allows up-and-down movement.
- **Calcaneus**: the heel bone; it connects to the talus below.

Joint structure (inside the joint)

- **Articular cartilage**: smooth coating on bone ends; reduces friction.
- **Synovial membrane**: thin lining that makes lubricating fluid.
- **Synovial fluid**: keeps the joint moving smoothly.
- **Joint capsule**: a watertight sac of ligaments and soft tissue that surrounds the joint.

Main movements The ankle moves in four directions

The talocrural joint mainly allows dorsiflexion and plantarflexion (about 20° dorsiflexion and 30–50° plantarflexion).

- **Dorsiflexion** (extension): bring your toes toward your head (upward).
- **Plantarflexion** (flexion): point your foot downward.

Inversion and eversion happen at the subtalar joint and other small joints in the foot.

- **Inversion**: turn the sole of your foot inward.
- **Eversion**: turn the sole of your foot outward.

Inversion sprains most common; the foot turns inward too far, stretching the lateral ligaments on the outside.

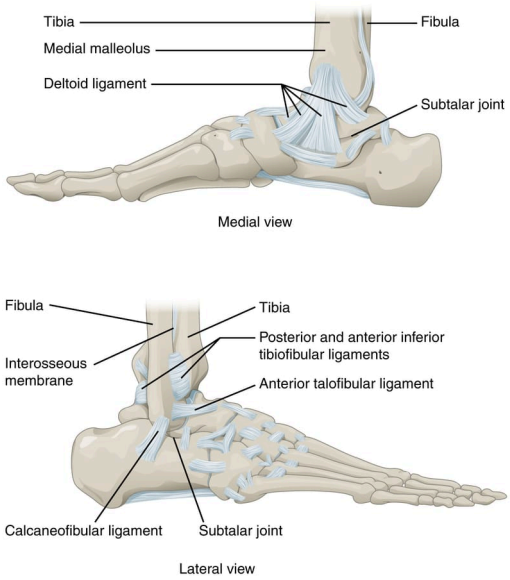


Figure 9.6.8: The talocrural (ankle) joint is a uniaxial hinge joint that only allows for dorsiflexion or plantar flexion of the foot. Movements at the subtalar joint, between the talus and calcaneus bones, combined with motions at other intertarsal joints, enables eversion/inversion movements of the foot. Ligaments that unite the medial or lateral malleolus with the talus and calcaneus bones serve to support the talocrural joint and to resist excess eversion or inversion of the foot. (CC BY 4.0; via Anatomy of Selected Synovial Joints). Alternate text description of the Figure 9.6.8.

Disorders of the...

Joints

The ankle is the most frequently injured joint in the body, with the most common injury being an inversion ankle sprain. A sprain is the stretching or tearing of the supporting ligaments. Excess inversion causes the talus bone to tilt laterally, thus damaging the ligaments on the lateral side of the ankle. The anterior talofibular ligament is most commonly injured, followed by the calcaneofibular ligament. In severe inversion injuries, the forceful lateral movement of the talus not only ruptures the lateral ankle ligaments, but also fractures the distal fibula.

Less common are eversion sprains of the ankle, which involve stretching of the deltoid ligament on the medial side of the ankle. Forcible eversion of the foot, for example, with an awkward landing from a jump or when a football player has a foot planted and is hit on the lateral ankle, can result in a Pott's fracture and dislocation of the ankle joint. In this injury, the very strong deltoid ligament does not tear, but instead shears off the medial malleolus of the tibia. This frees the talus, which moves laterally and fractures the distal fibula. In extreme cases, the posterior margin of the tibia may also be sheared off.

Above the ankle, the distal ends of the tibia and fibula are united by a strong syndesmosis formed by the interosseous membrane and ligaments at the distal tibiofibular joint. These connections prevent separation between the distal ends of the tibia and fibula and maintain the talus locked into position between the medial malleolus and lateral malleolus. Injuries that produce a lateral twisting of the leg on top of the planted foot can result in stretching or tearing of the tibiofibular ligaments, producing a syndesmotic ankle sprain or "high ankle sprain."

Most ankle sprains can be treated using the RICE technique: Rest, Ice, Compression, and Elevation. Reducing joint mobility using a brace or cast may be required for a period of time. More severe injuries involving ligament tears or bone fractures may require surgery.

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9.7: Terms and Definitions

Key Terms

Select to view definitions

Abduction
movement in the coronal plane that moves a limb laterally away from the body; spreading of the fingers

Acetabular labrum
lip of fibrocartilage that surrounds outer margin of the acetabulum on the hip bone

Adduction
movement in the coronal plane that moves a limb medially toward or across the midline of the body; bringing fingers together

Amphiarthrosis
slightly mobile joint

Annular ligament
intrinsic ligament of the elbow articular capsule that surrounds and supports the head of the radius at the proximal radioulnar joint

Anterior cruciate ligament
intracapsular ligament of the knee; extends from anterior, superior surface of the tibia to the inner aspect of the lateral condyle of the femur; resists hyperextension of knee

Anterior talofibular ligament
intrinsic ligament located on the lateral side of the ankle joint, between talus bone and lateral malleolus of fibula; supports talus at the talocrural joint and resists excess inversion of the foot

Articular capsule
connective tissue structure that encloses the joint cavity of a synovial joint

Articular cartilage
thin layer of hyaline cartilage that covers the articulating surfaces of bones at a synovial joint

Articular disc
meniscus; a fibrocartilage structure found between the bones of some synovial joints; provides padding or smooths movements between the bones; strongly unites the bones together

Articulation
joint of the body

Atlanto-occipital joint
articulation between the occipital condyles of the skull and the superior articular processes of the atlas (C1 vertebra)

Atlantoaxial joint
series of three articulations between the atlas (C1) vertebra and the axis (C2) vertebra, consisting of the joints between the inferior articular processes of C1 and the superior articular processes of C2, and the articulation between the dens of C2 and the anterior arch of C1

Ball-and-socket joint
synovial joint formed between the spherical end of one bone (the ball) that fits into the depression of a second bone (the socket); found at the hip and shoulder joints; functionally classified as a multiaxial joint

Biaxial joint
type of diarthrosis; a joint that allows for movements within two planes (two axes)

Bursa
connective tissue sac containing lubricating fluid that prevents friction between adjacent structures, such as skin and bone, tendons and bone, or between muscles

Calcaneofibular ligament
intrinsic ligament located on the lateral side of the ankle joint, between the calcaneus bone and lateral malleolus of the fibula; supports the talus bone at the ankle joint and resists excess inversion of the foot

Cartilaginous joint
joint at which the bones are united by hyaline cartilage (synchondrosis) or fibrocartilage (symphysis)

Circumduction
circular motion of the arm, thigh, hand, thumb, or finger that is produced by the sequential combination of flexion, abduction, extension, and adduction

Condyloid joint
synovial joint in which the shallow depression at the end of one bone receives a rounded end from a second bone or a rounded structure formed by two bones; found at the metacarpophalangeal joints of the fingers or the radiocarpal joint of the wrist; functionally classified as a biaxial joint

Coracohumeral ligament
intrinsic ligament of the shoulder joint; runs from the coracoid process of the scapula to the anterior humerus

Deltoid ligament
broad intrinsic ligament located on the medial side of the ankle joint; supports the talus at the talocrural joint and resists excess eversion of the foot

Depression
downward (inferior) motion of the scapula or mandible

Diarthrosis
freely mobile joint

Dorsiflexion
movement at the ankle that brings the top of the foot toward the anterior leg

Elbow joint
humeroulnar joint

Elevation
upward (superior) motion of the scapula or mandible

Eversion
foot movement involving the intertarsal joints of the foot in which the bottom of the foot is turned laterally, away from the midline

Extension
movement in the sagittal plane that increases the angle of a joint (straightens the joint); motion involving posterior bending of the vertebral column or returning to the upright position from a flexed position

Extrinsic ligament
ligament located outside of the articular capsule of a synovial joint

Femoropatellar joint
portion of the knee joint consisting of the articulation between the distal femur and the patella

Fbrous joint
joint where the articulating areas of the adjacent bones are connected by fibrous connective tissue

Fibular collateral ligament
extrinsic ligament of the knee joint that spans from the lateral epicondyle of the femur to the head of the fibula; resists hyperextension and rotation of the extended knee

Fexion
movement in the sagittal plane that decreases the angle of a joint (bends the joint); motion involving anterior bending of the vertebral column

Fontanelles
expanded areas of fibrous connective tissue that separate the braincase bones of the skull prior to birth and during the first year after birth

Glenohumeral joint
shoulder joint; articulation between the glenoid cavity of the scapula and head of the humerus; multiaxial ball-and-socket joint that allows for flexion/extension, abduction/adduction, circumduction, and medial/lateral rotation of the humerus

Glenohumeral ligament
one of the three intrinsic ligaments of the shoulder joint that strengthen the anterior articular capsule

Glenoid labrum
lip of fibrocartilage located around the outside margin of the glenoid cavity of the scapula

Gomphosis
type of fibrous joint in which the root of a tooth is anchored into its bony jaw socket by strong periodontal ligaments

Hinge joint
synovial joint at which the convex surface of one bone articulates with the concave surface of a second bone; includes the elbow, knee, ankle, and interphalangeal joints; functionally classified as a uniaxial joint

Humeroradial joint
articulation between the capitulum of the humerus and head of the radius

Humeroulnar joint
articulation between the trochlea of humerus and the trochlear notch of the ulna; uniaxial hinge joint that allows for flexion/extension of the forearm

Hyperextension
excessive extension of joint, beyond the normal range of movement

Hyperflexion
excessive flexion of joint, beyond the normal range of movement

Iliofemoral ligament
intrinsic ligament spanning from the ilium of the hip bone to the femur, on the superior-anterior aspect of the hip joint

Inferior rotation
movement of the scapula during upper limb adduction in which the glenoid cavity of the scapula moves in a downward direction as the medial end of the scapular spine moves in an upward direction

Interosseous membrane
wide sheet of fibrous connective tissue that fills the gap between two parallel bones, forming a syndesmosis; found between the radius and ulna of the forearm and between the tibia and fibula of the leg

Intracapsular ligament
ligament that is located within the articular capsule of a synovial joint

Intrinsic ligament
ligament that is fused to or incorporated into the wall of the articular capsule of a synovial joint

Inversion
foot movement involving the intertarsal joints of the foot in which the bottom of the foot is turned toward the midline

Ischiofemoral ligament
intrinsic ligament spanning from the ischium of the hip bone to the femur, on the posterior aspect of the hip joint

Joint
site at which two or more bones or bone and cartilage come together (articulate)

Joint cavity
space enclosed by the articular capsule of a synovial joint that is filled with synovial fluid and contains the articulating surfaces of the adjacent bones

Joint interzone
site within a growing embryonic limb bud that will become a synovial joint

Lateral (external) rotation
movement of the arm at the shoulder joint or the thigh at the hip joint that moves the anterior surface of the limb away from the midline of the body

Lateral excursion
side-to-side movement of the mandible away from the midline, toward either the right or left side

Lateral flexion
bending of the neck or body toward the right or left side

Lateral meniscus
C-shaped fibrocartilage articular disc located at the knee, between the lateral condyle of the femur and the lateral condyle of the tibia

Lateral tibiofemoral joint
portion of the knee consisting of the articulation between the lateral condyle of the tibia and the lateral condyle of the femur; allows for flexion/extension at the knee

Ligament
strong band of dense connective tissue spanning between bones

Ligament of the head of the femur
intracapsular ligament that runs from the acetabulum of the hip bone to the head of the femur

Medial (internal) rotation
movement of the arm at the shoulder joint or the thigh at the hip joint that brings the anterior surface of the limb toward the midline of the body

Medial excursion
side-to-side movement that returns the mandible to the midline

Medial meniscus
C-shaped fibrocartilage articular disc located at the knee, between the medial condyle of the femur and medial condyle of the tibia

Medial tibiofemoral joint
portion of the knee consisting of the articulation between the medial condyle of the tibia and the medial condyle of the femur; allows for flexion/extension at the knee

Meniscus
articular disc

Multiaxial joint
type of diarthrosis; a joint that allows for movements within three planes (three axes)

Opposition
thumb movement that brings the tip of the thumb in contact with the tip of a finger

Patellar ligament
ligament spanning from the patella to the anterior tibia; serves as the final attachment for the quadriceps femoris muscle

Periodontal ligament
band of dense connective tissue that anchors the root of a tooth into the bony jaw socket

Pivot joint
synovial joint at which the rounded portion of a bone rotates within a ring formed by a ligament and an articulating bone; functionally classified as uniaxial joint

Plane joint
synovial joint formed between the flattened articulating surfaces of adjacent bones; functionally classified as a multiaxial joint

Plantar flexion
foot movement at the ankle in which the heel is lifted off of the ground

Posterior cruciate ligament
intracapsular ligament of the knee; extends from the posterior, superior surface of the tibia to the inner aspect of the medial condyle of the femur; prevents anterior displacement of the femur when the knee is flexed and weight bearing

Posterior talofibular ligament
intrinsic ligament located on the lateral side of the ankle joint, between the talus bone and lateral malleolus of the fibula; supports the talus at the talocrural joint and resists excess inversion of the foot

Pronated position
forearm position in which the palm faces backward

Pronation
forearm motion that moves the palm of the hand from the palm forward to the palm backward position

Protraction
anterior motion of the scapula or mandible

Proximal radioulnar joint
articulation between head of radius and radial notch of ulna; uniaxial pivot joint that allows for rotation of radius during pronation/supination of forearm

Pubofemoral ligament
intrinsic ligament spanning from the pubis of the hip bone to the femur, on the anterior-inferior aspect of the hip joint

Radial collateral ligament
intrinsic ligament on the lateral side of the elbow joint; runs from the lateral epicondyle of humerus to merge with the annular ligament

Reposition
movement of the thumb from opposition back to the anatomical position (next to index finger)

Retraction
posterior motion of the scapula or mandible

Rotation
movement of a bone around a central axis (atlantoaxial joint) or around its long axis (proximal radioulnar joint; shoulder or hip joint); twisting of the vertebral column resulting from the summation of small motions between adjacent vertebrae

Rotator cuff
strong connective tissue structure formed by the fusion of four rotator cuff muscle tendons to the articular capsule of the shoulder joint; surrounds and supports superior, anterior, lateral, and posterior sides of the humeral head

Saddle joint
synovial joint in which the articulating ends of both bones are convex and concave in shape, such as at the first carpometacarpal joint at the base of the thumb; functionally classified as a biaxial joint

Subacromial bursa
bursa that protects the supraspinatus muscle tendon and superior end of the humerus from rubbing against the acromion of the scapula

Subcutaneous bursa
bursa that prevents friction between skin and an underlying bone

Submuscular bursa
bursa that prevents friction between bone and a muscle or between adjacent muscles

Subscapular bursa
bursa that prevents rubbing of the subscapularis muscle tendon against the scapula

Subtalar joint
articulation between the talus and calcaneus bones of the foot; allows motions that contribute to inversion/eversion of the foot

Subtendinous bursa
bursa that prevents friction between bone and a muscle tendon

Superior rotation
movement of the scapula during upper limb abduction in which the glenoid cavity of the scapula moves in an upward direction as the medial end of the scapular spine moves in a downward direction

Supinated position
forearm position in which the palm faces anteriorly (anatomical position)

Supination
forearm motion that moves the palm of the hand from the palm backward to the palm forward position

Suture
fibrous joint that connects the bones of the skull (except the mandible); an immobile joint (synarthrosis)

Symphysis
type of cartilaginous joint where the bones are joined by fibrocartilage

Synarthrosis
immobile or nearly immobile joint

Synchondrosis
type of cartilaginous joint where the bones are joined by hyaline cartilage

Syndesmosis
type of fibrous joint in which two separated, parallel bones are connected by an interosseous membrane

Synostosis
site at which adjacent bones or bony components have fused together

Synovial fluid
thick, lubricating fluid that fills the interior of a synovial joint

Synovial joint
joint at which the articulating surfaces of the bones are located within a joint cavity formed by an articular capsule

Synovial membrane
: thin layer that lines the inner surface of the joint cavity at a synovial joint; produces the synovial fluid

Talocrural joint
: ankle joint; articulation between the talus bone of the foot and medial malleolus of the tibia, distal tibia, and lateral malleolus of the fibula; a uniaxial hinge joint that allows only for dorsiflexion and plantar flexion of the foot

Temporomandibular joint (TMJ)
: articulation between the condyle of the mandible and the mandibular fossa and articular tubercle of the temporal bone of the skull; allows for depression/elevation (opening/closing of mouth), protraction/retraction, and side-to-side motions of the mandible

Tendon
: dense connective tissue structure that anchors a muscle to bone

Tendon sheath
: connective tissue that surrounds a tendon at places where the tendon crosses a joint; contains a lubricating fluid to prevent friction and allow smooth movements of the tendon

Tibial collateral ligament
: extrinsic ligament of knee joint that spans from the medial epicondyle of the femur to the medial tibia; resists hyperextension and rotation of extended knee

Ulnar collateral ligament
: intrinsic ligament on the medial side of the elbow joint; spans from the medial epicondyle of the humerus to the medial ulna

Uniaxial joint
: type of diarthrosis; joint that allows for motion within only one plane (one axis)

Zygapophysial joints
: facet joints; plane joints between the superior and inferior articular processes of adjacent vertebrae that provide for only limited motions between the vertebrae

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9.8: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. The joint between adjacent vertebral bodies that includes an intervertebral disc is functionally classified as which type of joint?
   A. Diarthrosis
   B. Multiaxial joint
   C. Amphiarthrosis
   D. Synarthrosis

2. Which of these joints is functionally classified as a synarthrosis in the adult?
   A. Pubic symphysis
   B. Manubriosternal joint after it fuses
   C. Intervertebral disc joint
   D. Shoulder joint

3. Which of these joints is best classified as a biaxial diarthrosis?
   A. Metacarpophalangeal (knuckle) joint
   B. Hip joint
   C. Elbow joint
   D. Pubic symphysis

4. Which statement best describes a synovial joint?
   A. It may be functionally classified as a synarthrosis.
   B. The bones are joined exclusively by hyaline cartilage.
   C. It may be functionally classified as an amphiarthrosis.
   D. The bones articulate within a fluid-filled joint cavity enclosed by a capsule.

5. Which type of fibrous joint connects the distal tibia and fibula?
   A. Syndesmosis
   B. Symphysis
   C. Suture
   D. Gomphosis

6. Which of the following is an example of a wide fibrous joint?
   A. Interosseous membrane of the forearm
   B. Periodontal ligament of a gomphosis
   C. Sagittal suture of the skull
   D. Synostosis of the frontal bone

7. A gomphosis is which type of joint?
   A. A joint formed by an interosseous membrane

B. A joint connecting the tibia and fibula bones of the leg
C. A synovial joint containing a joint cavity
D. A fibrous joint that anchors a tooth to the jaw

8. A syndesmosis is best described as which type of joint?
A. A narrow fibrous joint found between most skull bones
B. A fibrous joint that unites parallel bones by a ligament or interosseous membrane
C. The fibrous joint that anchors teeth in the jaws
D. A cartilaginous joint between vertebral bodies

9. A cartilaginous joint has which characteristic?
A. A true joint cavity lined by a synovial membrane
B. It is called a symphysis when the bones are united by fibrocartilage.
C. It anchors the teeth to the jaws.
D. It is formed by a broad sheet of fibrous connective tissue.

10. Which best describes a synchondrosis?
A. Found at the pubic symphysis
B. A joint where bones are connected by fibrocartilage
C. A type of fibrous joint
D. Found at the first sternocostal joint between the first rib and the manubrium

11. Which of the following pairs of bones are joined together by a symphysis?
A. Adjacent vertebral bodies
B. First rib and sternum
C. Diaphysis and epiphysis of a long bone
D. Radius and ulna

12. The epiphyseal plate of a growing long bone in a child is structurally classified as which type of joint?
A. Synchondrosis
B. Synostosis
C. Symphysis
D. Syndesmosis

13. Which type of synovial joint provides the greatest range of motion in all planes?
A. Ball-and-socket joint
B. Hinge joint
C. Condyloid (ellipsoid) joint
D. Plane (gliding) joint

14. Which type of synovial joint allows movement primarily around a single axis (uniaxial)?
A. Saddle joint
B. Hinge joint
C. Condyloid joint
D. Ball-and-socket joint

15. Which of the following is an example of a synovial joint type?
A. Synostosis
B. Suture
C. Plane joint
D. Synchondrosis

16. What is the role of a bursa at or near a synovial joint?
A. It completely surrounds a tendon where the tendon crosses a joint.
B. It secretes synovial fluid for the joint cavity.
C. It reduces friction between skin and bone or between a tendon and bone.
D. It forms the strong band of connective tissue that holds bones together at a joint.

17. Which statement is correct regarding synovial joints?
A. The articulating ends of the bones are directly connected by dense fibrous tissue.
B. The ends of the bones are enclosed within a space called a subcutaneous bursa.
C. Intrinsic ligaments are always entirely outside the articular capsule.
D. The joint cavity is filled with a thick, lubricating synovial fluid.

18. At a synovial joint, what is the primary function of the synovial membrane?
A. It forms the fibrous outer wall of the joint capsule.
B. It is the layer of cartilage that covers the articulating surfaces.
C. It forms intracapsular ligaments.
D. It secretes the lubricating synovial fluid into the joint cavity.

19. Which statement about condyloid (ellipsoid) joints is correct?
A. They are a special type of ball-and-socket joint.
B. They include the radiocarpal (wrist) joint.
C. They are uniaxial diarthroses.
D. They are found at the proximal radioulnar joint.

20. A meniscus found in a synovial joint such as the knee is best described as which of the following?
A. A fibrocartilage pad that improves fit and provides cushioning between bones
B. A fluid-filled sac that reduces friction between a tendon and bone
C. The hyaline articular cartilage covering the ends of a bone
D. The lubricating fluid within a synovial joint

21. The joints between the articular processes of adjacent vertebrae (facet joints) primarily allow which movement of the spine?
A. Lateral flexion
B. Circumduction
C. Dorsiflexion
D. Abduction

22. Which motion moves the sole of the foot away from the midline of the body?
A. Elevation
B. Dorsiflexion
C. Eversion
D. Plantar flexion

23. Movement of a body segment in a circular, cone-shaped path at a condyloid joint is termed which of the following?
A. Rotation
B. Elevation
C. Abduction
D. Circumduction

24. Supination at the forearm is the motion that moves which structure into which position?
A. Moves the hand from palm backward (posterior) to palm forward (anterior) position
B. Moves the foot so that the sole faces toward the midline of the body
C. Moves the hand from palm forward (anterior) to palm backward (posterior) position
D. Moves the scapula in an upward direction on the thoracic cage

25. Movement at the shoulder joint that moves the upper limb laterally away from the midline of the body is called which of the following?
A. Elevation
B. Eversion
C. Abduction
D. Lateral rotation

26. The primary dynamic stability of the glenohumeral (shoulder) joint is provided by which structure or group?
A. Coracohumeral ligament

B. Glenoid labrum
C. Rotator cuff muscles
D. Subacromial bursa

27. The proximal radioulnar joint has which characteristic?
A. It is stabilized by the annular ligament around the head of the radius.
B. It contains an articular disc that strongly unites the radius and ulna.
C. It is supported by the ulnar collateral ligament.
D. It is a hinge joint that allows flexion and extension of the forearm.

28. Which statement about the knee joint is true?
A. The lateral meniscus is an intrinsic ligament on the lateral side of the joint.
B. Hyperextension is primarily resisted by the posterior cruciate ligament.
C. The anterior cruciate ligament supports the knee when it is flexed and weight-bearing.
D. The medial meniscus is attached firmly to the tibial (medial) collateral ligament.

29. The talocrural (ankle) joint has which characteristic?
A. It is also called the subtalar joint.
B. It allows gliding movements that mainly produce inversion/eversion.
C. It is a uniaxial hinge joint permitting dorsiflexion and plantar flexion.
D. It is supported by the tibial collateral ligament on the lateral side.

30. In which region of the vertebral column is the range of motion for axial rotation (twisting) greatest?
A. Sacral region
B. Cervical region
C. Lumbar region
D. Thoracic region

31. Intramembranous ossification primarily produces which group of bones?
A. Bones of the upper and lower limbs
B. Bones forming the top and sides of the skull
C. Bones of the facial skeleton and base of the skull
D. Bones that begin as a hyaline cartilage model

32. During skeletal development, synovial joints form at which specific region within the developing limb or cartilage model?
A. At the fontanelles of the fetal skull
B. Directly by intramembranous ossification
C. At a specialized interzone between developing skeletal elements
D. Only after endochondral ossification is fully complete

33. Which statement best distinguishes a symphysis from a synchondrosis?
A. A symphysis unites bones with fibrocartilage, whereas a synchondrosis unites bones with hyaline cartilage.
B. A symphysis is always synarthrotic, whereas a synchondrosis is always diarthrotic.
C. A symphysis has a fluid-filled cavity, whereas a synchondrosis does not.
D. A symphysis occurs only in the skull, whereas a synchondrosis occurs only in the limbs.

34. Which of the following movements is an example of opposition?
A. Moving the thumb to touch the tips of the other fingers
B. Turning the sole of the foot inward
C. Lifting the scapula toward the ears
D. Rotating the forearm so the palm faces downward

35. Which factor is most likely to increase joint stability while decreasing overall range of motion at a synovial joint?
A. Shallower articular surfaces and looser ligaments
B. Deeper congruent articular surfaces and strong surrounding ligaments
C. Absence of surrounding muscle tone
D. Absence of intracapsular ligaments

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9.9: Applied Thinking Self-Check

Challenge Yourself

- Purpose: Show how joint structure explains joint movement and stability.
- How to answer (per question):
  a. Direct answer: one sentence that clearly answers the main prompt.
  b. Mechanism: 3 to 5 sentences that explain how structure (bones, cartilage, ligaments, capsule, muscles) creates the function (movement/stability). Use cause → effect language.
  c. Example or small diagram: 1 to 2 sentences (or a simple labeled sketch) that supports your claim.

1. Define how joints are classified based on function. Describe and give an example for each functional type of joint.
2. The periodontal ligaments are made of collagen fibers and are responsible for connecting the roots of the teeth to the jaws. Describe how scurvy, a disease that inhibits collagen production, can affect the teeth.
3. A student reports jaw clicking and brief “lock” when chewing gum. Explain how the temporomandibular joint (a modified hinge with an articular disc) can cause these symptoms. Include the role of the disc, the joint’s gliding + hinge motions, and muscle tension. Suggest one self-care change (e.g., softer diet, limiting gum) and the mechanism for relief.
4. Which joint is more mobile and which is more stable: the shoulder (glenohumeral) or the hip? Explain how their structures (socket depth, labrum, capsule tightness, surrounding ligaments, muscle support) create these differences. Give one common injury risk for each joint and one strategy to protect it in daily life.
5. Explain how the knee becomes stable in full extension (“locks”) and how it “unlocks” to start flexion. Then predict what movement or activity becomes harder or riskier if the anterior cruciate ligament (ACL) is torn, and why. Include the role of rolling-gliding and one stabilizer (e.g., menisci, collateral ligaments, capsule).
6. The elbow does two main things: hinge flexion/extension and forearm pronation/supination. Name the joints that do each movement (humeroulnar/humeroradial vs proximal radioulnar) and explain how their shapes (hinge vs pivot) allow these actions. Give one everyday task for each movement (e.g., lifting a cup vs turning a doorknob) and link it to the joint.
7. Compare the pubic symphysis (fibrocartilage, limited movement) with the knee (synovial, hinge with menisci). How does each joint’s tissue and design match its function in walking and load-bearing? Predict one problem that occurs if the meniscus is torn or if the pubic symphysis becomes too mobile, and explain why.

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9.10: Alternate Text Descriptions

Figure 9.1.1: Suture Joints of Skull

This image shows a side view of the skull with three cranial sutures labeled. The coronal suture is labeled near the front of the skull, separating the frontal bone from the parietal region. The squamous suture is labeled along the side of the skull above the ear region, where the parietal bone meets the temporal bone. The lambdoid suture is labeled toward the back of the skull, where the parietal region meets the occipital region.

Figure 9.1.2: Intervertebral Disc

This image shows a lateral view of two adjacent vertebrae. The purpose of the diagram is to identify the intervertebral disc and its position between neighboring vertebral bodies. The upper and lower bones are labeled as vertebral body. Between them is a labeled intervertebral disc, shown separating the two vertebral bodies. The image emphasizes the disc as the cartilaginous connection between adjacent vertebrae in the spine.

Figure 9.1.3: Multiaxial Joint

This image shows the hip joint as an example of a ball-and-socket synovial joint.

On the left, the image shows the head of the femur fitting into the acetabulum of the hip bone. The rounded head of the femur forms the ball, and the acetabulum forms the socket. The labeled structures emphasize how the femur articulates with the pelvis.

On the right, a simplified mechanical diagram represents the same type of joint. Curved arrows around the model indicate that this joint allows movement in multiple directions, including rotation and movement through more than one plane.

Figure 9.2.1: Fibrous Joints

This image compares three types of fibrous joints in panels (a), (b), and (c).

In panel (a), a section of skull bone shows a suture. The image labels the suture line, the suture, and the dense fibrous connective tissue that joins adjacent skull bones. This panel emphasizes the tightly joined fibrous connection between skull bones.

In panel (b), the ulna and radius are connected by the antebrachial interosseous membrane. The joint type is labeled syndesmosis. This panel emphasizes a fibrous connection between two bones linked by a ligament-like sheet of connective tissue.

In panel (c), a tooth is anchored in its socket. The joint is labeled gomphosis, and the periodontal ligament is labeled between the root of the tooth and the socket. This panel emphasizes the fibrous attachment that holds a tooth in place.

Overall, the figure demonstrates three forms of fibrous joints: sutures between skull bones, syndesmoses between bones joined by connective tissue, and gomphoses between a tooth and its socket.

Figure 9.2.2: The Newborn Skull

This image shows a lateral view of an infant skull, with the profile facing to the right. The figure highlights the locations of fontanelles, ossification centers, and major cranial bones that are not yet fully fused.

The overall organization shows the infant skull as a group of developing bones separated by fontanelles, which are soft connective tissue regions between bones. The labels in the image include frontal bone, parietal bone, temporal bone, occipital bone, anterior fontanelle, posterior fontanelle, sphenoidal (anterolateral) fontanelle, mastoid (posterolateral) fontanelle, and ossification center. The figure emphasizes how the infant skull differs from an adult skull by showing flexible regions and active sites of bone formation.

The frontal bone is located at the front of the skull. Its functions are to form the forehead and upper region of the face and to protect the developing brain. The parietal bone is located on the upper and lateral sides of the skull. Its functions are to protect the upper brain and expand outward as the brain grows. The temporal bone, specifically its squamous portion, is located on the side of the skull near the ear region. Its functions are to contribute to the lateral wall of the skull and protect structures related to hearing and balance. The occipital bone is located at the posterior part of the skull. Its functions are to protect the back of the brain and form the base of the skull.

The figure identifies several fontanelles, which are flexible connective tissue areas that allow skull growth and deformation during birth. The anterior fontanelle is a large soft region at the junction of the frontal and parietal bones. Its functions are to allow expansion of the skull as the brain grows, facilitate passage of the head during birth, and remain open longer than the other fontanelles. The posterior fontanelle is located at the junction of the parietal and occipital bones. Its functions are to allow limited flexibility in the posterior skull and to close earlier than the anterior fontanelle. The sphenoidal, or anterolateral, fontanelle is located on the lateral skull near the frontal, parietal, temporal, and sphenoid bones. Its functions are to allow flexibility in the anterior lateral skull and provide space for brain growth. The mastoid, or posterolateral, fontanelle is located near the temporal and occipital bones. Its functions are to allow movement and expansion of the skull in the posterior lateral region.

The figure also identifies an ossification center within the parietal bone. This is a region where bone formation begins. Its functions are to indicate the process of bone development, or ossification, and support the gradual formation and strengthening of the skull.

Figure 9.3.1: Epiphyseal Plate

This image contains two labeled examples of cartilaginous joints.

In panel (a), the image shows a section through the end of a long bone. A labeled epiphyseal plate appears between the end region and the shaft of the bone. The label identifies it as a temporary hyaline cartilage joint. The image emphasizes the location of the growth plate within a developing long bone.

In panel (b), the image shows the pelvis from the front. The label points to the pubic symphysis, which joins the left and right pubic bones at the midline. The joint is shown as a vertical pad-like structure between the two sides of the pelvis.

Figure 9.4.1: Synovial Joints

This image shows a section through a synovial joint, with two articulating long bones facing one another and the structures that allow movement, lubrication, and joint stability.

The overall organization shows two opposing bones whose ends are covered by articular cartilage. Between them is a joint cavity containing synovial fluid. The joint is enclosed by an articular capsule made of two layers: an outer fibrous membrane and an inner synovial membrane. The labels in the image include bone, spongy bone, articular cartilage, joint cavity, synovial fluid, articular capsule, fibrous membrane, and synovial membrane.

Figure 9.4.2: Bursae

This image shows a cross-sectional, sagittal view of the knee joint, illustrating the bones, ligaments, tendons, bursae, and synovial structures that support movement, stability, and force transmission.

The overall organization shows the knee joint between the femur, which is the upper bone of the leg, and the tibia, which is the lower bone. The patella, or kneecap, is positioned anterior to the joint. The figure also shows stabilizing ligaments, a synovial cavity containing fluid, and several bursae that reduce friction. The labels in the image include femur, tibia, patella, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), patellar ligament, tendon of quadriceps femoris, synovial cavity, articular cartilage, suprapatellar bursa, prepatellar bursa, infrapatellar bursa, and infrapatellar fat pad.

Figure 9.4.3: Synovial Joints

This image shows a full skeleton in the center with arrows pointing to six types of synovial joints arranged around it. Each joint

type is paired with a body example and a simplified mechanical model that shows its movement pattern.

a. Pivot joint is shown with the example between the C1 and C2 vertebrae. The model shows rotation around a central axis.
b. Hinge joint is shown with the example elbow. The model shows movement mainly in one plane, like bending and straightening.
c. Saddle joint is shown with the example between the trapezium carpal bone and first metacarpal bone. The model shows movement in two directions.
d. Plane joint is shown with the example between tarsal bones. The model shows flat surfaces sliding past one another.
e. Condyloid joint is shown with the example between the radius and carpal bones of the wrist. The model shows movement in two planes without axial rotation.
f. Ball-and-socket joint is shown with the example hip joint. The model shows movement in multiple directions, including rotation.

Overall, the figure compares the major synovial joint types by linking each one to a body location and a characteristic range of motion.

Figure 9.4.4: Osteoarthritis

This image compares a normal hip joint with a damaged hip joint.

On the left, the image labeled normal hip joint shows the rounded head of the femur fitting smoothly into the socket of the hip bone. The articular surface appears intact, and the joint space is preserved.

On the right, the damaged hip joint is labeled with decreased joint space, worn cartilage, and exposed bone. The articular surface is irregular rather than smooth, and areas of cartilage loss reveal underlying bone. The space between the articulating surfaces is reduced compared with the normal joint.

Figure 9.5.1: Anatomical Movements at Joints

This image is a multi-panel overview of common anatomical movements at joints. The panels are labeled (a) through (f) and show examples of flexion, extension, abduction, adduction, circumduction, and rotation.

- In panels (a) and (b), the figure shows flexion and extension at the shoulder and knee. Flexion is shown as bending that decreases the angle at the joint, while extension is shown as straightening that increases the angle.
- In panel (c), the figure shows flexion and extension of the neck. Flexion brings the head forward, and extension moves it backward.
- In panel (d), the figure shows flexion and extension of the vertebral column. Flexion bends the trunk forward, and extension bends it backward.
- In panel (e), the figure shows abduction, adduction, and circumduction of the upper limb at the shoulder. Abduction moves the limb away from the midline, adduction moves it back toward the midline, and circumduction moves the limb in a circular path.
- In panel (f), the figure shows rotation. The head and neck are shown rotating left and right. The lower limb is also shown with medial rotation and lateral rotation, indicating inward and outward turning around its long axis.

Figure 9.5.2: Anatomical Movements

This image is a multi-panel diagram of named anatomical movements. The panels are labeled (g) through (l) and each panel pairs a movement term with a body example.

- In panel (g), the figure shows pronation and supination of the forearm. During pronation, the radius rotates over the ulna. During supination, the radius and ulna are parallel.
- In panel (h), the figure shows dorsiflexion and plantar flexion at the ankle. Dorsiflexion lifts the front of the foot upward, and plantar flexion points the foot downward.
- In panel (i), the figure shows inversion and eversion of the foot. Inversion turns the sole inward, and eversion turns the sole outward.
- In panel (j), the figure shows retraction and protraction of the mandible. Retraction moves the mandible backward, and protraction moves it forward.

- In panel (k), the figure shows elevation and depression of the mandible. Elevation raises the mandible, and depression lowers it.

Figure 9.6.1: Atlantoaxial Joint

This image shows a superior view of the atlas, or C1 vertebra. At the center of the figure, the dens of C2 (axis) projects upward through the ring of the atlas, where it serves as a pivot for head rotation. The anterior arch of C1 is located at the front of the ring and forms a joint with the dens. A transverse ligament extends behind the dens, holding it against the anterior arch and stabilizing the joint while protecting the spinal cord. On the left and right sides, the superior articular facets are shown as smooth surfaces that articulate with the skull, allowing nodding movements of the head.

Figure 9.6.2: Temporomandibular Joint

This image shows a sagittal section of the temporomandibular joint (TMJ), illustrating the connection between the mandible, or lower jaw, and the temporal bone of the skull. A small inset at the top shows the location of the TMJ on the skull, and the main image presents a magnified cross-section of the joint.

The labels in the image include mandibular condyle, mandibular fossa, articular tubercle, ramus of mandible, articular disc, superior joint cavity, inferior joint cavity, and articular capsule.

The mandibular condyle is the rounded upper portion of the mandible. Its functions are to articulate with the temporal bone and enable movement of the jaw during speaking and chewing. The mandibular fossa is a depression in the temporal bone that receives the mandibular condyle and forms part of the joint surface. The articular tubercle is a raised area anterior to the mandibular fossa. Its functions are to guide movement of the condyle during jaw opening and help stabilize the joint. The ramus of the mandible is the vertical portion of the mandible connected to the condyle and provides attachment for muscles that move the jaw.

The articular disc is a thin fibrous structure located between the mandibular condyle and the temporal bone. Its functions are to divide the joint into two compartments, act as a cushion to absorb forces, and allow smooth movement between the bone surfaces.

The superior joint cavity is the space above the articular disc. Its function is to allow sliding, or gliding, movements of the jaw. The inferior joint cavity is the space below the articular disc. Its function is to allow hinge, or rotational, movements.

The articular capsule is the fibrous covering surrounding the joint. Its functions are to enclose the joint structures, provide stability and protection, and maintain the internal environment of the joint.

Figure 9.6.3: Glenohumeral Joint

This image shows a sectional view of the shoulder joint, also called the glenohumeral joint. The figure illustrates the relationship among the head of the humerus, the glenoid cavity of the scapula, and the surrounding structures that support joint movement and stability.

At the center of the figure, the rounded head of the humerus articulates with the shallow glenoid cavity of the scapula. Both articular surfaces are covered by articular cartilage, which creates smooth, low-friction surfaces where the bones meet. Surrounding the rim of the glenoid cavity is the glenoid labrum, a ring of fibrocartilage that deepens the socket.

The joint is enclosed by an articular capsule. The capsule has two layers:

- Fibrous membrane: the outer layer of the capsule
- Synovial membrane: the inner layer of the capsule

Together, these layers surround the joint cavity and help stabilize and lubricate the joint.

Superior to the joint is the acromion of the scapula, which forms part of the roof of the shoulder. The clavicle articulates with the acromion and is connected by the acromioclavicular ligament. Extending between the coracoid process and the acromion is the coracoacromial ligament, which forms an arch over the humeral head.

Passing beneath this arch is the tendon of the supraspinatus muscle, one of the rotator cuff tendons. Between this tendon and the overlying acromion is the subacromial bursa, a fluid-filled sac that reduces friction during shoulder movement.

The tendon of the biceps brachii muscle (long head) passes through the shoulder joint and along the proximal humerus. This tendon is surrounded by a tendon sheath, which reduces friction as the tendon moves.

The figure labels the following structures:

- Clavicle
- Acromioclavicular ligament
- Acromion of scapula
- Coracoacromial ligament
- Tendon of supraspinatus muscle
- Subacromial bursa
- Glenoid labrum
- Glenoid cavity
- Scapula
- Articular cartilage
- Articular capsule
  - Fibrous membrane
  - Synovial membrane
- Tendon sheath
- Tendon of biceps brachii muscle (long head)
- Head of humerus
- Humerus

The figure demonstrates how the shoulder joint combines mobility and stability. The head of the humerus articulates with the glenoid cavity of the scapula, while the glenoid labrum, articular capsule, ligaments, tendons, and surrounding bursae provide additional support. The supraspinatus tendon and the tendon of the long head of the biceps brachii help stabilize the joint, while the subacromial bursa and articular cartilage reduce friction during movement. Together, these structures allow the shoulder to achieve a wide range of motion while maintaining joint integrity.

Figure 9.6.4: Right Elbow Joint

This figure shows the right elbow joint in three panels: (a) a medial sagittal section, (b) a lateral view, and (c) a medial view. Together, the panels illustrate the bones, ligaments, tendons, bursae, and synovial structures that contribute to movement, stability, and friction reduction at the elbow.

The elbow is a synovial hinge joint formed primarily by the articulation of the humerus and ulna, with additional articulation between the humerus and radius. The labels in the figure include humerus, ulna, radius, trochlea, trochlear notch, articular cartilage, synovial cavity, synovial membrane, articular capsule, tendon of triceps muscle, tendon of brachialis muscle, bursa, olecranon bursa, fat pad, radial collateral ligament, annular ligament, olecranon process, lateral epicondyle, ulnar collateral ligament, and coronoid process of ulna.

In panel (a), the humerus forms the superior part of the joint and articulates with the ulna. The trochlea of the humerus fits into the trochlear notch of the ulna to form the hinge mechanism that permits flexion and extension. Articular cartilage covers the articulating surfaces, reducing friction during movement. The synovial cavity contains synovial fluid, and the synovial membrane lines the inner surface of the articular capsule, producing lubricating fluid. The articular capsule encloses and stabilizes the joint. The tendon of the triceps muscle lies posterior to the joint and contributes to elbow extension, whereas the tendon of the brachialis muscle lies anterior to the joint and contributes to elbow flexion. A bursa, including the olecranon bursa located near the posterior aspect of the elbow, reduces friction between adjacent tissues. A fat pad is also present within the joint region.

In panel (b), the lateral side of the elbow is shown. The radial collateral ligament extends from the lateral epicondyle of the humerus to the lateral side of the joint and helps resist excessive side-to-side movement. The annular ligament encircles the head of the radius and holds it against the ulna while allowing rotation during pronation and supination of the forearm. The lateral epicondyle serves as an attachment site for ligaments and muscles. The olecranon process forms the prominent posterior projection of the ulna.

In panel (c), the medial side of the elbow is shown. The ulnar collateral ligament extends from the medial side of the humerus to the ulna and reinforces the medial aspect of the joint. The coronoid process of the ulna projects anteriorly and contributes to elbow stability during flexion. The annular ligament is again visible surrounding the head of the radius. Together, the radial collateral ligament on the lateral side and the ulnar collateral ligament on the medial side provide stability to opposite sides of the elbow joint, helping maintain alignment during movement.

Figure 9.6.5: Right Hip Joint

This figure shows the right hip joint in three panels: (a) a frontal section through the joint, (b) an anterior view of the right hip joint with the capsule in place, and (c) a posterior view of the right hip joint with the capsule in place. The figure illustrates the articulating bones, labrum, capsule, and supporting ligaments of the hip.

The hip joint is a synovial ball-and-socket joint formed between the head of the femur and the acetabulum of the coxal bone. Labels in the figure include acetabular labrum, articular cartilage, femur, synovial cavity, ligament of the head of the femur, articular capsule, anterior inferior iliac spine, greater trochanter of femur, iliofemoral ligament, pubofemoral ligament, and ischiofemoral ligament.

In panel (a), a frontal section of the right hip joint is shown. The head of the femur fits into the acetabulum of the coxal bone. Articular cartilage covers the articulating surfaces and reduces friction during movement. The acetabular labrum forms a ring around the rim of the acetabulum, deepening the socket and increasing joint stability. The synovial cavity lies between the articular surfaces and contains synovial fluid. The ligament of the head of the femur extends from the femoral head to the acetabulum within the joint. The articular capsule surrounds and encloses the joint.

In panel (b), an anterior view of the right hip joint is shown with the capsule in place. The iliofemoral ligament extends from the ilium to the femur across the anterior surface of the joint and occupies a superior position on the front of the capsule. Inferior and medial to it is the pubofemoral ligament, which extends from the pubic region of the coxal bone to the femur along the anteroinferior aspect of the joint. Together, these ligaments reinforce the anterior portion of the hip joint and help resist excessive movement.

In panel (c), a posterior view of the right hip joint is shown with the capsule in place. The ischiofemoral ligament extends from the ischium to the femur and reinforces the posterior aspect of the joint capsule. Unlike the iliofemoral and pubofemoral ligaments, which are located on the front of the hip joint, the ischiofemoral ligament is positioned on the back of the joint. The greater trochanter of the femur is visible lateral to the joint, and the ischium is labeled as part of the coxal bone. Together, the anterior and posterior ligaments strengthen the hip joint while helping maintain stability during weight-bearing and movement.

Figure 9.6.6: Right Knee Joint

This image shows the right knee joint in three panels: (a) a sagittal section, (b) a superior view, and (c) an anterior view. Together, the panels illustrate the bones, ligaments, menisci, tendons, bursae, and synovial structures that support movement, stability, shock absorption, and friction reduction in the knee.

The overall organization shows the knee as a synovial hinge joint connecting the femur, tibia, and patella. The figure emphasizes flexion and extension, stabilization through internal and external ligaments, shock absorption by the menisci, and friction reduction through synovial fluid and bursae. The labels in the figure include femur, tibia, patella, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), lateral meniscus, medial meniscus, synovial cavity, articular capsule, tendon of quadriceps femoris, patellar ligament, suprapatellar bursa, prepatellar bursa, infrapatellar bursa, infrapatellar fat pad, articular cartilage, tibial collateral ligament, fibular collateral ligament, medial patellar retinaculum, lateral patellar retinaculum, and fibula.

In panel (a), the femur forms the superior part of the joint and transfers body weight downward. The tibia forms the lower base of the joint and supports body weight from the femur while allowing hinge motion. The patella sits anterior to the joint and protects it while improving the leverage of the quadriceps muscle during extension. The ACL runs from the tibia to the femur inside the joint and prevents forward movement of the tibia, helping stabilize the knee during motion. The PCL, located behind the ACL, prevents backward displacement of the tibia and adds further stability. The lateral meniscus is a curved cartilaginous pad between the femur and tibia that acts as a shock absorber and helps distribute weight. The synovial cavity is the space within the joint that allows movement and contains lubricating synovial fluid. The articular capsule encloses the joint and helps maintain joint integrity. The tendon of quadriceps femoris connects the quadriceps muscle to the patella and enables knee extension. The patellar ligament extends from the patella to the tibia and transfers force to extend the lower leg. The suprapatellar bursa,

prepatellar bursa, and infrapatellar bursa each reduce friction in different regions around the joint, while the infrapatellar fat pad cushions and stabilizes the joint.

In panel (b), the superior view highlights the internal arrangement of the medial meniscus and lateral meniscus on the tibial surface. The medial meniscus absorbs shock and helps stabilize movement on the medial side, while the lateral meniscus helps distribute load across the lateral side of the joint. The ACL and PCL cross within the joint and together provide rotational as well as anterior-posterior stability. The articular cartilage covers the surfaces of the femoral condyles and allows smooth, low-friction movement.

In panel (c), the anterior view highlights the external supporting structures. The quadriceps femoris muscle is shown above the knee as the primary muscle for knee extension. Its tendon connects to the patella, transmitting force for movement. The tibial collateral ligament on the medial side helps prevent excessive medial movement, while the fibular collateral ligament on the lateral side helps prevent excessive lateral movement. The patellar ligament connects the patella to the tibia and enables extension of the knee. The medial and lateral patellar retinacula are fibrous bands that stabilize the patella during movement. The fibula, located lateral to the tibia, provides attachment for ligaments and contributes to lateral stability.

Figure 9.6.7: Knee Injury

This image shows an anterior view of the knee with lateral labeled on the left side of the image and medial on the right. A large arrow labeled direction of force points from the lateral side toward the medial side, indicating a sideways force applied to the knee.

The diagram labels three injured structures. Inside the joint, the anterior cruciate ligament is labeled as torn. On the medial side, the tibial (medial) collateral ligament is labeled as torn. The medial meniscus is also labeled.

A dashed oval highlights the central joint region involved in the injury pattern. Overall, the figure illustrates a knee injury mechanism in which a force applied from the lateral side is associated with damage to the anterior cruciate ligament, medial collateral ligament, and medial meniscus.

Figure 9.6.8: The Talocrural (ankle) Joint

This image shows the ankle region in two views: a medial view on the top and a lateral view on the bottom. It highlights the bones and ligaments that stabilize the ankle and support foot movement.

The overall organization shows the ankle as a joint region involving the tibia, fibula, and foot bones including the talus and calcaneus, which are inferred from the articulations shown. The figure emphasizes the ligament structures on the medial and lateral sides, the role of those ligaments in joint stability, and the subtalar joint, which contributes to foot motion. The labels in the image include tibia, medial malleolus, fibula, deltoid ligament, subtalar joint, interosseous membrane, anterior talofibular ligament, calcaneofibular ligament, and tibiofibular ligaments.

In the medial view, the tibia is the larger, medial bone of the lower leg. Its functions are to carry most of the body's weight and form the main ankle articulation. The medial malleolus is the bony projection at the distal end of the tibia. Its functions are to provide attachment for ligaments and help stabilize the ankle joint. The fibula, which is partially visible, is the smaller lateral bone of the lower leg and contributes to ankle stability. The deltoid ligament is a broad, fan-shaped ligament extending from the medial malleolus to bones of the foot. Its functions are to provide strong medial stability and prevent excessive eversion, or outward turning, of the foot. The subtalar joint, located between the talus and calcaneus, allows inversion and eversion of the foot and helps the foot adapt during walking.

In the lateral view, the tibia and fibula together form the ankle mortise surrounding the talus and help maintain alignment of the ankle joint. The interosseous membrane is a fibrous sheet between the tibia and fibula. Its functions are to stabilize the bones and distribute forces between them. The anterior talofibular ligament connects the fibula to the talus anteriorly. Its functions are to prevent excessive forward displacement of the talus and provide lateral support. The calcaneofibular ligament extends from the fibula to the calcaneus. Its functions are to stabilize the ankle during side-to-side movement and prevent excessive inversion. The tibiofibular ligaments, both anterior and posterior, connect the tibia and fibula near the ankle. Their functions are to maintain the integrity of the ankle mortise and prevent separation of the tibia and fibula. The subtalar joint again contributes to inversion and eversion and helps the foot adapt to uneven surfaces.

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10: THE MUSCLE TISSUE

Chapter Overview

Welcome to the fascinating world of muscle tissue! You've encountered muscle tissue daily, even if you didn't realize it. Think about the last time you lifted something heavy, went for a run, or even just smiled—you were using your muscles. This chapter will dive into the different types of muscle tissue and how they work together to support your body's movements and functions.



Figure 10.1: Tennis players rely on toned skeletal muscles to supply the force required for movement. (CC BY 4.0 ; via Introduction).

Muscle tissue is specialized for contraction and underlies movement, posture, and vital functions. There are three main types. Skeletal muscle is voluntary and moves the skeleton, as when you raise your hand. Cardiac muscle, found only in the heart, contracts automatically to pump blood. Smooth muscle, in the walls of hollow organs and blood vessels, moves materials like food and regulates blood flow without conscious control.

Shared Properties and Excitability

All muscle types are excitable: their membranes can depolarize and conduct action potentials that trigger contraction. They are also contractile (can generate tension and shorten), extensible (can be stretched), and elastic (recoil to resting length). Skeletal muscle relies entirely on somatic motor neurons to initiate contraction. Cardiac and smooth muscle are influenced by the autonomic nervous system but can also respond to hormones and local signals and, in the case of cardiac muscle, intrinsic pacemaker cells.

Excitation–Contraction Coupling and the Role of Calcium

Contraction begins with an electrical signal and ends in mechanical shortening of the muscle cell, a process known as excitation–contraction coupling. In skeletal muscle, this starts at the neuromuscular junction, where a motor neuron releases the neurotransmitter acetylcholine (ACh) into the synaptic cleft. ACh binds to receptors on the muscle fiber membrane, initiating an action potential that travels along the sarcolemma and down T-tubules. This signal causes the sarcoplasmic reticulum (SR) to release calcium ions (Ca^{2+}) into the cytosol.

In striated muscles (skeletal and cardiac), contraction occurs when myosin heads pull on actin filaments. Under resting conditions, the actin-binding sites are blocked by the regulatory proteins troponin and tropomyosin. When Ca^{2+} binds to troponin, it causes a conformational change that moves tropomyosin away, exposing the binding sites on actin. Myosin heads, energized by

ATP hydrolysis, form cross-bridges with actin and perform power strokes that slide filaments past one another, shortening the sarcomere.

In smooth muscle, Ca^{2+} is also essential, but the mechanism is different. Instead of binding troponin, Ca^{2+} binds to a protein called calmodulin. The Ca^{2+}–calmodulin complex activates myosin light-chain kinase (MLCK), an enzyme that phosphorylates myosin heads and allows them to interact with actin. In all muscle types, ATP is required for cross-bridge cycling and for detachment of myosin from actin. Relaxation occurs when Ca^{2+} is removed from the cytosol, actin-binding sites become re-shielded (in striated muscle), and cross-bridge cycling ceases.

Motor Units, Force Generation, and Muscle Tone

Force production in skeletal muscle depends on several factors, including the number of active cross-bridges, the initial sarcomere length, and the number of active fibers. The basic functional unit of neural control is the motor unit, defined as a single motor neuron and all the muscle fibers it innervates. Small motor units permit precise control, while large motor units generate greater force with less finesse.

A single stimulus to a motor unit produces a brief contraction called a twitch. When stimuli arrive in rapid succession, their effects can add together, a process known as summation. At very high frequencies, individual twitches fuse into a sustained, maximal contraction called tetanus. The nervous system can increase muscle force by recruiting additional motor units and by increasing the firing frequency of active motor neurons. Even at rest, skeletal muscles maintain a low level of involuntary activity known as muscle tone. Tone stabilizes joints, maintains posture, and ensures that muscles are ready to respond.

Energy for Contraction and Muscle Fatigue

Contraction requires a continuous supply of ATP. Skeletal muscle fibers draw ATP from three main sources. Creatine phosphate provides a rapid way to regenerate ATP for the first few seconds of intense activity. Anaerobic glycolysis breaks down glucose without oxygen to produce ATP quickly for short, high-intensity efforts, but it also generates lactate. Aerobic metabolism, which uses oxygen in mitochondria to oxidize carbohydrates and fats, provides ATP more slowly but can support prolonged, lower-intensity activity.

Different skeletal muscle fibers specialize in these pathways. Slow oxidative fibers have abundant mitochondria, myoglobin, and capillaries, making them fatigue-resistant but lower in maximal power; they are well suited for posture and endurance. Fast oxidative fibers are intermediate in power and fatigue resistance. Fast glycolytic fibers generate high power quickly using anaerobic metabolism but fatigue rapidly; they are recruited for brief, intense efforts.

Muscle fatigue occurs when a muscle cannot sustain its required level of tension. Contributing factors include depletion of energy substrates, accumulation of metabolic by-products, and impaired excitation–contraction coupling. After intense exercise, the body incurs an oxygen debt, the extra oxygen needed to restore ATP and creatine phosphate stores, reconvert lactate, and re-establish resting conditions.

Cardiac Muscle

Cardiac muscle cells are striated, branched, and usually have one central nucleus. They are linked end to end by intercalated discs containing desmosomes (strong mechanical links) and gap junctions (electrical connections), allowing the heart to contract as a functional syncytium. Ca^{2+} for contraction comes from the sarcoplasmic reticulum and from voltage-gated channels in the cell membrane. Specialized pacemaker cells set the basic rhythm, which is then modulated by autonomic input and hormones.

Smooth Muscle

Smooth muscle cells are spindle-shaped, nonstriated, and usually have a single nucleus. Their actin and myosin are not arranged in regular sarcomeres, giving a smooth microscopic appearance, but they are highly efficient for sustained, low-energy contraction. Ca^{2+} entering the cell binds calmodulin and activates myosin light-chain kinase, enabling cross-bridge formation. Smooth muscle in vessel walls regulates diameter and blood pressure; in the digestive, urinary, respiratory, and reproductive tracts, it moves and mixes contents; in the skin and other organs, it controls small movements and passageways.

Development and Regeneration

All muscle tissues arise from mesoderm. Skeletal muscle fibers form by fusion of myoblasts into long, multinucleated cells. After development, skeletal muscle has limited repair capacity through satellite cells, which can help repair or enlarge fibers. Smooth muscle can regenerate more readily, partly via pericytes and related progenitor cells. Cardiac muscle has minimal regenerative ability; dead cardiac myocytes are usually replaced by noncontractile scar tissue.

Integrating Muscle Types in Physiology

At the undergraduate level, studying muscle tissue means connecting shared principles - excitability, Ca^{2+}-dependent contraction, and ATP use - with the specializations of skeletal, cardiac, and smooth muscle. Together, these tissues generate voluntary movement, maintain posture, pump blood, and move and regulate materials throughout the body, forming a coordinated system central to human physiology.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own.

By the end of this chapter, students should be able to:

- Describe how a skeletal muscle is organized (muscle → fascicles → fibers/cells → myofibrils → sarcomeres) and name the connective tissue layers (epimysium, perimysium, endomysium), blood supply, and nerves.
- Distinguish skeletal, cardiac, and smooth muscle by location, function, cell structure (striations, nuclei, branching), and control (voluntary vs involuntary).
- Explain how muscles pull on tendons (and aponeuroses) to move bones at joints, using simple lever ideas (origin, insertion, line of pull, torque).
- Trace excitation–contraction coupling in skeletal muscle from motor neuron signal to contraction and relaxation: ACh at the NMJ → sarcolemma/T-tubules → SR Ca^{2+} release → troponin–tropomyosin shift → cross-bridge cycling with ATP → Ca^{2+} reuptake and ACh breakdown.
- Compare contraction control in the three muscle types: skeletal (troponin), cardiac (intercalated discs, pacemaker cells, $Ca2^{+}$ from SR and membrane), and smooth (calmodulin–myosin light-chain kinase).
- Use the sliding filament model to relate sarcomere length to force (length–tension) and predict how too short or too long a starting length affects tension.
- Explain how the nervous system controls muscle tension: motor units, recruitment of more units, rate coding (summation, tetanus), and baseline muscle tone.
- Define muscle metabolism pathways (creatine phosphate, anaerobic glycolysis, aerobic metabolism) and identify which pathway dominates in common activities (e.g., sprint vs jog vs lift).
- Classify muscle fiber types (slow oxidative, fast oxidative, fast glycolytic) and relate each to speed, fatigue resistance, and typical activities.
- Relate exercise to performance changes: endurance training (more mitochondria, myoglobin, capillaries), resistance training (hypertrophy), inactivity (atrophy), and aging (sarcopenia).

- Describe development and repair: mesoderm → myoblast fusion (multinucleated skeletal fibers), satellite cells in repair, smooth muscle regeneration (pericytes), and limited cardiac regeneration (scar formation).
- Apply these ideas to simple cases (e.g., why posture needs tone, why a sprinter tires, why heart cells beat together) using correct terms and short cause→effect explanations.

10.1: Skeletal Muscle
10.2: Muscle Fiber Contraction and Relaxation
10.3: Nervous System Control of Muscle Tension
10.4: Types of Muscle Fibers
10.5: Exercise and Muscle Performance
10.6: Cardiac Muscle Tissue
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10.8: Terms and Definitions
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10.1: Skeletal Muscle

Functions and Structure of Skeletal Muscle

The best-known feature of skeletal muscle is its ability to contract and cause movement. Skeletal muscles act not only to produce movement but also to stop movement, such as resisting gravity to maintain posture. Small, constant adjustments of the skeletal muscles are needed to hold a body upright or balanced in any position. Muscles also prevent excess movement of the bones and joints, maintaining skeletal stability and preventing skeletal structure damage or deformation. Joints can become misaligned or dislocated entirely by pulling on the associated bones; muscles work to keep joints stable. Skeletal muscles are located throughout the body at the openings of internal tracts to control the movement of various substances. These muscles allow functions, such as swallowing, urination, and defecation, to be under voluntary control. Skeletal muscles also protect internal organs (particularly abdominal and pelvic organs) by acting as an external barrier or shield to external trauma and by supporting the weight of the organs.

Skeletal muscles contribute to the maintenance of homeostasis in the body by generating heat. Muscle contraction requires energy, and when ATP is broken down, heat is produced. This heat is very noticeable during exercise, when sustained muscle movement causes body temperature to rise, and in cases of extreme cold, when shivering produces random skeletal muscle contractions to generate heat.

Each skeletal muscle is an organ that consists of various integrated tissues. These tissues include the skeletal muscle fibers, blood vessels, nerve fibers, and connective tissue. Each skeletal muscle has three layers of connective tissue that enclose it and provide structure to the muscle as a whole, and also compartmentalize the muscle fibers within the muscle (Figure 10.1.1). Each muscle is wrapped in a sheath of dense, irregular connective tissue called the epimysium, which allows a muscle to contract and move powerfully while maintaining its structural integrity. The epimysium also separates muscle from other tissues and organs in the area, allowing the muscle to move independently.

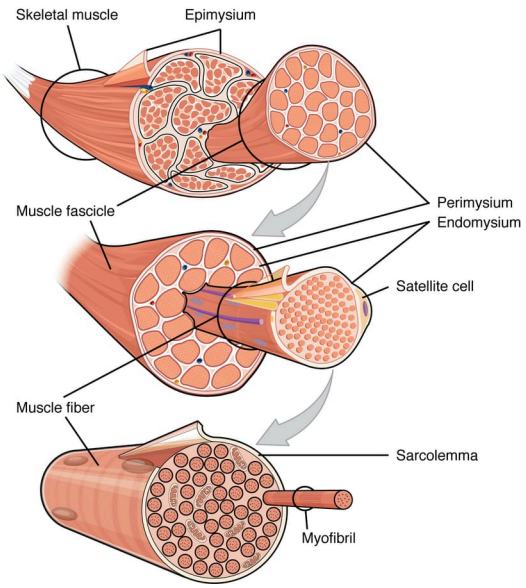


Figure 10.1.1: Bundles of muscle fibers, called fascicles, are covered by the perimysium. Muscle fibers are covered by the endomysium. (CC BY 4.0 ; via Skeletal Muscle). Alternate text description of the Figure 10.1.1.

Skeletal Muscle Fibers

Because skeletal muscle cells are long and cylindrical, they are commonly referred to as muscle fibers. Skeletal muscle fibers can be quite large for human cells, with diameters up to 100 μm and lengths up to 30 cm (11.8 in) in the Sartorius of the upper leg. During early development, embryonic myoblasts, each with its own nucleus, fuse with up to hundreds of other myoblasts to form the multinucleated skeletal muscle fibers. Multiple nuclei mean multiple copies of genes, permitting the production of the large

amounts of proteins and enzymes needed for muscle contraction.

Some other terminology associated with muscle fibers is rooted in the Greek *sarco*, which means “flesh.” The plasma membrane of muscle fibers is called the sarcolemma, the cytoplasm is referred to as sarcoplasm, and the specialized smooth endoplasmic reticulum, which stores, releases, and retrieves calcium ions (Ca^{++}) is called the sarcoplasmic reticulum (SR) (Figure 10.1.2). As will soon be described, the functional unit of a skeletal muscle fiber is the sarcomere, a highly organized arrangement of the contractile myofilaments actin (thin filament) and myosin (thick filament), along with other support proteins.

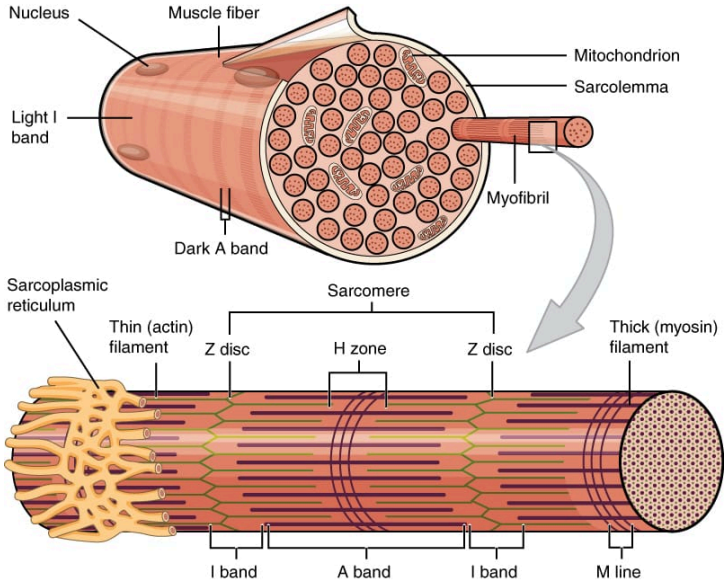


Figure 10.1.2: A skeletal muscle fiber is surrounded by a plasma membrane called the sarcolemma, which contains sarcoplasm, the cytoplasm of muscle cells. A muscle fiber is composed of many fibrils, which give the cell its striated appearance. (CC BY 4.0 ; via Skeletal Muscle).
Alternate text description of the Figure 10.1.2.

The Sarcomere

The striated appearance of skeletal muscle fibers is due to the arrangement of the myofilaments of actin and myosin in sequential order from one end of the muscle fiber to the other. Each packet of these microfilaments and their regulatory proteins, troponin and tropomyosin (along with other proteins) is called a sarcomere.

The sarcomere is the functional unit of the muscle fiber. The sarcomere itself is bundled within the myofibril that runs the entire length of the muscle fiber and attaches to the sarcolemma at its end. As myofibrils contract, the entire muscle cell contracts. Because myofibrils are only approximately 1.2 μm in diameter, hundreds to thousands (each with thousands of sarcomeres) can be found inside one muscle fiber. Each sarcomere is approximately 2 μm in length with a three-dimensional cylinder-like arrangement and is bordered by structures called Z-discs (also called Z-lines, because pictures are two-dimensional), to which the actin myofilaments are anchored (Figure 10.1.3). Because the actin and its troponin-tropomyosin complex (projecting from the Z-discs toward the center of the sarcomere) form strands that are thinner than the myosin, it is called the thin filament of the sarcomere. Likewise, because the myosin strands and their multiple heads (projecting from the center of the sarcomere, toward but not all to way to, the Z-discs) have more mass and are thicker, they are called the thick filament of the sarcomere.

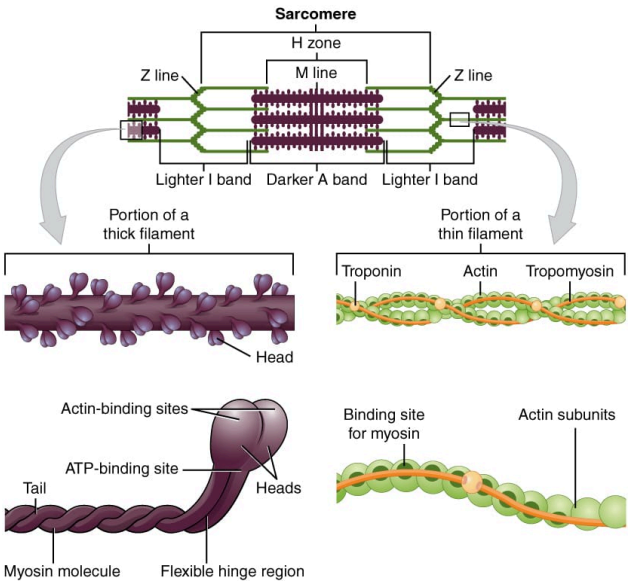


Figure 10.1.3: The sarcomere, the region from one Z-line to the next Z-line, is the functional unit of a skeletal muscle fiber. (CC BY 4.0 ; via Skeletal Muscle). Alternate text description of the Figure 10.1.3.

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10.2: Muscle Fiber Contraction and Relaxation

Excitation-Contraction Coupling

The neuromuscular junction (NMJ) initiates muscle contraction by transmitting an action potential from a motor neuron to a muscle fiber via acetylcholine (ACh). This triggers excitation-contraction (E-C) coupling.

All living cells have membrane potentials, or electrical gradients across their membranes. The inside of the membrane is usually around -60 to -90 mV, relative to the outside. This is referred to as a cell's membrane potential. Neurons and muscle cells can use their membrane potentials to generate electrical signals. They do this by controlling the movement of charged particles, called ions (like Na^+, K^+, Ca^{2+}, Cl^-), across their membranes to create electrical currents. This is achieved by opening and closing specialized proteins in the membrane called ion channels. Although the currents generated by ions moving through these channel proteins are very small, they form the basis of both neural signaling and muscle contraction.

Both neurons and skeletal muscle cells are electrically excitable, meaning that they are able to generate action potentials. An action potential is a special type of electrical signal that can travel along a cell membrane as a wave.

The term excitation-contraction coupling comes down to this: for a skeletal muscle fiber to contract, its membrane must first be "excited"—in other words, it must be stimulated to fire an action potential. The muscle fiber action potential, which sweeps along the sarcolemma as a wave, is "coupled" to the actual contraction through the release of calcium ions (Ca^{++}) from the SR. Once released, the Ca^{++} interacts with the shielding proteins, forcing them to move aside so that the actin-binding sites are available for attachment by myosin heads. The myosin then pulls the actin filaments toward the center, shortening the muscle fiber.

In skeletal muscle, this sequence begins with signals from the somatic motor division of the nervous system. In other words, the "excitation" step in skeletal muscles is always triggered by signaling from the nervous system (Figure 10.2.1).

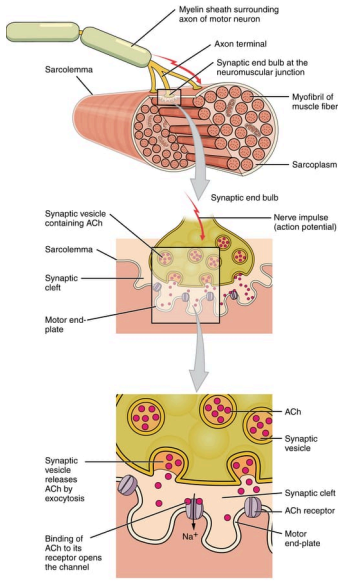


Figure 10.2.1: At the NMJ, the axon terminal releases ACh. The motor end-plate is the location of the ACh-receptors in the muscle fiber sarcolemma. When ACh molecules are released, they diffuse across a minute space called the synaptic cleft and bind to the receptors. (CC BY 4.0 ; via Skeletal Muscle). Alternate text description of the Figure 10.2.1.

Voluntary commands for skeletal muscle start in the motor cortex of the brain. Upper motor neurons carry these signals down the corticospinal tracts to the spinal cord (for most body parts) and down the corticobulbar tracts to the brainstem (for face, head, and neck). Many axons travel together inside peripheral nerves, like many wires inside one cable. Reflexes and local spinal circuits can modify these signals, but the motor cortex provides the main "go" signal for voluntary movement.

The motor end plate is the special area of a muscle fiber's membrane (sarcolemma) under a motor neuron ending. It has many

folds and many acetylcholine (ACh) receptors.

1. Voltage-gated calcium (Ca^{2+}) channels in the nerve terminal open; Ca^{2+} flows in.
2. Ca^{2+} triggers vesicles filled with ACh to fuse with the nerve membrane and release ACh into the synaptic cleft (exocytosis).
3. Across the gap, ACh quickly diffuses across the tiny gap (synaptic cleft) to the motor end plate.
4. ACh binds to nicotinic ACh receptors (ligand-gated channels) on the motor end plate.
5. These channels open and let ions move: mostly sodium (Na^{+}) in, some potassium (K^{+}) out.
6. The inside of the muscle membrane becomes less negative (depolarizes). This local change is the end-plate potential (EPP).
7. If the EPP is big enough, it reaches nearby membrane rich in voltage-gated Na^{+} channels (at the edges of the end plate).
8. Those channels open and start a muscle action potential that travels along the sarcolemma and down T-tubules.
9. The arrangement of a T-tubule with the membranes of SR on either side is called a triad (Figure 10.2.5). The T-tubules carry the action potential into the interior of the cell, which triggers the opening of calcium channels in the membrane of the adjacent SR, causing Ca^{++} to diffuse out of the SR and into the sarcoplasm. It is the arrival of Ca^{++} in the sarcoplasm that initiates contraction of the muscle fiber by its contractile units, or sarcomeres.The triad surrounds the cylindrical structure called a myofibril, which contains actin and myosin.
10. The muscle action potential triggers Ca^{2+} release from the sarcoplasmic reticulum, which starts cross-bridge cycling and contraction (excitation–contraction coupling).
11. Turn off and reset: Acetylcholinesterase (AChE) in the cleft breaks ACh into acetate and choline; Choline is taken back up into the nerve terminal and used to make new ACh; vesicles are recycled: Ca^{2+} leaves the nerve terminal (pumps/exchangers), channels close, and the nerve terminal returns to rest.

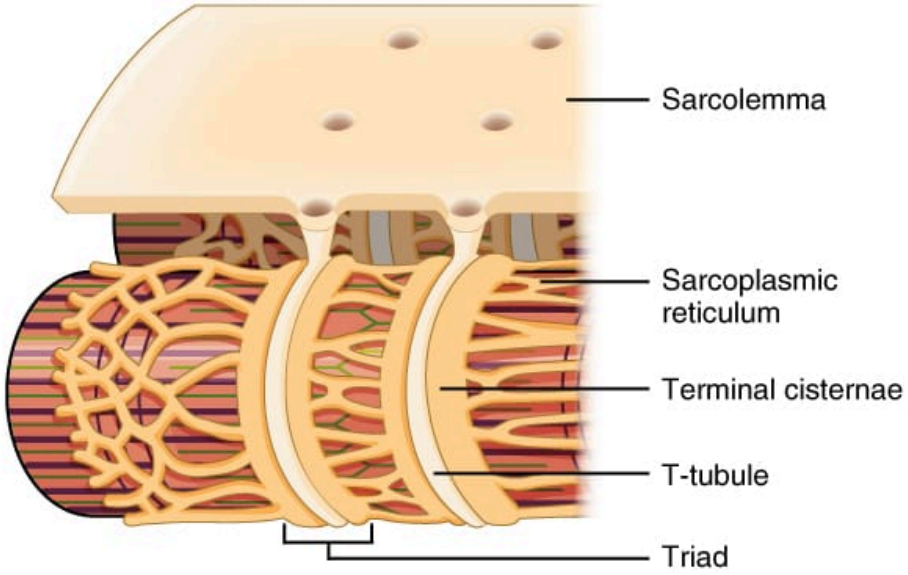


Figure 10.2.2: T-tubules permit the conduction of electrical impulses. The SR functions to regulate intracellular levels of calcium. Two terminal cisternae (where enlarged SR connects to the T-tubule) and one T-tubule comprise a triad—a "threesome" of membranes, with those of SR on two sides and the T-tubule sandwiched between them. (CC BY 4.0 ; via Skeletal Muscle). Alternate text description of the Figure 10.2.2.

As stated above, the local membrane of the fiber will depolarize as positively charged sodium ions (Na^{+}) enter, triggering an action potential that spreads to the rest of the membrane which will depolarize, including the T-tubules. This triggers the release of calcium ions (Ca^{++}) from storage in the sarcoplasmic reticulum (SR). The Ca^{++} then initiates contraction, which is sustained by ATP (Figure 10.2.3). As long as Ca^{++} ions remain in the sarcoplasm to bind to troponin, which keeps the actin-binding sites "unshielded," and as long as ATP is available to drive the cross-bridge cycling and the pulling of actin strands by myosin, the muscle fiber will continue to shorten to an anatomical limit.

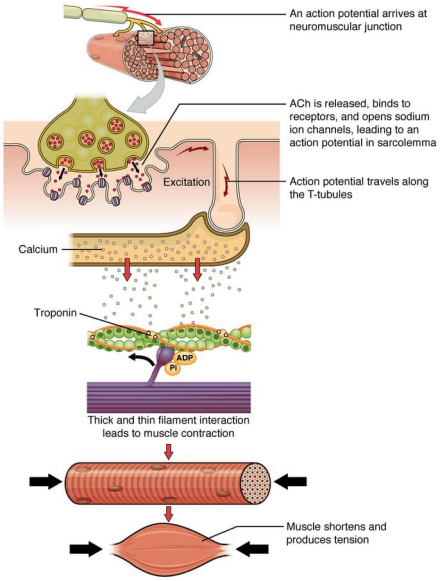


Figure 10.2.3: A cross-bridge forms between actin and the myosin heads triggering contraction. As long as Ca++ ions remain in the sarcoplasm to bind to troponin, and as long as ATP is available, the muscle fiber will continue to shorten. (CC BY 4.0 ; via Muscle Fiber Contraction and Relaxation). Alternate text description of the Figure 10.2.3.

Muscle contraction usually stops when signaling from the motor neuron ends, which repolarizes the sarcolemma and T-tubules, and closes the voltage-gated calcium channels in the SR. Ca^{++} ions are then pumped back into the SR, which causes the tropomyosin to reshield (or re-cover) the binding sites on the actin strands. A muscle also can stop contracting when it runs out of ATP and becomes fatigued (Figure 10.2.4).

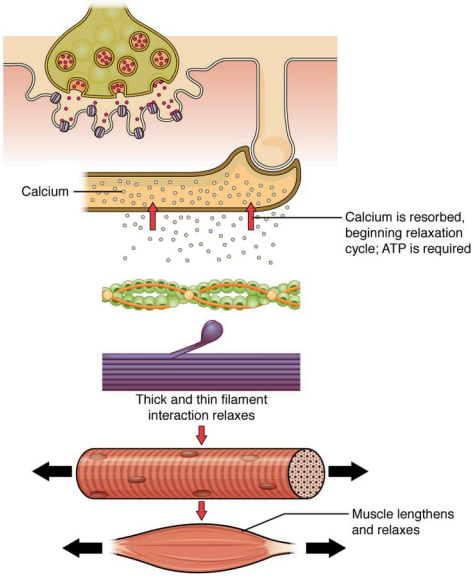


Figure 10.2.4: Ca++ ions are pumped back into the SR, which causes the tropomyosin to reshield the binding sites on the actin strands. A muscle may also stop contracting when it runs out of ATP and becomes fatigued. (CC BY 4.0 ; via Muscle Fiber Contraction and Relaxation). Alternate text description of the Figure 10.2.4.

The Sliding Filament Model of Contraction

When signaled by a motor neuron, a skeletal muscle fiber contracts as the thin filaments are pulled and then slide past the thick filaments within the fiber's sarcomeres. This process is known as the sliding filament model of muscle contraction (Figure 10.2.5). The sliding can only occur when myosin-binding sites on the actin filaments are exposed by a series of steps that begins with

Ca^{++} entry into the sarcoplasm.

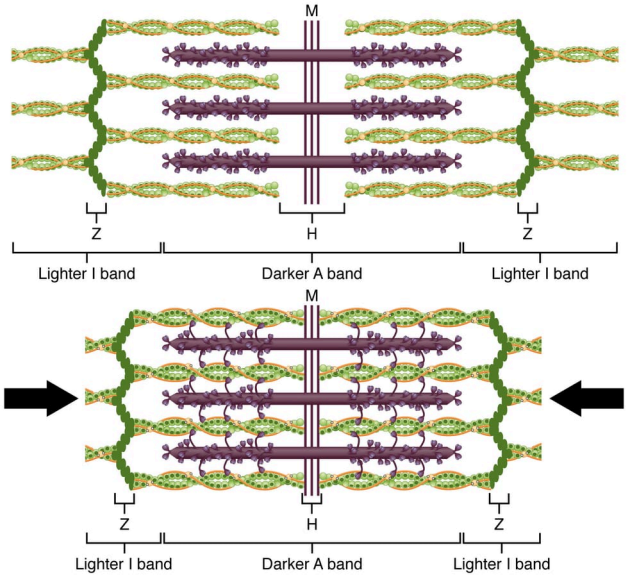


Figure 10.2.5: When a sarcomere contracts, the Z lines move closer together, and the I band becomes smaller. The A band stays the same width. At full contraction, the thin and thick filaments overlap completely. (CC BY 4.0 ; via Muscle Fiber Contraction and Relaxation). Alternate text description of the Figure 10.2.5.

Tropomyosin is a protein that winds around the chains of the actin filament and covers the myosin-binding sites to prevent actin from binding to myosin. Tropomyosin binds to troponin to form a troponin-tropomyosin complex. The troponin-tropomyosin complex prevents the myosin “heads” from binding to the active sites on the actin microfilaments. Troponin also has a binding site for Ca^{++} ions.

To initiate muscle contraction, tropomyosin has to expose the myosin-binding site on an actin filament to allow cross-bridge formation between the actin and myosin microfilaments. The first step in the process of contraction is for Ca^{++} to bind to troponin so that tropomyosin can slide away from the binding sites on the actin strands. This allows the myosin heads to bind to these exposed binding sites and form cross-bridges. The thin filaments are then pulled by the myosin heads to slide past the thick filaments toward the center of the sarcomere. But each head can only pull a very short distance before it has reached its limit and must be “re-cocked” before it can pull again, a step that requires ATP.

ATP and Muscle Contraction

For thin filaments to continue to slide past thick filaments during muscle contraction, myosin heads must pull the actin at the binding sites, detach, re-cock, attach to more binding sites, pull, detach, re-cock, etc. This repeated movement is known as the cross-bridge cycle. This motion of the myosin heads is similar to the oars when an individual rows a boat: The paddle of the oars (the myosin heads) pull, are lifted from the water (detach), repositioned (re-cocked) and then immersed again to pull (Figure 10.2.6). Each cycle requires energy, and the action of the myosin heads in the sarcomeres repetitively pulling on the thin filaments also requires energy, which is provided by ATP.

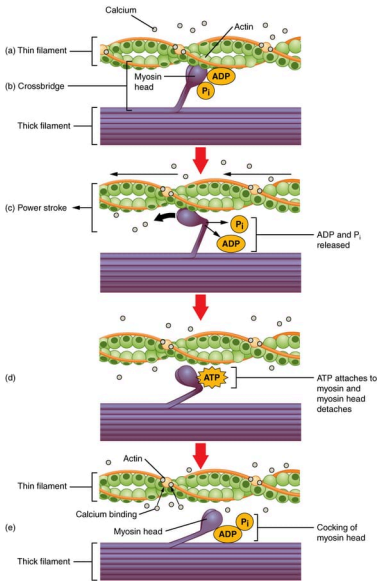


Figure 10.2.6: Diagram showing stages of the myosin–actin cross-bridge cycle in muscle contraction. (CC BY 4.0 ; via Muscle Fiber Contraction and Relaxation). Alternate text description of the Figure 10.2.6.

As this cycle repeats many times, actin slides past myosin, sarcomeres shorten, and the muscle generates continuous force.

When the myosin head is cocked, myosin is in a high-energy configuration. This energy is expended as the myosin head moves through the power stroke, and at the end of the power stroke, the myosin head is in a low-energy position. After the power stroke, ADP is released; however, the formed cross-bridge is still in place, and actin and myosin are bound together. As long as ATP is available, it readily attaches to myosin, the cross-bridge cycle can recur, and muscle contraction can continue.

Note that each thick filament of roughly 300 myosin molecules has multiple myosin heads, and many cross-bridges form and break continuously during muscle contraction. Multiply this by all of the sarcomeres in one myofibril, all the myofibrils in one muscle fiber, and all of the muscle fibers in one skeletal muscle, and you can understand why so much energy (ATP) is needed to keep skeletal muscles working. In fact, it is the loss of ATP that results in the rigor mortis observed soon after someone dies. With no further ATP production possible, there is no ATP available for myosin heads to detach from the actin-binding sites, so the cross-bridges stay in place, causing the rigidity in the skeletal muscles.

Sources of ATP

ATP supplies the energy for muscle contraction to take place. In addition to its direct role in the cross-bridge cycle, ATP also provides the energy for the active-transport Ca^{++} pumps in the SR. Muscle contraction does not occur without sufficient amounts of ATP. The amount of ATP stored in muscle is very low, only sufficient to power a few seconds worth of contractions. As it is broken down, ATP must therefore be regenerated and replaced quickly to allow for sustained contraction. There are three mechanisms by which ATP can be regenerated in muscle cells: creatine phosphate metabolism, anaerobic glycolysis, and aerobic respiration.

Creatine phosphate is a molecule that can store energy in its phosphate bonds. In a resting muscle, excess ATP transfers its energy to creatine, producing ADP and creatine phosphate. This acts as an energy reserve that can be used to quickly create more ATP. When the muscle starts to contract and needs energy, creatine phosphate transfers its phosphate back to ADP to form ATP and creatine. This reaction is catalyzed by the enzyme creatine kinase and occurs very quickly; thus, creatine phosphate-derived ATP powers the first few seconds of muscle contraction. However, creatine phosphate can only provide approximately 15 seconds worth of energy, at which point another energy source has to be used (Figure 10.2.7).

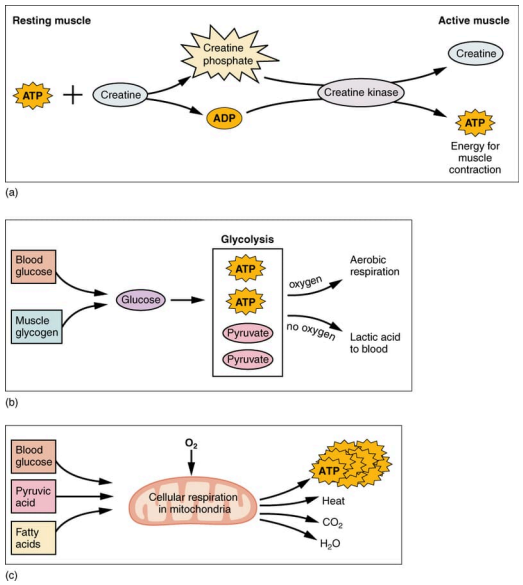


Figure 10.2.7: Three-part illustration comparing creatine phosphate transfer, glycolysis, and mitochondrial respiration as sources of ATP during muscle activity. Each panel highlights key inputs, steps, and products involved in supplying usable energy for contraction. (CC BY 4.0 ; via Muscle Fiber Contraction and Relaxation). Alternate text description of the Figure 10.2.7.

If oxygen is available, pyruvic acid is used in aerobic respiration. However, if oxygen is not available, pyruvic acid is converted to lactic acid, which may contribute to muscle fatigue. This conversion allows the recycling of the enzyme NAD^+ from NADH, which is needed for glycolysis to continue. This occurs during strenuous exercise when high amounts of energy are needed but oxygen cannot be sufficiently delivered to muscle. Glycolysis itself cannot be sustained for very long (approximately 1 minute of muscle activity), but it is useful in facilitating short bursts of high-intensity output. This is because glycolysis does not utilize glucose very efficiently, producing a net gain of two ATPs per molecule of glucose, and the end product of lactic acid, which may contribute to muscle fatigue as it accumulates.

Aerobic respiration is the breakdown of glucose or other nutrients in the presence of oxygen (O_2) to produce carbon dioxide, water, and ATP. Approximately 95 percent of the ATP required for resting or moderately active muscles is provided by aerobic respiration, which takes place in mitochondria. The inputs for aerobic respiration include glucose circulating in the bloodstream, pyruvic acid, and fatty acids. Aerobic respiration is much more efficient than anaerobic glycolysis, producing approximately 36 ATPs per molecule of glucose versus four from glycolysis. However, aerobic respiration cannot be sustained without a steady supply of O_2 to the skeletal muscle and is much slower (Figure 10.2.7c). To compensate, muscles store small amount of excess oxygen in proteins call myoglobin, allowing for more efficient muscle contractions and less fatigue. Aerobic training also increases the efficiency of the circulatory system so that O_2 can be supplied to the muscles for longer periods of time.

Muscle fatigue occurs when a muscle can no longer contract in response to signals from the nervous system. The exact causes of muscle fatigue are not fully known, although certain factors have been correlated with the decreased muscle contraction that occurs during fatigue. ATP is needed for normal muscle contraction, and as ATP reserves are reduced, muscle function may decline. This may be more of a factor in brief, intense muscle output rather than sustained, lower intensity efforts. Lactic acid buildup may lower intracellular pH, affecting enzyme and protein activity. Imbalances in Na^+ and K^+ levels as a result of membrane depolarization may disrupt Ca^{++} flow out of the SR. Long periods of sustained exercise may damage the SR and the sarcolemma, resulting in impaired Ca^{++} regulation.

Intense muscle activity results in an oxygen debt, which is the amount of oxygen needed to compensate for ATP produced without oxygen during muscle contraction. Oxygen is required to restore ATP and creatine phosphate levels, convert lactic acid to pyruvic acid, and, in the liver, to convert lactic acid into glucose or glycogen. Other systems used during exercise also require oxygen, and all of these combined processes result in the increased breathing rate that occurs after exercise. Until the oxygen debt has been met, oxygen intake is elevated, even after exercise has stopped.

Relaxation of a Skeletal Muscle

Relaxing skeletal muscle fibers, and ultimately, the skeletal muscle, begins with the motor neuron, which stops releasing its chemical signal, ACh, into the synapse at the NMJ. The muscle fiber will repolarize, which closes the gates in the SR where Ca^{++} was being released. ATP-driven pumps will move Ca^{++} out of the sarcoplasm back into the SR. This results in the "reshielding" of the actin-binding sites on the thin filaments. Without the ability to form cross-bridges between the thin and thick filaments, the muscle fiber loses its tension and relaxes.

Muscle Strength

The number of skeletal muscle fibers in a given muscle is genetically determined and does not change. Muscle strength is directly related to the amount of myofibrils and sarcomeres within each fiber. Factors, such as hormones and stress (and artificial anabolic steroids), acting on the muscle can increase the production of sarcomeres and myofibrils within the muscle fibers, a change called hypertrophy, which results in the increased mass and bulk in a skeletal muscle. Likewise, decreased use of a skeletal muscle results in atrophy, where the number of sarcomeres and myofibrils disappear (but not the number of muscle fibers). It is common for a limb in a cast to show atrophied muscles when the cast is removed, and certain diseases, such as polio, show atrophied muscles.

Disorders of the...

Muscular System

Duchenne muscular dystrophy (DMD) is a progressive weakening of the skeletal muscles. It is one of several diseases collectively referred to as "muscular dystrophy." DMD is caused by a lack of the protein dystrophin, which helps the thin filaments of myofibrils bind to the sarcolemma. Without sufficient dystrophin, muscle contractions cause the sarcolemma to tear, causing an influx of Ca^{++}, leading to cellular damage and muscle fiber degradation. Over time, as muscle damage accumulates, muscle mass is lost, and greater functional impairments develop.

DMD is an inherited disorder caused by an abnormal X chromosome. It primarily affects males, and it is usually diagnosed in early childhood. DMD usually first appears as difficulty with balance and motion, and then progresses to an inability to walk. It continues progressing upward in the body from the lower extremities to the upper body, where it affects the muscles responsible for breathing and circulation. It ultimately causes death due to respiratory failure, and those afflicted do not usually live past their 20s.

Because DMD is caused by a mutation in the gene that codes for dystrophin, it was thought that introducing healthy myoblasts into patients might be an effective treatment. Myoblasts are the embryonic cells responsible for muscle development, and ideally, they would carry healthy genes that could produce the dystrophin needed for normal muscle contraction. This approach has been largely unsuccessful in humans. A recent approach has involved attempting to boost the muscle's production of utrophin, a protein similar to dystrophin that may be able to assume the role of dystrophin and prevent cellular damage from occurring.

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10.3: Nervous System Control of Muscle Tension

Skeletal Muscle Contraction and Neural Control

To move an object, referred to as load, the sarcomeres in the muscle fibers of the skeletal muscle must shorten. The force generated by the contraction of the muscle (or shortening of the sarcomeres) is called muscle tension. However, muscle tension also is generated when the muscle is contracting against a load that does not move, resulting in two main types of skeletal muscle contractions: isotonic contractions and isometric contractions.

- Isotonic contraction (same tension, length changes): The muscle changes length while producing force to move a load. Two types: concentric and eccentric.
  - Concentric contraction - A type of isotonic contraction where the muscle shortens. Occurs when the force generated by the muscle exceeds the opposing force. The body part moves in the direction of the muscle's action.
    - Example: Lifting a weight during a bicep curl (biceps work concentrically). As the biceps brachii contract, the angle of the elbow joint decreases as the forearm is brought toward the body. Here, the biceps brachii contracts as sarcomeres in its muscle fibers are shortening and cross-bridges form; the myosin heads pull the actin.
  - Eccentric contraction - A type of isotonic contraction where the muscle lengthens. Occurs when the opposing force is greater than the force the muscle is producing.
    - Examples: – Lower the weight back down: biceps lengthen while controlling the drop. In this case, the hand weight is lowered in a slow and controlled manner as the amount of cross-bridges being activated by nervous system stimulation decreases. As tension is released from the biceps brachii, the angle of the elbow joint increases. Eccentric contractions are also used for movement and balance of the body.
  - Isometric contraction - A contraction where the muscle generates force without changing its length. Occurs as the muscle produces tension without changing the angle of a skeletal joint. Isometric contractions involve sarcomere shortening and increasing muscle tension, but do not move a load, as the force produced cannot overcome the resistance provided by the load.
    - Example**:** Pushing against a stationary wall or holding a heavy object in a fixed position; there will be sarcomere activation and shortening to a point, and ever-increasing muscle tension, but no change in the angle of the elbow joint.

In everyday living, isometric contractions are active in maintaining posture and maintaining bone and joint stability. However, holding your head in an upright position occurs not because the muscles cannot move the head, but because the goal is to remain stationary and not produce movement. Most actions of the body are the result of a combination of isotonic and isometric contractions working together to produce a wide range of outcomes (Figure 10.3.1).

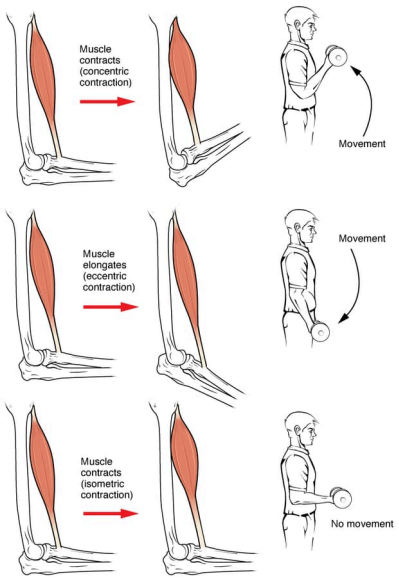


Figure 10.3.1: During isotonic contractions, muscle length changes to move a load. During isometric contractions, muscle length does not change because the load exceeds the tension the muscle can generate. (CC BY 4.0; via Nervous System Control of Muscle Tension). Alternate text description of the Figure 10.3.1.

Motor Units

A skeletal muscle contracts only when it gets a signal from a motor neuron (nerve cell). Each muscle fiber (muscle cell) connects to only one motor neuron. A motor unit = one motor neuron + all the muscle fibers it controls. The size of a motor unit is variable depending on the nature of the muscle.

- Small motor unit: one neuron controls a few fibers. – Purpose: very fine, precise movement. The best example in humans is the small motor units of the extraocular eye muscles that move the eyeballs. There are thousands of muscle fibers in each muscle, but every six or so fibers are supplied by a single motor neuron, as the axons branch to form synaptic connections at their individual NMJs. This allows for exquisite control of eye movements so that both eyes can quickly focus on the same object. Small motor units are also involved in the many fine movements of the fingers and thumb of the hand for grasping, texting, etc.
- Large motor unit: is an arrangement where a single motor neuron supplies a large number of muscle fibers in a muscle. Large motor units are concerned with simple, or “gross,” movements, such as powerfully extending the knee joint. The best example is the large motor units of the thigh muscles or back muscles, where a single motor neuron will supply thousands of muscle fibers in a muscle, as its axon splits into thousands of branches.

There is a wide range of motor units within many skeletal muscles, which gives the nervous system a wide range of control over the muscle. It is important to understand how the brain controls force (recruitment). The nervous system turns on motor units in order, from small to large (small = easier to excite). Small units fire first → small, precise force. Need more force? The brain “recruits” (adds) larger motor units with bigger fibers. As more motor units are recruited, total muscle force increases smoothly. In some muscles, the biggest units can make ~50× more force than the smallest units. Example: This allows a feather to be picked up using the biceps brachii arm muscle with minimal force, and a heavy weight to be lifted by the same muscle by recruiting the largest motor units.

When necessary, the maximal number of motor units in a muscle can be recruited simultaneously, producing the maximum force of contraction for that muscle, but this cannot last for very long because of the energy requirements to sustain the contraction. To prevent complete muscle fatigue, motor units are generally not all simultaneously active, but instead some motor units rest while others are active, which allows for longer muscle contractions. The nervous system uses recruitment as a mechanism to efficiently utilize a skeletal muscle.

The Length-Tension Range of a Sarcomere

When a skeletal muscle fiber contracts, myosin heads attach to actin to form cross-bridges followed by the thin filaments sliding

over the thick filaments as the heads pull the actin, and this results in sarcomere shortening, creating the tension of the muscle contraction. The cross-bridges can only form where thin and thick filaments already overlap, so that the length of the sarcomere has a direct influence on the force generated when the sarcomere shortens. This is called the length-tension relationship.

The ideal length of a sarcomere to produce maximal tension occurs at 80 percent to 120 percent of its resting length, with 100 percent being the state where the medial edges of the thin filaments are just at the most-medial myosin heads of the thick filaments (Figure 10.3.2). This length maximizes the overlap of actin-binding sites and myosin heads. If a sarcomere is stretched past this ideal length (beyond 120 percent), thick and thin filaments do not overlap sufficiently, which results in less tension produced. If a sarcomere is shortened beyond 80 percent, the zone of overlap is reduced with the thin filaments jutting beyond the last of the myosin heads and shrinks the H zone, which is normally composed of myosin tails. Eventually, there is nowhere else for the thin filaments to go and the amount of tension is diminished. If the muscle is stretched to the point where thick and thin filaments do not overlap at all, no cross-bridges can be formed, and no tension is produced in that sarcomere. This amount of stretching does not usually occur, as accessory proteins and connective tissue oppose extreme stretching.

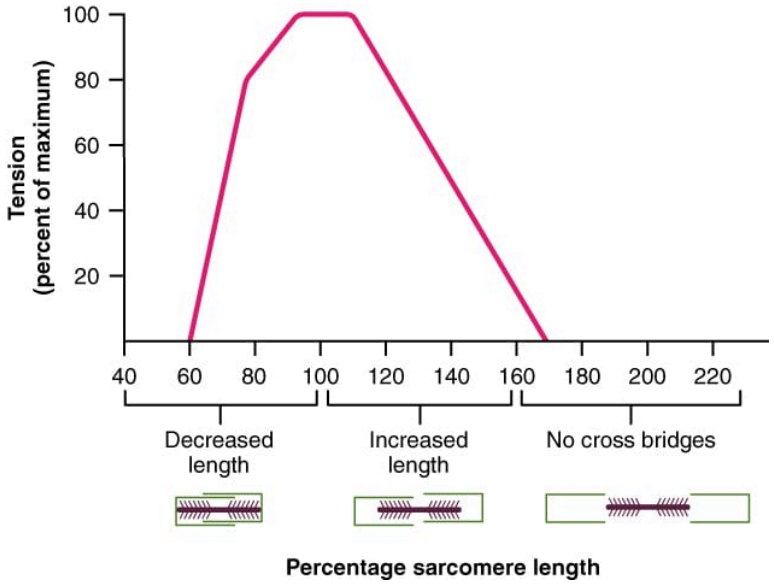


Figure 10.3.2: Sarcomeres produce maximal tension when thick and thin filaments overlap between about 80 percent to 120 percent. (CC BY 4.0; via Nervous System Control of Muscle Tension). Alternate text description of the Figure 10.3.2.

The Frequency of Motor Neuron Stimulation

A single action potential from a motor neuron will produce a single contraction in the muscle fibers of its motor unit. This isolated contraction is called a twitch. A twitch can last for a few milliseconds or 100 milliseconds, depending on the muscle type. The tension produced by a single twitch can be measured by a myogram, an instrument that measures the amount of tension produced over time (Figure 10.3.3). Each twitch undergoes three phases. The first phase is the latent period, during which the action potential is being propagated along the sarcolemma and Ca^{++} ions are released from the SR. This is the phase during which excitation and contraction are being coupled but contraction has yet to occur. The contraction phase occurs next. The Ca^{++} ions in the sarcoplasm have bound to troponin, tropomyosin has shifted away from actin-binding sites, cross-bridges have formed, and sarcomeres are actively shortening to the point of peak tension. The last phase is the relaxation phase, when tension decreases as contraction stops. Ca^{++} ions are pumped out of the sarcoplasm into the SR, and cross-bridge cycling stops, returning the muscle fibers to their resting state.

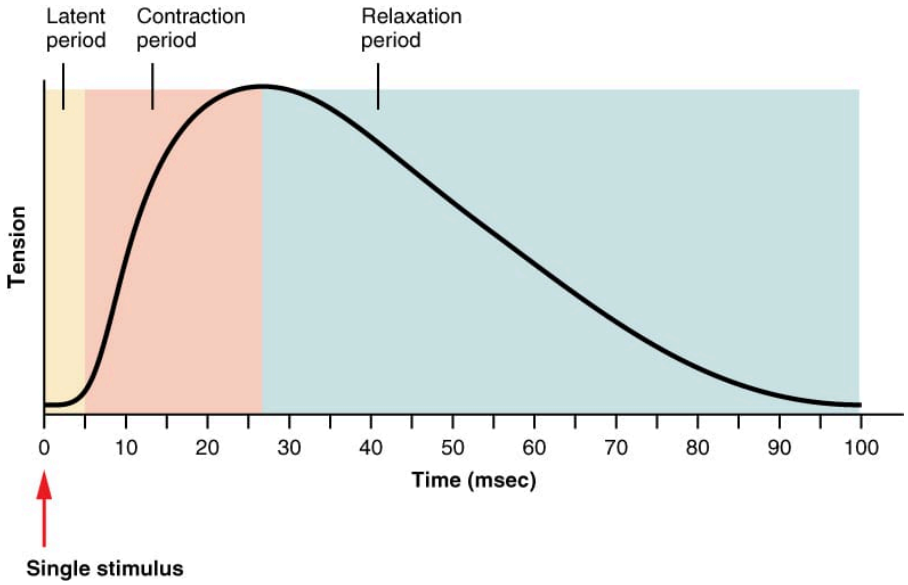


Figure 10.3.3: Graph illustrating the phases of a single muscle twitch. After a stimulus, tension rises during the latent and contraction periods and then decreases through the relaxation period. (CC BY 4.0; via Nervous System Control of Muscle Tension). Alternate text description of the Figure 10.3.3.

Although a person can experience a muscle "twitch," a single twitch does not produce any significant muscle activity in a living body. A series of action potentials to the muscle fibers is necessary to produce a muscle contraction that can produce work. Normal muscle contraction is more sustained, and it can be modified by input from the nervous system to produce varying amounts of force; this is called a graded muscle response. The frequency of action potentials (nerve impulses) from a motor neuron and the number of motor neurons transmitting action potentials both affect the tension produced in skeletal muscle.

The rate at which a motor neuron fires action potentials affects the tension produced in the skeletal muscle. If the fibers are stimulated while a previous twitch is still occurring, the second twitch will be stronger. This response is called wave summation, because the excitation-contraction coupling effects of successive motor neuron signaling is summed, or added together (Figure 10.3.4a). At the molecular level, summation occurs because the second stimulus triggers the release of more Ca^{++} ions, which become available to activate additional sarcomeres while the muscle is still contracting from the first stimulus. Summation results in greater contraction of the motor unit.

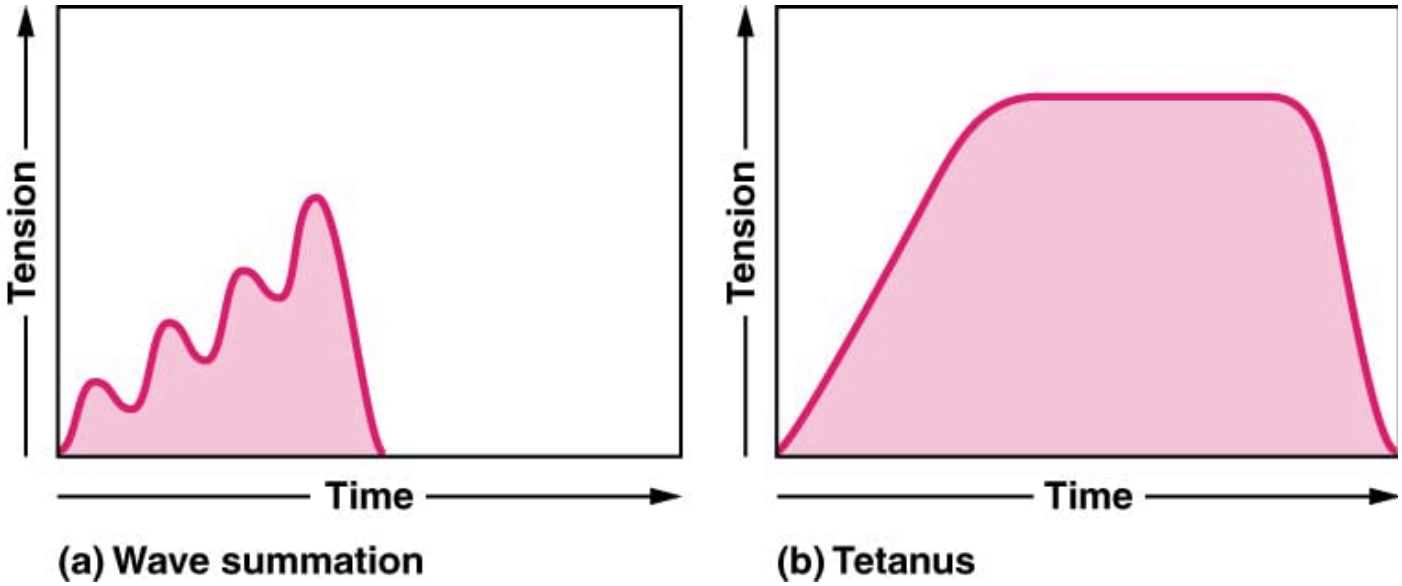


Figure 10.3.4: Side-by-side graphs illustrating muscle tension responses to repeated stimuli. The first shows wave summation with gradually increasing peaks, and the second shows tetanus with sustained maximal tension. (CC BY 4.0; via Nervous System Control of Muscle Tension). Alternate text description of the Figure \(\PageIndex{4}\).

If the frequency of motor neuron signaling increases, summation and subsequent muscle tension in the motor unit continues to rise until it reaches a peak point. The tension at this point is about three to four times greater than the tension of a single twitch, a state referred to as incomplete tetanus. During incomplete tetanus, the muscle goes through quick cycles of contraction with a short relaxation phase for each. If the stimulus frequency is so high that the relaxation phase disappears completely, contractions become continuous in a process called complete tetanus (Figure 10.3.4*b*).

During tetanus, the concentration of Ca^{++} ions in the sarcoplasm allows virtually all of the sarcomeres to form cross-bridges and shorten, so that a contraction can continue uninterrupted (until the muscle fatigues and can no longer produce tension).

Treppe

When a skeletal muscle has been dormant for an extended period and then activated to contract, with all other things being equal, the initial contractions generate about one-half the force of later contractions. The muscle tension increases in a graded manner that to some looks like a set of stairs. This tension increase is called treppe, a condition where muscle contractions become more efficient. It's also known as the "staircase effect" (Figure 10.3.5).

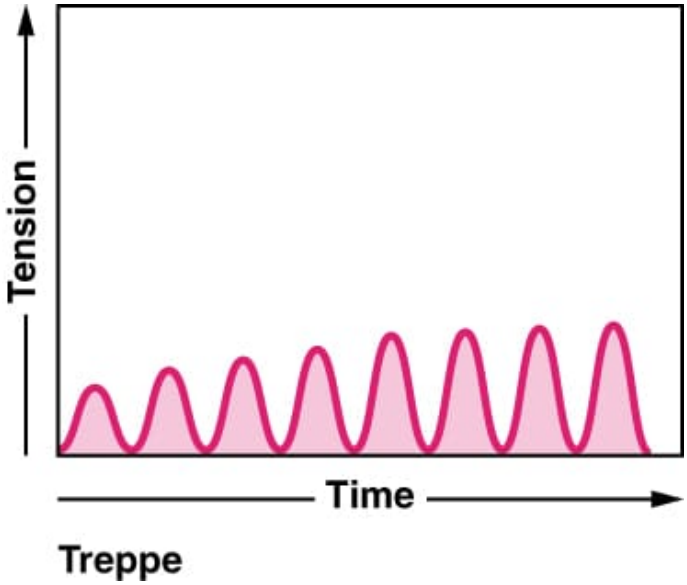


Figure 10.3.5: When muscle tension increases in a graded manner that looks like a set of stairs, it is called treppe. The bottom of each wave represents the point of stimulus. (CC BY 4.0; via Nervous System Control of Muscle Tension). Alternate text description of the Figure 10.3.5.

Muscle Tone

Muscle tone is the small, constant tension in a resting muscle. It comes from low-level, involuntary activation of some motor units (a motor neuron and the fibers it controls). Tone is not the same as a full contraction. It is a gentle "readiness" that does not move the joint. Skeletal muscles are rarely completely relaxed. Even if a muscle is not producing movement, it is contracted a small amount to maintain its contractile proteins and produce muscle tone. The tension produced by muscle tone allows muscles to continually stabilize joints and maintain posture, supports joints and protects ligaments, lets muscles react quickly, and helps venous return and makes a little heat.

Muscle tone is accomplished by a complex interaction between the nervous system and skeletal muscles that results in the activation of a few motor units at a time, most likely in a cyclical manner. In this manner, muscles never fatigue completely, as some motor units can recover while others are active.

The absence of the low-level contractions that lead to muscle tone is referred to as hypotonia, and can result from damage to parts of the central nervous system (CNS), such as the cerebellum, or from loss of innervations to a skeletal muscle (peripheral nerve injury), as in poliomyelitis. Hypotonic muscles have a flaccid appearance and display functional impairments, such as weak reflexes. Conversely, excessive muscle tone is referred to as hypertonia, accompanied by hyperreflexia (excessive reflex responses), often the result of damage to upper motor neurons in the CNS. Hypertonia can present with muscle rigidity (as seen in Parkinson's disease) or spasticity, a phasic change in muscle tone, where a limb will "snap" back from passive stretching (as

seen in some strokes). Cramps and spasms are brief, painful contractions; not the same as baseline tone.

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10.4: Types of Muscle Fibers

Classification of Skeletal Muscle Fiber Types

Skeletal muscle fibers are classified using two main criteria: contraction speed and how they produce ATP (metabolic profile). This classification system divides muscle into three primary types, each suited to different functional demands. Using these criteria, there are three main types of skeletal muscle fibers.

- Type I: Slow oxidative (SO) fibers contract relatively slowly. Used for endurance and sustained activity. Relies on aerobic metabolism, which uses oxygen to produce energy (ATP). These fibers generate low-power contractions over extended periods and are slow to fatigue.They contain abundant mitochondria, a rich capillary network, and high concentrations of myoglobin—a red oxygen-binding pigment that improves oxygen delivery. Because of this myoglobin content, Type I fibers are called "red fibers." They are recruited first during muscle contraction and are found in higher proportions in postural muscles (e.g., erector spinae, soleus) and during low-intensity, prolonged activities like walking or endurance sports.
- Type IIa: Fast oxidative (FO) fibers, sometimes called intermediate fibers because they possess characteristics that are intermediate between fast fibers and slow fibers. They produce ATP relatively quickly, more quickly than SO fibers, and thus can produce relatively high amounts of tension. They are oxidative because they produce ATP aerobically, possess high amounts of mitochondria, and do not fatigue quickly. However, FO fibers do not possess significant myoglobin, giving them a lighter color than the red SO fibers. FO fibers are used primarily for movements, such as walking, that require more energy than postural control but less energy than an explosive movement, such as sprinting. FO fibers are useful for this type of movement because they produce more tension than SO fibers but they are more fatigue-resistant than FG fibers.
- Type IIb: Fast glycolytic (FG) fibers primarily use anaerobic glycolysis as their ATP source. They have a large diameter and possess high amounts of glycogen, which is used in glycolysis to generate ATP quickly to produce high levels of tension. Because they do not primarily use aerobic metabolism, they do not possess substantial numbers of mitochondria or significant amounts of myoglobin and therefore have a white color. FG fibers are used to produce rapid, forceful contractions to make quick, powerful movements. These fibers fatigue quickly, permitting them to only be used for short periods.

Table 10.4.1: Comparison of Characteristics of Skeletal Muscle Fiber types

Characteristics	Type I Slow twitch Oxidative (SO)	Type IIa Fast twitch Oxidative (FO)	Tyoe IIx Fast Glycolytic (FG)
Examples in Major Locations	Postutal muscles of the back (erector spinae, Soleus)	Activities needing both power and endurancem like sprinting, repreated weightlifting, sets, swimming, cycling, or stop-strat sports such as basketball, soccer, and tennis (quadriceps, hamstring)	Produce rapis, foreceful contrsctions to make quick, powerful movements (such as Tibialis anterior, Vastus lateralis)
Contractile Speed	Relatively slow	Fast	Fast
Main ATP Source	Oxidative Phosphorylation	Oxidative Phosphorylation	Anaerobic glycolysis
Myoglobin Content	High (red fiber)	High (red fiber)	Low (white fiber)
Glycogen Content	Low	Intermediate	High
Mitochondria and Capillaries	High, rich capillary network	Many	Few
Myosin ATPase Activity	Low	High	High

Characteristics	Type I Slow twitch Oxidative (SO)	Type IIa Fast twitch Oxidative (FO)	Tyoe IIx Fast Glycolytic (FG)
Rate of Fatigue	Slow, generate low-power contractions over extended periods and are slow to fatigue	Intermediate, mostly fatigue resistant	Fast, fatigue quickly, permitting them to only be used for short periods.

Most muscles possess a mixture of each fiber type. The number of slow and fast-twitch fibers contained in the body varies greatly between individuals and is determined by a person's genetics. People who do well at endurance sports tend to have a higher number of slow-twitch fibers, whereas people who are better at sprint events tend to have higher numbers of fast-twitch muscle fibers. Both the slow twitch and fast-twitch fibers can be influenced by training. It is possible through sprint training to improve the power generated by slow twitch fibers, and through endurance training, it is possible to increase the endurance level of fast-twitch fibers. The level of improvement varies, depending on the individual, and training can never make slow-twitch fibers as powerful as fast- twitch, nor can training make fast-twitch fibers as fatigue resistant as slow-twitch fibers. The speed of contraction is dependent on how quickly myosin's ATPase hydrolyzes ATP to produce cross-bridge action. Fast fibers hydrolyze ATP approximately twice as quickly as slow fibers, resulting in much quicker cross-bridge cycling (which pulls the thin filaments toward the center of the sarcomeres at a faster rate).

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10.5: Exercise and Muscle Performance

Effects of Endurance and Resistance Training on Skeletal Muscle

Physical training alters the appearance of skeletal muscles and can produce changes in muscle performance. Conversely, a lack of use can result in decreased performance and muscle appearance. Although muscle cells can change in size, new cells are not formed when muscles grow. Instead, structural proteins are added to muscle fibers in a process called hypertrophy, so cell diameter increases. The reverse, when structural proteins are lost and muscle mass decreases, is called atrophy. Age-related muscle atrophy is called sarco penia. Cellular components of muscles can also undergo changes in response to changes in muscle use.

Endurance Exercise

Slow fibers are predominantly used in endurance exercises that require little force but involve numerous repetitions. The aerobic metabolism used by slow-twitch fibers allows them to maintain contractions over long periods. Endurance training modifies these slow fibers to make them even more efficient by producing more mitochondria to enable more aerobic metabolism and more ATP production. Endurance exercise can also increase the amount of myoglobin in a cell, as increased aerobic respiration increases the need for oxygen. Myoglobin is found in the sarcoplasm and acts as an oxygen storage supply for the mitochondria.

The training can trigger the formation of more extensive capillary networks around the fiber, a process called angiogenesis, to supply oxygen and remove metabolic waste. To allow these capillary networks to supply the deep portions of the muscle, muscle mass does not greatly increase in order to maintain a smaller area for the diffusion of nutrients and gases. All of these cellular changes result in the ability to sustain low levels of muscle contractions for greater periods without fatiguing.

The proportion of SO muscle fibers in muscle determines the suitability of that muscle for endurance, and may benefit those participating in endurance activities. Postural muscles have a large number of SO fibers and relatively few FO and FG fibers, to keep the back straight (Figure 10.5.1). Endurance athletes, like marathon-runners also would benefit from a larger proportion of SO fibers, but it is unclear if the most-successful marathoners are those with naturally high numbers of SO fibers, or whether the most successful marathon runners develop high numbers of SO fibers with repetitive training. Endurance training can result in overuse injuries such as stress fractures and joint and tendon inflammation.



Figure 10.5.1: Long-distance runners have a large number of SO fibers and relatively few FO and FG fibers. (CC BY 4.0; via Exercise and Muscle Performance). Alternate text description of the Figure 10.5.1.

Resistance Exercise

Resistance exercises, as opposed to endurance exercise, require large amounts of FG fibers to produce short, powerful movements that are not repeated over long periods. The high rates of ATP hydrolysis and cross-bridge formation in FG fibers result in powerful muscle contractions. Muscles used for power have a higher ratio of FG to SO/FO fibers, and trained athletes possess even higher levels of FG fibers in their muscles. Resistance exercise affects muscles by increasing the formation of myofibrils, thereby increasing the thickness of muscle fibers. This added structure causes hypertrophy, or the enlargement of muscles, exemplified by the large skeletal muscles seen in body builders and other athletes (Figure 10.5.2). Because this muscular enlargement is achieved by the addition of structural proteins, athletes trying to build muscle mass often ingest large amounts of protein.



Figure 10.5.2: Body builders have a large number of FG fibers and relatively few FO and SO fibers. (CC BY 4.0; via Exercise and Muscle Performance). Alternate text description of the Figure 10.5.2.

Except for the hypertrophy that follows an increase in the number of sarcomeres and myofibrils in a skeletal muscle, the cellular changes observed during endurance training do not usually occur with resistance training. There is usually no significant increase in mitochondria or capillary density. However, resistance training does increase the development of connective tissue, which adds to the overall mass of the muscle and helps to contain muscles as they produce increasingly powerful contractions. Tendons also become stronger to prevent tendon damage, as the force produced by muscles is transferred to tendons that attach the muscle to bone.

For effective strength training, the intensity of the exercise must continually be increased. For instance, continued weight lifting without increasing the weight of the load does not increase muscle size. To produce ever-greater results, the weights lifted must become increasingly heavier, making it more difficult for muscles to move the load. The muscle then adapts to this heavier load, and an even heavier load must be used if even greater muscle mass is desired.

If done improperly, resistance training can lead to overuse injuries of the muscle, tendon, or bone. These injuries can occur if the load is too heavy or if the muscles are not given sufficient time between workouts to recover or if joints are not aligned properly during the exercises. Cellular damage to muscle fibers that occurs after intense exercise includes damage to the sarcolemma and myofibrils. This muscle damage contributes to the feeling of soreness after strenuous exercise, but muscles gain mass as this damage is repaired, and additional structural proteins are added to replace the damaged ones. Overworking skeletal muscles can also lead to tendon damage and even skeletal damage if the load is too great for the muscles to bear.

Performance-Enhancing Substances

Some athletes attempt to boost their performance by using various agents that may enhance muscle performance. Anabolic steroids are one of the more widely known agents used to boost muscle mass and increase power output. Anabolic steroids are a form of testosterone, a male sex hormone that stimulates muscle formation, leading to increased muscle mass.

Endurance athletes may also try to boost the availability of oxygen to muscles to increase aerobic respiration by using substances such as erythropoietin (EPO), a hormone normally produced in the kidneys, which triggers the production of red blood cells. The extra oxygen carried by these blood cells can then be used by muscles for aerobic respiration. Human growth hormone (hGH) is another supplement, and although it can facilitate building muscle mass, its main role is to promote the healing of muscle and other tissues after strenuous exercise. Increased hGH may allow for faster recovery after muscle damage, reducing the rest required after exercise, and allowing for more sustained high-level performance.

Although performance-enhancing substances often do improve performance, most are banned by governing bodies in sports and are illegal for nonmedical purposes. Their use to enhance performance raises ethical issues of cheating because they give users an unfair advantage over nonusers. A greater concern, however, is that their use carries serious health risks. The side effects of these substances are often significant, nonreversible, and in some cases fatal. The physiological strain caused by these substances is often greater than what the body can handle, leading to effects that are unpredictable and dangerous. Anabolic steroid use has been linked to infertility, aggressive behavior, cardiovascular disease, and brain cancer.

Similarly, some athletes have used creatine to increase power output. Creatine phosphate provides quick bursts of ATP to muscles in the initial stages of contraction. Increasing the amount of creatine available to cells is thought to produce more ATP and therefore increase explosive power output, although its effectiveness as a supplement has been questioned.

Everyday Connection

Aging and Muscle Tissue

Although atrophy due to disuse can often be reversed with exercise, muscle atrophy with age, referred to as sarco penia, is irreversible. This is a primary reason why even highly trained athletes succumb to declining performance with age. This decline is noticeable in athletes whose sports require strength and powerful movements, such as sprinting, whereas the effects of age are less noticeable in endurance athletes such as marathon runners or long-distance cyclists. As muscles age, muscle fibers die, and they are replaced by connective tissue and adipose tissue (Figure 10.5.3). Because those tissues cannot contract and generate force as muscle can, muscles lose the ability to produce powerful contractions. The decline in muscle mass causes a loss of strength, including the strength required for posture and mobility. This may be caused by a reduction in FG fibers that hydrolyze ATP quickly to produce short, powerful contractions. Muscles in older people sometimes possess greater numbers of SO fibers, which are responsible for longer contractions and do not produce powerful movements. There may also be a reduction in the size of motor units, resulting in fewer fibers being stimulated and less muscle tension being produced.

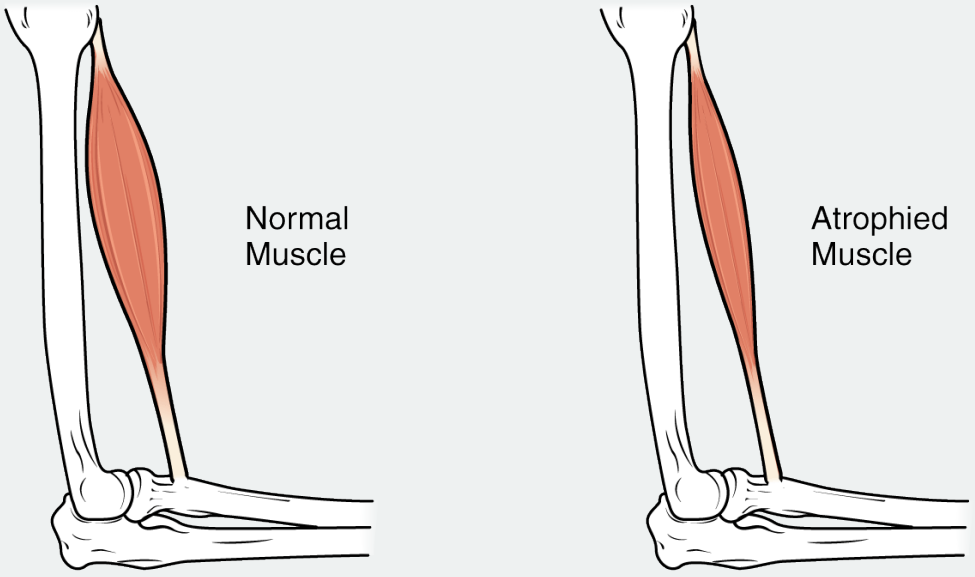


Figure 10.5.3: Muscle mass is reduced as muscles atrophy with disuse. (CC BY 4.0; via Exercise and Muscle Performance). Alternate text description of the Figure 10.5.3.

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10.6: Cardiac Muscle Tissue

Anatomy of Cardiac Muscle Tissue

Cardiac muscle tissue is only found in the heart. Highly coordinated contractions of cardiac muscle pump blood into the vessels of the circulatory system. Similar to skeletal muscle, cardiac muscle is striated and organized into sarcomeres, possessing the same banding organization as skeletal muscle (Figure 10.6.1). However, cardiac muscle fibers are shorter than skeletal muscle fibers and usually contain only one nucleus, which is located in the central region of the cell. Cardiac muscle fibers also possess many mitochondria and myoglobin, as ATP is produced primarily through aerobic metabolism. Cardiac muscle fibers cells also are extensively branched and are connected to one another at their ends by intercalated discs. An intercalated disc allows the cardiac muscle cells to contract in a wave-like pattern so that the heart can work as a pump.

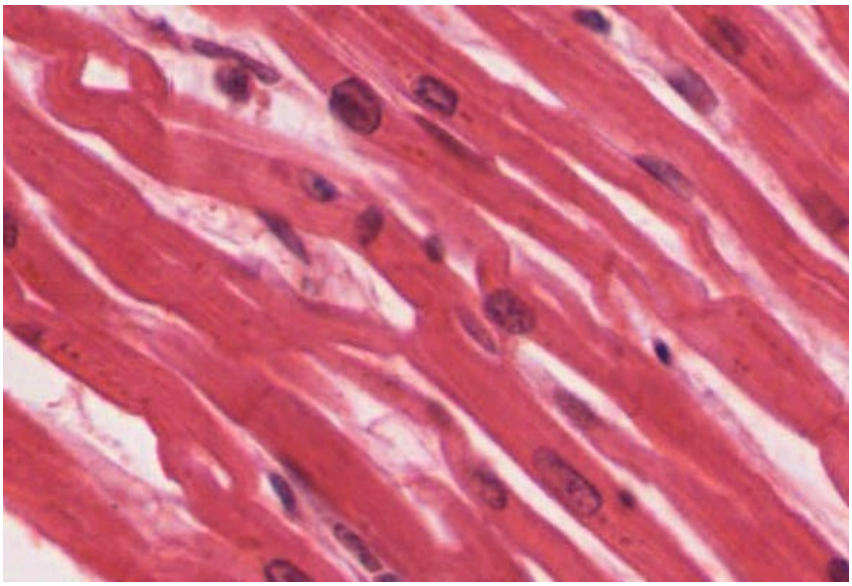


Figure 10.6.1: Cardiac muscle tissue is only found in the heart. LM × 1600. (CC BY 4.0; via Cardiac Muscle Tissue). Alternate text description of the Figure 10.6.1.

Intercalated Discs and Cellular Connections

Intercalated discs are part of the sarcolemma and contain two structures important in cardiac muscle contraction: gap junctions and desmosomes. A gap junction forms channels between adjacent cardiac muscle fibers that allow the depolarizing current produced by cations to flow from one cardiac muscle cell to the next. This joining is called electric coupling, and in cardiac muscle it allows the quick transmission of action potentials and the coordinated contraction of the entire heart. This network of electrically connected cardiac muscle cells creates a functional unit of contraction called a syncytium. The remainder of the intercalated disc is composed of desmosomes. A desmosome is a cell structure that anchors the ends of cardiac muscle fibers together so the cells do not pull apart during the stress of individual fibers contracting (Figure 10.6.2).

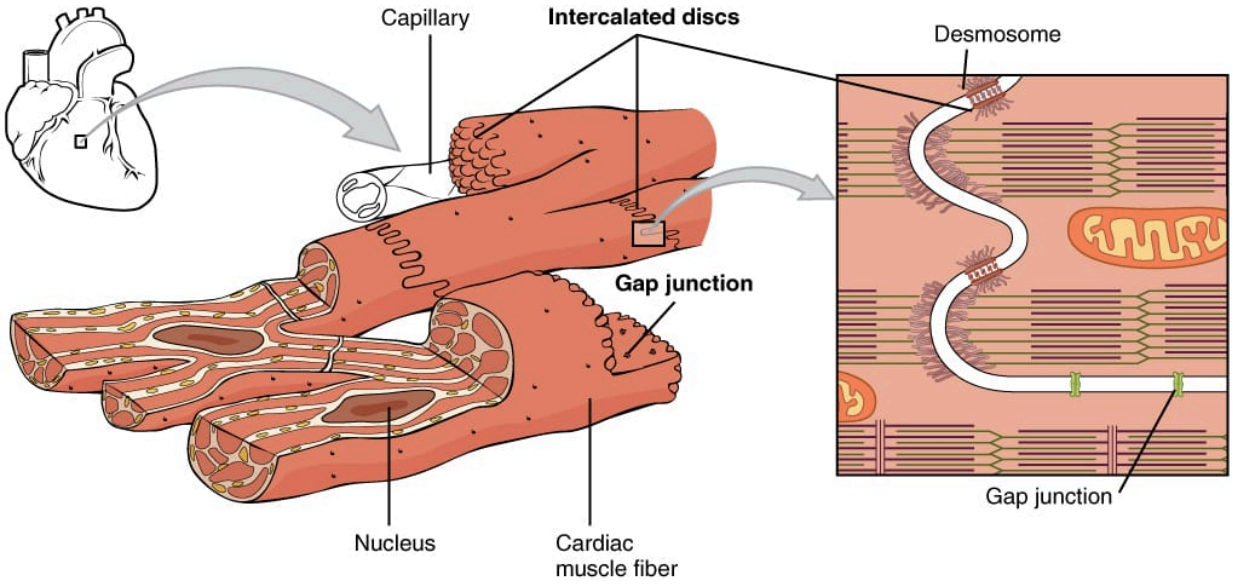


Figure 10.6.2: Intercalated discs are part of the cardiac muscle sarcolemma and they contain gap junctions and desmosomes. (CC BY 4.0; via Cardiac Muscle Tissue). Alternate text description of the Figure 10.6.2.

Pacemaker Cells and Regulation of Heart Rate

Contractions of the heart (heartbeats) are controlled by specialized cardiac muscle cells called pacemaker cells that directly control heart rate. Although cardiac muscle cannot be consciously controlled, the pacemaker cells respond to signals from the autonomic nervous system (ANS) to speed up or slow down the heart rate. The pacemaker cells can also respond to various hormones that modulate heart rate to control blood pressure.

The wave of contraction that allows the heart to work as a unit, called a functional syncytium, begins with the pacemaker cells. This group of cells is self-excitable and able to depolarize to threshold and fire action potentials on their own, a feature called auto rhythmicity; they do this at set intervals which determine heart rate. Because they are connected with gap junctions to surrounding muscle fibers and the specialized fibers of the heart's conduction system, the pacemaker cells are able to transfer the depolarization to the other cardiac muscle fibers in a manner that allows the heart to contract in a coordinated manner.

Another feature of cardiac muscle is its relatively long action potentials in its fibers, having a sustained depolarization "plateau." The plateau is produced by Ca^{++} entry though voltage-gated calcium channels in the sarcolemma of cardiac muscle fibers. This sustained depolarization (and Ca^{++} entry) provides for a longer contraction than is produced by an action potential in skeletal muscle. Unlike skeletal muscle, a large percentage of the Ca^{++} that initiates contraction in cardiac muscles comes from outside the cell rather than from the SR.

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10.7: Smooth Muscle

Structure and Function of Smooth Muscle

Smooth muscle (so-named because the cells do not have striations) is present in the walls of hollow organs like the urinary bladder, uterus, stomach, intestines, and in the walls of passageways, such as the arteries and veins of the circulatory system, and the tracts of the respiratory, urinary, and reproductive systems. Smooth muscle is also present in the eyes, where it functions to change the size of the iris and alter the shape of the lens; and in the skin where it causes hair to stand erect in response to cold temperature or fear.

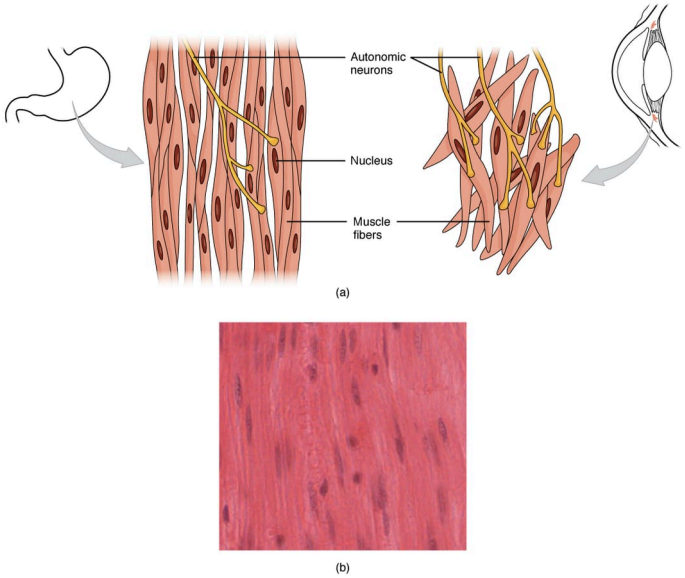


Figure 10.7.1: Smooth muscle tissue is found around organs in the digestive, respiratory, reproductive tracts and the iris of the eye. LM × 1600. (CC BY 4.0; via Smooth Muscle). Alternate text description of the Figure 10.7.1.

Smooth muscle fibers are spindle-shaped (wide in the middle and tapered at both ends, somewhat like a football) and have a single nucleus; they range from about 30 to 200 μm (thousands of times shorter than skeletal muscle fibers), and they produce their own connective tissue, endomysium. Although they do not have striations and sarcomeres, smooth muscle fibers do have actin and myosin contractile proteins, and thick and thin filaments. These thin filaments are anchored by dense bodies. A dense body is analogous to the Z-discs of skeletal and cardiac muscle fibers and is fastened to the sarcolemma. Calcium ions are supplied by the SR in the fibers and by sequestration from the extracellular fluid through membrane indentations called calveoli.

Because smooth muscle cells do not contain troponin, cross-bridge formation is not regulated by the troponin-tropomyosin complex but instead by the regulatory protein calmodulin. In a smooth muscle fiber, external Ca^{++} ions passing through opened calcium channels in the sarcolemma, and additional Ca^{++} released from SR, bind to calmodulin. The Ca^{++}-calmodulin complex then activates an enzyme called myosin (light chain) kinase, which, in turn, activates the myosin heads by phosphorylating them (converting ATP to ADP and P_i, with the P_i attaching to the head). The heads can then attach to actin-binding sites and pull on the thin filaments. The thin filaments also are anchored to the dense bodies; the structures invested in the inner membrane of the sarcolemma (at adherens junctions) that also have cord-like intermediate filaments attached to them. When the thin filaments slide past the thick filaments, they pull on the dense bodies, structures tethered to the sarcolemma, which then pull on the intermediate filaments networks throughout the sarcoplasm. This arrangement causes the entire muscle fiber to contract in a manner whereby the ends are pulled toward the center, causing the midsection to bulge in a corkscrew motion (Figure 10.7.2).

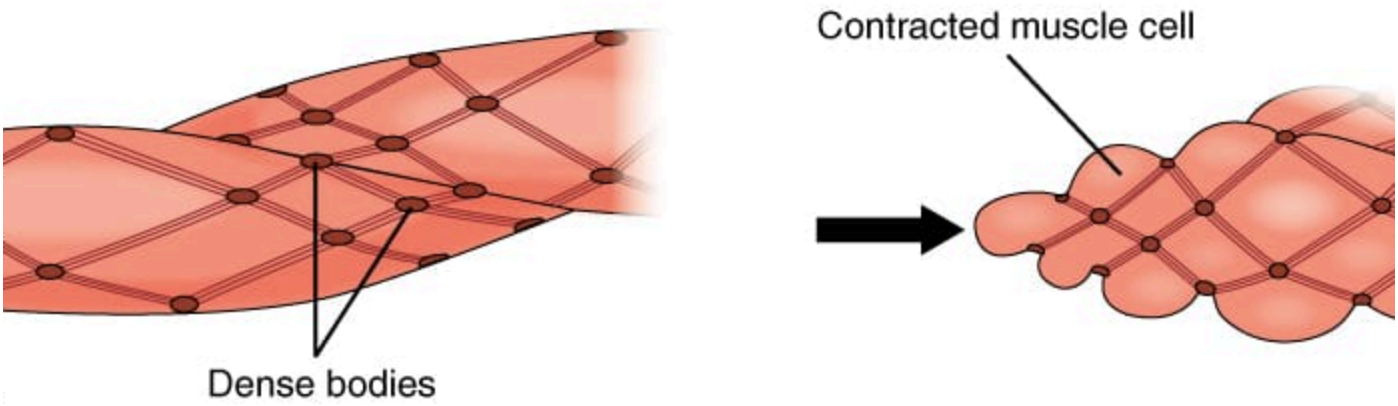


Figure 10.7.2: The dense bodies and intermediate filaments are networked through the sarcoplasm, which cause the muscle fiber to contract. (CC BY 4.0; via Smooth Muscle). Alternate text description of the Figure 10.7.2.

Although smooth muscle contraction relies on the presence of Ca^{++} ions, smooth muscle fibers have a much smaller diameter than skeletal muscle cells. T-tubules are not required to reach the interior of the cell and therefore not necessary to transmit an action potential deep into the fiber. Smooth muscle fibers have a limited calcium-storing SR but have calcium channels in the sarcolemma (similar to cardiac muscle fibers) that open during the action potential along the sarcolemma. The influx of extracellular Ca^{++} ions, which diffuse into the sarcoplasm to reach the calmodulin, accounts for most of the Ca^{++} that triggers contraction of a smooth muscle cell.

Muscle contraction continues until ATP-dependent calcium pumps actively transport Ca^{++} ions back into the SR and out of the cell. However, a low concentration of calcium remains in the sarcoplasm to maintain muscle tone. This remaining calcium keeps the muscle slightly contracted, which is important in certain tracts and around blood vessels.

Because most smooth muscles must function for long periods without rest, their power output is relatively low, but contractions can continue without using large amounts of energy. Some smooth muscle can also maintain contractions even as Ca^{++} is removed and myosin kinase is inactivated/dephosphorylated. This can happen as a subset of cross-bridges between myosin heads and actin, called latch-bridges, keep the thick and thin filaments linked together for a prolonged period, and without the need for ATP. This allows for the maintaining of muscle “tone” in smooth muscle that lines arterioles and other visceral organs with very little energy expenditure.

Regulation and Types of Smooth Muscle

Smooth muscle is not under voluntary control; thus, it is called involuntary muscle. The triggers for smooth muscle contraction include hormones, neural stimulation by the ANS, and local factors. In certain locations, such as the walls of visceral organs, stretching the muscle can trigger its contraction (the stress-relaxation response).

Axons of neurons in the ANS do not form the highly organized NMJs with smooth muscle, as seen between motor neurons and skeletal muscle fibers. Instead, there is a series of neurotransmitter-filled bulges called varicosities as an axon courses through smooth muscle, loosely forming motor units (Figure 10.7.3). A varicosity releases neurotransmitters into the synaptic cleft. Also, visceral muscle in the walls of the hollow organs (except the heart) contains pacesetter cells. A pacesetter cell can spontaneously trigger action potentials and contractions in the muscle.

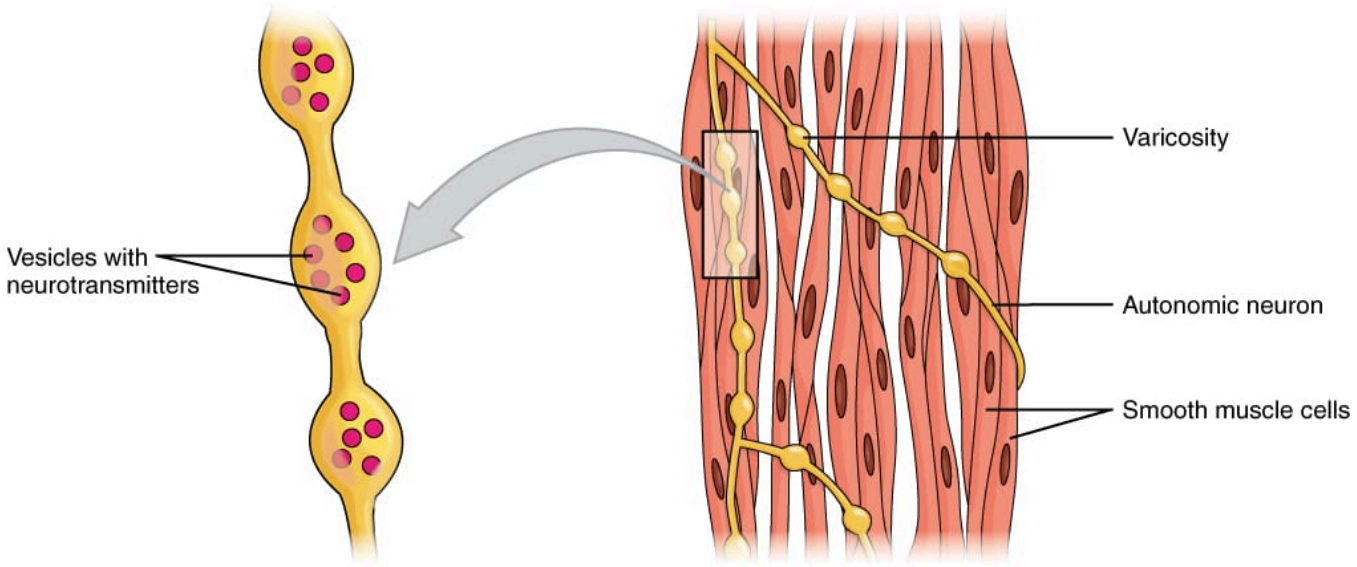


Figure 10.7.3: A series of axon-like swelling, called varicosities or "boutons," from autonomic neurons form motor units through the smooth muscle. (CC BY 4.0; via Smooth Muscle). Alternate text description of the Figure 10.7.3.

Smooth muscle is organized in two ways: as single-unit smooth muscle, which is much more common; and as multiunit smooth muscle. The two types have different locations in the body and have different characteristics. Single-unit muscle has its muscle fibers joined by gap junctions so that the muscle contracts as a single unit. This type of smooth muscle is found in the walls of all visceral organs except the heart (which has cardiac muscle in its walls), and so it is commonly called visceral muscle. Because the muscle fibers are not constrained by the organization and stretchability limits of sarcomeres, visceral smooth muscle has a stress-relaxation response. This means that as the muscle of a hollow organ is stretched when it fills, the mechanical stress of the stretching will trigger contraction, but this is immediately followed by relaxation so that the organ does not empty its contents prematurely. This is important for hollow organs, such as the stomach or urinary bladder, which continuously expand as they fill. The smooth muscle around these organs also can maintain a muscle tone when the organ empties and shrinks, a feature that prevents "flabbiness" in the empty organ. In general, visceral smooth muscle produces slow, steady contractions that allow substances, such as food in the digestive tract, to move through the body.

Multiunit smooth muscle cells rarely possess gap junctions, and thus are not electrically coupled. As a result, contraction does not spread from one cell to the next, but is instead confined to the cell that was originally stimulated. Stimuli for multiunit smooth muscles come from autonomic nerves or hormones but not from stretching. This type of tissue is found around large blood vessels, in the respiratory airways, and in the eyes.

Similar to skeletal and cardiac muscle cells, smooth muscle can undergo hypertrophy to increase in size. Unlike other muscle, smooth muscle can also divide to produce more cells, a process called hyperplasia. This can most evidently be observed in the uterus at puberty, which responds to increased estrogen levels by producing more uterine smooth muscle fibers, and greatly increases the size of the myometrium.

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10.8: Terms and Definitions

Key Terms

Select to view definitions

Acetylcholine (ACh)
neurotransmitter that binds at a motor end-plate to trigger depolarization

Actin
protein that makes up most of the thin myofilaments in a sarcomere muscle fiber

Action potential
change in voltage of a cell membrane in response to a stimulus that results in transmission of an electrical signal; unique to neurons and muscle fibers

Aerobic respiration
production of ATP in the presence of oxygen

Angiogenesis
formation of blood capillary networks

aponeurosis
broad, tendon-like sheet of connective tissue that attaches a skeletal muscle to another skeletal muscle or to a bone

ATPase
enzyme that hydrolyzes ATP to ADP

Atrophy
loss of structural proteins from muscle fibers

Autorhythmicity
heart's ability to control its own contractions

Calmodulin
regulatory protein that facilitates contraction in smooth muscles

Cardiac muscle
striated muscle found in the heart; joined to one another at intercalated discs and under the regulation of pacemaker cells, which contract as one unit to pump blood through the circulatory system. Cardiac muscle is under involuntary control.

Concentric contraction
muscle contraction that shortens the muscle to move a load

Contractility
ability to shorten (contract) forcibly

Contraction phase
twitch contraction phase when tension increases

Creatine phosphate
phosphagen used to store energy from ATP and transfer it to muscle

Dense body
sarcoplasmic structure that attaches to the sarcolemma and shortens the muscle as thin filaments slide past thick filaments

Depolarize
to reduce the voltage difference between the inside and outside of a cell's plasma membrane (the sarcolemma for a muscle fiber), making the inside less negative than at rest

Desmosome
cell structure that anchors the ends of cardiac muscle fibers to allow contraction to occur

Eccentric contraction
muscle contraction that lengthens the muscle as the tension is diminished

Elasticity
ability to stretch and rebound

Endomysium
loose, and well-hydrated connective tissue covering each muscle fiber in a skeletal muscle

Epimysium
outer layer of connective tissue around a skeletal muscle

Excitability
ability to undergo neural stimulation

Excitation-contraction coupling
sequence of events from motor neuron signaling to a skeletal muscle fiber to contraction of the fiber's sarcomeres

Extensibility
ability to lengthen (extend)

Fascicle
bundle of muscle fibers within a skeletal muscle

Fast glycolytic (FG)
muscle fiber that primarily uses anaerobic glycolysis

Fast oxidative (FO)
intermediate muscle fiber that is between slow oxidative and fast glycolytic fibers

Fibrosis
replacement of muscle fibers by scar tissue

Glycolysis
anaerobic breakdown of glucose to ATP

Graded muscle response
modification of contraction strength

Hyperplasia
process in which one cell splits to produce new cells

Hypertonia
abnormally high muscle tone

Hypertrophy
addition of structural proteins to muscle fibers

Hypotonia
abnormally low muscle tone caused by the absence of low-level contractions

Intercalated disc
part of the sarcolemma that connects cardiac tissue, and contains gap junctions and desmosomes

Isometric contraction
muscle contraction that occurs with no change in muscle length

Isotonic contraction
muscle contraction that involves changes in muscle length

Lactic acid
product of anaerobic glycolysis

Latent period
the time when a twitch does not produce contraction

Motor end-plate
sarcolemma of muscle fiber at the neuromuscular junction, with receptors for the neurotransmitter acetylcholine

Motor unit
motor neuron and the group of muscle fibers it innervates

Muscle tension
force generated by the contraction of the muscle; tension generated during isotonic contractions and isometric contractions

Muscle tone
low levels of muscle contraction that occur when a muscle is not producing movement

Myoblast
muscle-forming stem cell

Myofibril
long, cylindrical organelle that runs parallel within the muscle fiber and contains the sarcomeres

Myogram
instrument used to measure twitch tension

Myosin
protein that makes up most of the thick cylindrical myofilament within a sarcomere muscle fiber

Neuromuscular junction (NMJ)
synapse between the axon terminal of a motor neuron and the section of the membrane of a muscle fiber with receptors for the acetylcholine released by the terminal

Neurotransmitter
signaling chemical released by nerve terminals that bind to and activate receptors on target cells

Oxygen debt
amount of oxygen needed to compensate for ATP produced without oxygen during muscle contraction

Pacesetter cell
cell that triggers action potentials in smooth muscle

Pericyte
stem cell that regenerates smooth muscle cells

Perimysium
connective tissue that bundles skeletal muscle fibers into fascicles within a skeletal muscle

Power stroke
action of myosin pulling actin inward (toward the M line)

Pyruvic acid
product of glycolysis that can be used in aerobic respiration or converted to lactic acid

Recruitment
increase in the number of motor units involved in contraction

Relaxation phase
period after twitch contraction when tension decreases

Sarcolemma
plasma membrane of a skeletal muscle fiber

Sarcomere
longitudinally, repeating functional unit of skeletal muscle, with all of the contractile and associated proteins involved in contraction

Sarcopenia
age-related muscle atrophy

Sarcoplasm
cytoplasm of a muscle cell

Sarcoplasmic reticulum (SR)
specialized smooth endoplasmic reticulum, which stores, releases, and retrieves Ca^{++}

Satellite cell
stem cell that helps to repair muscle cells

Skeletal muscle
striated, multinucleated muscle that requires signaling from the nervous system to trigger contraction; most skeletal muscles are referred to as voluntary muscles that move bones and produce movement

Slow oxidative (SO)
muscle fiber that primarily uses aerobic respiration

Smooth muscle
nonstriated, mononucleated muscle in the skin that is associated with hair follicles; assists in moving materials in the walls of internal organs, blood vessels, and internal passageways

Somites
blocks of paraxial mesoderm cells

Stress-relaxation response
relaxation of smooth muscle tissue after being stretched

Synaptic cleft
space between a nerve (axon) terminal and a motor end-plate

T-tubule
projection of the sarcolemma into the interior of the cell

Tetanus
a continuous fused contraction

Thick filament
the thick myosin strands and their multiple heads projecting from the center of the sarcomere toward, but not all to way to, the Z-discs

Thin filament
thin strands of actin and its troponin-tropomyosin complex projecting from the Z-discs toward the center of the sarcomere

Treppe
stepwise increase in contraction tension

Triad
the grouping of one T-tubule and two terminal cisternae

Tropomyosin
regulatory protein that covers myosin-binding sites to prevent actin from binding to myosin

Troponin
regulatory protein that binds to actin, tropomyosin, and calcium

Twitch
single contraction produced by one action potential

Varicosity
enlargement of neurons that release neurotransmitters into synaptic clefts

Visceral muscle
smooth muscle found in the walls of visceral organs

Voltage-gated sodium channels
membrane proteins that open sodium channels in response to a sufficient voltage change, and initiate and transmit the action potential as Na^+ enters through the channel

Wave summation
addition of successive neural stimuli to produce greater contraction

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10.9: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. Muscle tissue that has a striped or banded appearance when viewed under the microscope is described as which type?
   A. Elastic
   B. Nonstriated
   C. Excitable
   D. Striated

2. Which ion directly triggers contraction by binding to the regulatory protein on the thin filament?
   A. Sodium ($Na^{\diamondsuit}$)
   B. Calcium ($Ca^{2\diamondsuit}$)
   C. Potassium ($K^{\diamondsuit}$)
   D. Chloride ($Cl^{\diamondsuit}$)

3. Which of the following properties is not shared by skeletal, cardiac, and smooth muscle tissues?
   A. Excitability
   B. The need for ATP to contract
   C. Use of regulatory proteins that block actin–myosin interaction at rest
   D. Elasticity

4. Which sequence correctly lists structural components of skeletal muscle from smallest to largest?
   A. Fascicle, filament, muscle fiber, myofibril
   B. Filament, myofibril, muscle fiber, fascicle
   C. Muscle fiber, fascicle, filament, myofibril
   D. Myofibril, muscle fiber, filament, fascicle

5. During depolarization of the sarcolemma, which electrical change occurs?
   A. The inside of the membrane becomes less negative as sodium ions enter the cell.
   B. The outside of the membrane becomes less negative as sodium ions enter the cell.
   C. The inside of the membrane becomes more negative as sodium ions enter the cell.
   D. The sarcolemma completely loses any electrical charge on both sides.

6. In a relaxed skeletal muscle fiber, which protein directly blocks the myosin-binding sites on actin?
   A. Titin
   B. Troponin
   C. Myoglobin
   D. Tropomyosin

7. According to the sliding filament model, when do the myosin-binding sites on actin become exposed?
   A. When creatine phosphate levels rise

B. When ATP levels rise
C. When acetylcholine levels rise in the synaptic cleft
D. When calcium ion concentration rises in the sarcoplasm

8. The plasma membrane of a skeletal muscle fiber is known by which term?
A. Myofibril
B. Sarcolemma
C. Sarcoplasm
D. Myofilament

9. What primary event leads to relaxation of a skeletal muscle fiber after contraction?
A. Calcium ions are actively transported out of the sarcoplasmic reticulum into the sarcoplasm.
B. Calcium ions diffuse out of the sarcoplasmic reticulum into the sarcoplasm.
C. Calcium ions are actively transported from the sarcoplasm back into the sarcoplasmic reticulum.
D. Calcium ions diffuse from the sarcoplasm back into the sarcoplasmic reticulum.

10. During the cross-bridge cycle, what must happen for the myosin head to detach from actin?
A. The myosin head binds to ADP only.
B. The myosin head binds to ATP.
C. Calcium ions bind directly to the myosin head.
D. Calcium ions bind directly to actin.

11. Thin and thick filaments are organized into repeating functional units along the length of a myofibril. What are these units called?
A. Myofibrils
B. Myofilaments
C. T-tubules
D. Sarcomeres

12. During a single muscle twitch, in which phase is the tension produced by the muscle fiber at its maximum?
A. Resting phase
B. Repolarization phase
C. Contraction phase
D. Relaxation phase

13. Which of the following best explains the primary cause of skeletal muscle fatigue during intense, prolonged activity?
A. Buildup of ATP and lactic acid
B. Exhaustion of energy reserves and buildup of lactic acid
C. Buildup of ATP and pyruvic acid
D. Exhaustion of energy reserves and buildup of pyruvic acid

14. Compared with a marathon runner, why does a 100-m sprinter typically experience muscle fatigue sooner during maximal effort?
A. Greater reliance on anaerobic metabolism in the sprinter's active muscles
B. Greater reliance on anaerobic metabolism in the marathon runner's active muscles
C. Greater reliance on aerobic metabolism in the sprinter's active muscles
D. Greater reliance on glycolysis in the marathon runner's active muscles

15. Which chemical feature of creatine phosphate allows it to serve as a rapid energy reserve for skeletal muscle?
A. ATPase activity in the creatine molecule
B. High-energy phosphate bonds that can regenerate ATP
C. High-energy carbon–carbon bonds
D. High-energy hydrogen bonds

16. A drug prevents muscle cells from regenerating ATP from ADP and inorganic phosphate. Assuming no other direct effect,

how will skeletal muscle cells most immediately respond?
A. They will absorb ATP directly from the bloodstream in sufficient amounts.
B. They will use ADP as an alternative direct energy source for contraction.
C. They will quickly lose the ability to maintain cross-bridge cycling and stop contracting.
D. They will continue contracting normally because glycogen is still present.

17. The muscles of an elite sprinter are most likely to have which approximate distribution of fiber types?
A. 80 percent fast-twitch fibers and 20 percent slow-twitch fibers
B. 20 percent fast-twitch fibers and 80 percent slow-twitch fibers
C. 50 percent fast-twitch fibers and 50 percent slow-twitch fibers
D. 40 percent fast-twitch fibers and 60 percent slow-twitch fibers

18. The muscles of an elite marathon runner are most likely to have which approximate distribution of fiber types?
A. 80 percent fast-twitch fibers and 20 percent slow-twitch fibers
B. 20 percent fast-twitch fibers and 80 percent slow-twitch fibers
C. 50 percent fast-twitch fibers and 50 percent slow-twitch fibers
D. 40 percent fast-twitch fibers and 60 percent slow-twitch fibers

19. Which statement about fast (type II) skeletal muscle fibers is accurate?
A. Fast fibers have a small diameter.
B. Fast fibers contain loosely packed myofibrils.
C. Fast fibers have large glycogen reserves.
D. Fast fibers contain many more mitochondria than slow fibers.

20. Which statement about slow (type I) skeletal muscle fibers is false?
A. Slow fibers have only a small network of capillaries.
B. Slow fibers contain the oxygen-binding pigment myoglobin.
C. Slow fibers contain a large number of mitochondria.
D. Slow fibers can maintain contractions for extended periods.

21. Which feature is present in cardiac muscle cells but absent in skeletal muscle fibers?
A. Striations formed by sarcomeres
B. Dependence on aerobic metabolism
C. Myofibrils made of actin and myosin
D. Intercalated discs connecting adjacent cells

22. If cardiac muscle cells were prevented from carrying out aerobic metabolism for an extended period, what would ultimately occur?
A. They would rely exclusively on glycolysis and maintain normal contraction indefinitely.
B. They would synthesize sufficient ATP using only stored creatine phosphate.
C. They would eventually be unable to produce adequate ATP and stop contracting.
D. They would begin to contract more rapidly to compensate.

23. Which statement best distinguishes smooth muscle from both skeletal and cardiac muscle?
A. Smooth muscle lacks myofibrils arranged into visible striations.
B. Smooth muscle is always under voluntary control.
C. Smooth muscle lacks myosin molecules.
D. Smooth muscle lacks actin filaments.

24. Which of the following accurately describes a property of smooth muscle cells?
A. They are highly resistant to fatigue and can sustain contractions for long periods.

B. They have a very rapid onset of contraction similar to fast-twitch skeletal fibers.

C. They are capable of producing tetanic contractions similar to skeletal muscle.

D. They rely primarily on anaerobic metabolism during normal activity.

25. From which embryonic cell type do skeletal muscle fibers ultimately develop?
A. Ganglion cells
B. Myotube cells
C. Myoblast cells
D. Satellite cells

26. Which cell type is most important for the repair and partial regeneration of injured skeletal muscle fibers in adults?
A. Ganglion cells
B. Myotube cells
C. Myoblast cells in the embryo only
D. Satellite cells adjacent to mature fibers

27. During excitation–contraction coupling in skeletal muscle, what is the primary role of the transverse (T) tubules?
A. To store calcium for release during contraction
B. To propagate the action potential into the interior of the muscle fiber
C. To synthesize ATP during contraction
D. To anchor thick and thin filaments at the Z disc

28. In an isometric contraction of a skeletal muscle, what happens at the level of the sarcomere?
A. Sarcomeres shorten and overall muscle length decreases.
B. Sarcomeres lengthen while muscle tension remains constant.

C. Cross-bridge cycling occurs and tension develops, but overall muscle length does not change.

D. No cross-bridges form and no tension is produced.

29. When a skeletal muscle is stimulated at a frequency that does not allow full relaxation between twitches, which phenomenon occurs?
A. Twitch summation leading to incomplete tetanus
B. Single twitch with no change in tension
C. Complete tetanus with zero tension
D. Muscle fatigue without any change in stimulation frequency

30. Which change would most likely increase the force of contraction produced by a whole skeletal muscle in vivo?
A. Decreasing the number of active motor units while keeping frequency constant
B. Increasing the frequency of action potentials in motor neurons to produce tetanus
C. Decreasing the initial length of the muscle to well below its optimal length
D. Preventing recruitment of additional motor units during stronger efforts

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10.10: Applied Thinking Self-Check

Instructions

- How to answer:
  1. Direct answer: one clear sentence.
  2. Mechanism: 3 to 5 sentences linking structure to function (cause → effect).
  3. Example: one sentence (or a simple labeled sketch).
- Length: 100 to 150 words. Short sentences are OK. Use precise terms.

Word bank (use as needed)

elasticity, extensibility, epimysium, perimysium, endomysium, tendon, aponeurosis, origin, insertion, leverage, posture, joint stability, heat, guarding openings, voltage-gated Na+ channel, voltage-gated K+ channel, depolarize, repolarize, T-tubule, sarcomere, A-band, I-band, Z disc, ATP, rigor, motor unit, recruitment, frequency summation, length–tension, creatine phosphate, glycolysis, aerobic respiration, mitochondria, myoglobin, hypertrophy, pacemaker, tetanus (fused contraction), gap junctions, calmodulin, dense bodies, single-unit, multiunit, fibrosis, satellite cells, pericytes.

Questions

1. Why is elasticity an important quality of muscle tissue?
   - Include: difference between elasticity (recoil) and extensibility (stretch); role of titin and connective tissues; how recoil helps muscles return to resting length and save energy.
   - Sentence starter: Elasticity matters because after stretch, muscle recoils to its resting length, which …
2. What would happen to skeletal muscle if the epimysium were destroyed?
   - Include: epimysium's role in protection, force transmission into tendon, pathway for vessels/nerves; predicted outcomes (weaker force, higher injury/tearing, poor coordination).
   - Sentence starter: Without the epimysium, force would … and the muscle would be more likely to …
3. Describe how tendons facilitate body movement.
   - Include: collagen continuity (endomysium/perimysium/epimysium → tendon → periosteum), origin/insertion, levers; elastic energy storage/release.
   - Sentence starter: Tendons transmit muscle pull to bone by …
4. What are the five primary functions of skeletal muscle?
   - Include: movement, posture/antigravity, joint stability/support soft tissues, guard body openings, heat production (thermogenesis). You may briefly justify each.
   - Sentence starter: The five key functions are …
5. What are the opposite roles of voltage-gated sodium channels and voltage-gated potassium channels?
   - Include: Na+ channels open to depolarize (upstroke), K^+ channels open to repolarize (and help end the AP), effect on excitability/refractory periods.
   - Sentence starter: Voltage-gated Na^+ channels start the spike by … whereas K^+ channels …
6. How would muscle contractions be affected if skeletal muscle fibers did not have T-tubules?
   - Include: slowed or uneven action potential spread; delayed Ca^{2+} release from SR; weaker, asynchronous contraction, especially in large fibers.
   - Sentence starter: Without T-tubules, the signal would not reach deep parts quickly, so …
7. What causes the striated appearance of skeletal muscle tissue?
   - Include: sarcomere banding (A-bands with thick filaments; I-bands with thin filaments; Z discs alignment across fibers).
   - Sentence starter: Striations come from repeating sarcomeres where …
8. How would muscle contractions be affected if ATP was completely depleted in a muscle fiber?
   - Sentence starter: With no ATP, myosin cannot release actin, leading to …
9. Why does a motor unit of the eye have few muscle fibers compared to a motor unit of the leg?

- Include: fine control vs power; innervation ratio; recruitment for precision vs strength.
- Sentence starter: Eye motor units are small to allow precise movements because …

10. What factors contribute to the amount of tension produced in an individual muscle fiber?
    - Include: number of cross-bridges (Ca^{2+} level), sarcomere length (length–tension), stimulation frequency (summation), fiber diameter, fatigue/temperature.
    - Sentence starter: Single-fiber tension depends on …
11. Why do muscle cells use creatine phosphate instead of glycolysis to supply ATP for the first few seconds of muscle contraction?
    - Include: speed and immediacy of the CK reaction; buffers ATP at onset; glycolysis is slower to ramp up.
    - Sentence starter: Creatine phosphate supplies ATP faster because …
12. Is aerobic respiration more or less efficient than glycolysis? Explain your answer.
    - Include: ATP per glucose (~30–32 vs 2), oxygen requirement, speed vs efficiency trade-off.
    - Sentence starter: Aerobic respiration is more efficient because …
13. What changes occur at the cellular level in response to endurance training?
    - Include: ↑ mitochondria, capillaries, myoglobin; enzyme shifts to oxidative metabolism; possible fiber shift IIx → IIa; improved fatty acid use.
    - Sentence starter: With endurance training, muscle fibers adapt by …
14. What changes occur at the cellular level in response to resistance training?
    - Include: hypertrophy (more myofibrils, larger Cross Sectional Area), neural adaptations early, satellite cell activation, ↑ glycolytic enzymes, connective tissue strengthening.
    - Sentence starter: Resistance training increases force mainly by …
15. What would be the drawback of cardiac contractions being the same duration as skeletal muscle contractions?
    - Include: risk of tetanus in heart, loss of filling/relaxation, pumping failure; cardiac long refractory period prevents this.
    - Sentence starter: If cardiac twitches were short like skeletal, the heart could …
16. Why is muscle that has sustained significant damage unable to produce the same amount of power as it could before being damaged? Which muscle type(s) can regenerate new fibers?
    - Include: loss of fibers, fibrosis/scar disrupting force transmission, altered innervation; regeneration.
    - Sentence starter: Damaged muscle is weaker because …; Of the three types, … can regenerate because …

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10.11: Alternative Text Descriptions

Figure 10.1.1: The Three Connective Tissue Layers

This image shows the structural organization of skeletal muscle in three progressively magnified sections. The top section shows an entire skeletal muscle surrounded by epimysium. Inside the muscle are bundles labeled muscle fascicles. The middle section enlarges one fascicle and shows multiple muscle fibers grouped together. These fibers are surrounded by perimysium at the fascicle level and endomysium around each individual muscle fiber. A satellite cell is shown along the outside of a muscle fiber. The bottom section enlarges a single muscle fiber, showing the sarcolemma surrounding the fiber and many myofibrils packed inside it. Curved arrows between sections indicate the progression from whole muscle to fascicle, to muscle fiber, to myofibril.

Skeletal muscle is organized in bundles. Inside a whole muscle, the long muscle cells, called muscle fibers, are grouped into smaller bundles called fascicles. Each fascicle is wrapped in perimysium, and each muscle fiber is wrapped in endomysium. The entire muscle is wrapped in epimysium. Together, these three connective tissue layers are called the mysia.

These connective tissue coverings help organize the muscle and transmit force. When muscle fibers contract, the pulling force passes through the endomysium, perimysium, and epimysium, then into a tendon or sometimes a broad flat tendon sheet called an aponeurosis. The tendon then connects to the periosteum of bone, allowing muscle contraction to produce movement.

The figure also supports the idea that skeletal muscle is richly supplied with blood vessels and nerve input. Each muscle fiber receives nutrients and oxygen through the blood supply and is controlled by a branch of a somatic motor neuron. This nerve signal is necessary for normal skeletal muscle contraction.

Figure 10.1.2: Structure of a Skeletal Muscle Fiber

This image illustrates the microscopic structure of a skeletal muscle fiber, moving through three levels of organization: the muscle fiber, the myofibrils inside the fiber, and the sarcomere, which is the functional unit of contraction.

The overall organization shows three nested levels of structure. The labels in the image include muscle fiber, nuclei, mitochondria, sarcolemma, myofibrils, sarcomere, Z disc, thin (actin) filaments, thick (myosin) filaments, A band, I band, H zone, M line, and sarcoplasmic reticulum. The figure emphasizes how the arrangement of these structures directly supports muscle contraction.

At the muscle fiber level, the image shows a long cylindrical cell labeled as a muscle fiber. This cell contains multiple nuclei, many mitochondria, and an outer membrane called the sarcolemma. The muscle fiber serves as the basic cellular unit of skeletal muscle, produces force through contraction, and depends on mitochondria for energy. The sarcolemma is the outer membrane of the muscle fiber. Its functions are to conduct electrical signals and initiate muscle contraction. Inside the muscle fiber are many myofibrils, which are cylindrical structures that contain the contractile machinery and shorten during contraction.

At the myofibril level, the image shows that each myofibril is made up of repeating units called sarcomeres. These repeating units create the striated, or striped, appearance of skeletal muscle and allow coordinated contraction along the length of the muscle fiber.

At the sarcomere level, the figure shows a segment between two Z discs. The Z disc forms the boundary at each end of a sarcomere and anchors the thin, or actin, filaments. The thin filaments extend from the Z disc toward the center and slide during contraction by interacting with myosin. The thick, or myosin, filaments are located in the center of the sarcomere and generate force by pulling actin inward. The A band is the darker region corresponding to the length of the thick filaments and remains relatively constant during contraction. The I band is the lighter region containing only thin filaments and shortens during contraction. The H zone is the central region containing only thick filaments and narrows or disappears during contraction. The M line is the center of the sarcomere and stabilizes the thick filaments. The sarcoplasmic reticulum is shown as a network surrounding the myofibrils. Its functions are to store and release calcium ions and regulate contraction.

Figure 10.1.3: Sarcomere

This image illustrates the organization of a sarcomere and enlarges the thick and thin filaments responsible for skeletal muscle

contraction. At the top of the figure, a single sarcomere extends between two Z lines. Thin filaments extend inward from each Z line toward the center of the sarcomere, while thick filaments occupy the central region. The darker A band corresponds to the full length of the thick filaments, including areas where thick and thin filaments overlap. The lighter I bands are located near the Z lines and contain only thin filaments. At the center of the A band, the H zone contains only thick filaments, and the M line marks the midpoint where the thick filaments are anchored.

Below the sarcomere, the left side shows an enlarged portion of a thick filament composed of many myosin molecules packed together. Numerous myosin heads project outward from the filament's surface. A further enlargement depicts a single myosin molecule with a long coiled tail, a flexible hinge region, and two globular heads. The heads contain actin-binding sites that attach to actin during contraction and ATP-binding sites that provide the energy needed for movement.

The right side shows an enlarged portion of a thin filament. The thin filament consists primarily of actin subunits arranged as intertwined strands. Running along the actin filament is tropomyosin, a long regulatory protein that lies over the myosin-binding sites on actin. Attached at intervals to the filament is troponin, a regulatory protein complex that controls the position of tropomyosin. A further enlargement shows individual actin subunits and a myosin-binding site on the actin filament.

The figure demonstrates that the banding pattern of a sarcomere is produced by the arrangement of thick and thin filaments and that muscle contraction depends on interactions between myosin heads on the thick filaments and binding sites on actin within the thin filaments.

Figure 10.2.1: Motor End-Plate and Innervation

This image illustrates the neuromuscular junction, the site where a motor neuron communicates with a skeletal muscle fiber. The figure is arranged as a series of enlargements that progress from the overall nerve-muscle connection to a detailed view of neurotransmitter release and receptor activation.

At the top of the figure, a myelinated motor neuron approaches a skeletal muscle fiber. The axon branches into multiple axon terminals, each ending in a synaptic end bulb at the surface of the muscle fiber. The outer membrane of the muscle fiber is the sarcolemma, while the interior contains sarcoplasm and numerous cylindrical myofibrils. A red arrow indicates a nerve impulse, or action potential, traveling along the motor neuron toward a synaptic end bulb.

The middle enlargement focuses on a single synaptic end bulb positioned above the motor end plate, a specialized region of the sarcolemma. The synaptic end bulb contains many synaptic vesicles filled with acetylcholine (ACh). Some vesicles are shown fusing with the membrane of the nerve terminal and releasing ACh into the synaptic cleft, the narrow gap between the neuron and muscle fiber. The motor end plate contains folded regions of the sarcolemma that increase surface area for communication between the neuron and the muscle fiber.

The lower enlargement provides a close-up view of neurotransmitter release. Synaptic vesicles within the synaptic end bulb contain multiple molecules of ACh. Several vesicles are shown releasing ACh by exocytosis into the synaptic cleft. The released ACh molecules diffuse across the cleft and bind to ACh receptors located on the motor end plate. The figure shows ACh binding to a receptor and opening an ion channel. An arrow indicates sodium ions (Na^+) moving through the open channel into the muscle fiber. This sequence illustrates how a nerve impulse reaching the synaptic end bulb triggers neurotransmitter release, receptor activation, and ion movement across the muscle membrane.

Overall, the figure demonstrates the structural relationship between a motor neuron and a skeletal muscle fiber and shows the sequence of events by which acetylcholine transmits a signal from the nervous system to the muscle cell at the neuromuscular junction.

Figure 10.2.2: The T-tubule Narrow

This image shows the triad structure in a skeletal muscle fiber. The instructional purpose is to identify the relationship between the sarcolemma, T-tubule, and sarcoplasmic reticulum in the region where excitation is linked to internal muscle signaling.

At the top, the sarcolemma is labeled as the outer membrane of the muscle fiber. Just beneath it, the figure shows inward extensions associated with the membrane system. Surrounding the myofibril region is a network labeled sarcoplasmic reticulum.

The central feature is the T-tubule, shown passing between two enlarged sacs of the sarcoplasmic reticulum labeled terminal

cisternae. The label triad identifies this three-part arrangement: one T-tubule plus two terminal cisternae, one on each side.

Figure 10.2.3: Contraction of a Muscle Fiber

This image illustrates the process of excitation–contraction coupling in skeletal muscle, showing how a nerve signal leads to muscle contraction through a sequence of electrical, chemical, and mechanical events.

The diagram is arranged vertically in sequential steps. It progresses from the neuromuscular junction at the top, to electrical signaling in the muscle fiber, to calcium release and actin–myosin interaction, and finally to muscle shortening and force generation at the bottom. Arrows show the downward direction of the process.

Step 1: Neuromuscular junction - A motor neuron axon terminal contacts a skeletal muscle fiber. The axon terminal contains synaptic vesicles filled with acetylcholine (ACh), and the muscle fiber membrane is labeled the sarcolemma. An action potential arrives at the neuromuscular junction and causes ACh to be released from the synaptic end bulb.

Step 2: Chemical signaling and muscle action potential - ACh diffuses across the synaptic cleft and binds to receptors on the motor end plate of the sarcolemma. This binding opens sodium ion channels, allowing sodium ions to enter the muscle fiber. That produces a muscle action potential.

Step 3: Signal propagation through T-tubules - The sarcolemma forms T-tubules that extend into the muscle fiber. The muscle action potential travels along the sarcolemma and down the T-tubules, carrying the signal into the interior of the muscle fiber.

Step 4: Calcium release from the sarcoplasmic reticulum - The T-tubules are closely associated with the sarcoplasmic reticulum, which stores calcium ions (Ca^{2+}). The electrical signal triggers release of calcium into the muscle cell, where it diffuses around the myofibrils.

Step 5: Molecular interaction between actin and myosin - Within the myofibrils, thin filaments (actin) and thick filaments (myosin) are shown, along with troponin on the actin filament. Calcium binds to troponin, which causes associated proteins to shift and expose binding sites on actin. Myosin heads then attach to actin. Using energy from ATP, myosin pulls the actin filaments inward. This process repeats across many sarcomeres.

Step 6: Muscle contraction - As the filaments slide, individual sarcomeres shorten. When many sarcomeres shorten together, the muscle fiber shortens and produces tension. The final part of the figure shows the whole muscle becoming shorter and thicker.

Figure 10.2.4: Relaxation of a Muscle Fiber

This image shows the process of skeletal muscle relaxation, illustrating how a muscle returns to its resting state after contraction. The diagram is arranged as a top-to-bottom sequence, linking decreasing calcium levels to reduced filament interaction, muscle fiber lengthening, and whole-muscle relaxation.

The overall organization progresses through five connected stages: ending stimulation at the neuromuscular junction, calcium reuptake into the sarcoplasmic reticulum, reduced activation of the thin filament, cessation of actin–myosin interaction, muscle fiber lengthening, and whole muscle relaxation. Arrows show the downward direction of change from an active contraction state toward relaxation.

Step 1: Neuromuscular junction - At the top of the image, a synaptic end bulb of a motor neuron lies above the muscle fiber membrane, and the muscle surface forms the motor end plate. This part of the diagram indicates that neural stimulation has already occurred, but at this stage the stimulation is ending, which initiates relaxation.

Step 2: Calcium reuptake into the sarcoplasmic reticulum - The sarcoplasmic reticulum is shown containing calcium ions, and arrows indicate calcium moving back into storage. This step shows that calcium ions are actively reabsorbed into the sarcoplasmic reticulum, a process that requires ATP. As calcium levels in the muscle cytoplasm decrease, the relaxation cycle begins.

Step 3: Reduced activation of thin filaments - A thin filament, or actin filament, is shown with regulatory proteins and reduced calcium in the surrounding area. As calcium detaches from troponin, associated proteins including tropomyosin shift to cover the myosin-binding sites on actin. This means the thin filament is no longer prepared for contraction.

Step 4: Cessation of thick and thin filament interaction - A myosin head is shown separated from the actin filament. The thick and thin filaments are no longer engaged. Cross-bridge formation stops, myosin heads detach from actin, and the sliding filament mechanism ceases.

Step 5: Muscle fiber lengthening - A cylindrical muscle fiber is shown with arrows pointing outward from both ends. Without active cross-bridge cycling, the sarcomeres return toward their resting length, and the muscle fiber elongates.

Step 6: Whole muscle relaxation - At the bottom of the image, the entire muscle is shown in a longer, less compact shape. The muscle relaxes and lengthens, and tension decreases. External forces, such as opposing muscles or gravity, help restore resting length.

Figure 10.2.5: The Sliding Filament Model of Muscle Contraction

This image shows two stacked views of a sarcomere, comparing its structure before contraction in the top panel and during contraction in the bottom panel. The figure highlights how the relative positions of thick (myosin) and thin (actin) filaments change to produce shortening.

The image is organized into two horizontal panels. The top panel shows a relaxed sarcomere, and the bottom panel shows a contracted sarcomere. In both panels, the sarcomere extends from one Z line to the other, with the M line at the center. Thick filaments are located in the middle, and thin filaments extend inward from the Z lines. In the bottom panel, black arrows point inward, indicating contraction.

Top panel: Relaxed sarcomere - In the top panel, the Z lines are located at the left and right ends of the sarcomere. Thin filaments extend inward from each Z line but do not fully overlap in the center. Thick filaments occupy the middle region. The H zone, which is the central region containing only thick filaments, is visible. The I bands, which are the regions containing only thin filaments near the Z lines, are relatively wide. This panel represents the sarcomere in a resting or relaxed state. There is relatively less overlap between actin and myosin, and the sarcomere is not shortened.

Bottom panel: Contracted sarcomere - In the bottom panel, the Z lines are closer together than in the top panel. Thin filaments have moved inward toward the center, increasing the overlap between actin and myosin filaments. The H zone is reduced or nearly absent, and the I bands are shorter than in the relaxed state. The A band remains the same width. This panel represents the sarcomere in a contracted state. Myosin has pulled actin filaments toward the center, increasing overlap and shortening the sarcomere.

Sliding filament mechanism - The image shows that thick filaments remain relatively stationary while thin filaments slide past them. The process is:

1. Myosin heads attach to actin
2. Myosin pulls actin toward the M line
3. Z lines move closer together
4. Sarcomere length decreases
5. Repeated shortening across many sarcomeres produces overall muscle contraction

Figure 10.2.6: The Cross-Bridge Cycle

This image shows the cross-bridge cycle, the repeating sequence of interactions between myosin in the thick filament and actin in the thin filament that produces muscle contraction. The diagram is arranged vertically and labeled in stages from (a) through (e).

The overall organization progresses from top to bottom in sequential steps. Each panel shows the thin filament across the top and the thick filament below it, with a myosin head projecting upward toward actin. Small labeled molecules include calcium ions, ADP, Pi, and ATP. Together, the panels show how calcium and ATP regulate attachment, pulling, release, and resetting of the myosin head.

Step (a): Thin filament activation - the thin filament is shown with actin and calcium present nearby, and the binding sites on actin are exposed. The myosin head is close to actin but not yet attached. This step shows that calcium allows regulatory proteins to expose the myosin-binding sites on actin, preparing the thin filament for cross-bridge formation.

Step (b): Cross-bridge formation - the myosin head attaches to actin, forming a cross-bridge. ADP and Pi remain attached to the myosin head. This indicates that myosin is in an energized state and has bound to actin in preparation for force generation.

Step (c): Power stroke - the myosin head pivots downward, and arrows show movement of the actin filament relative to myosin. ADP and Pi are released. This step represents the power stroke, in which the myosin head pulls the actin filament toward the center of the sarcomere, producing force and shortening.

Step (d): ATP binding and detachment - ATP binds to the myosin head, and the myosin head detaches from actin. This step shows that ATP binding breaks the cross-bridge and allows myosin to release actin. Without ATP, detachment cannot occur.

Step (e): Re-cocking of the myosin head - ATP is hydrolyzed into ADP and Pi, which remain attached to the myosin head. The myosin head returns to a cocked, energized position. This hydrolysis provides the energy needed to prepare myosin for the next cycle of attachment.

Functional integration - The main relationship shown in the figure is that the cross-bridge cycle repeats in a specific sequence:

1. Calcium exposes binding sites on actin
2. Myosin attaches to actin
3. Myosin pulls actin in the power stroke
4. ATP binds, causing detachment
5. ATP is hydrolyzed, resetting the myosin head

Figure 10.2.7: Biochemical Pathways

This image contains three labeled diagrams showing major biochemical pathways that produce ATP in muscle cells.

Panel (a) shows the creatine phosphate system. In resting muscle, ATP and creatine are used to form creatine phosphate and ADP. During muscle activity, the enzyme creatine kinase transfers a phosphate from creatine phosphate back to ADP, producing ATP that can be used for muscle contraction. The arrows show that this pathway can operate in opposite directions depending on whether the muscle is at rest or active.

Panel (b) shows glycolysis. Blood glucose and muscle glycogen both supply glucose, which enters glycolysis. Glycolysis produces ATP and pyruvate. When oxygen is available, pyruvate can enter aerobic respiration. When oxygen is not available, pyruvate is converted to lactic acid, which enters the blood. This panel emphasizes that glycolysis can supply ATP without oxygen, but it produces less ATP than aerobic respiration.

Panel (c) shows cellular respiration in mitochondria. Inputs include blood glucose, pyruvic acid, fatty acids, and oxygen. The outputs shown are ATP, heat, carbon dioxide, and water. This panel emphasizes that aerobic respiration produces a large amount of ATP compared with the other pathways.

Together, the three panels compare rapid ATP regeneration by the creatine phosphate system, short-term ATP production by glycolysis, and larger ATP production by aerobic respiration in mitochondria.

Figure 10.3.1: Types of Muscle Contractions

This image compares three types of muscle contraction using a biceps curl example. Each row shows the same arm muscle during a different kind of contraction, along with a matching movement example using a dumbbell. The purpose of the diagram is to distinguish concentric, eccentric, and isometric contractions by showing whether the muscle shortens, lengthens, or stays the same length while producing force.

In the top row, the labeled example is concentric contraction. The arm bends upward, the muscle becomes shorter and thicker, and the associated movement arrow curves upward during the lifting phase of the curl. This row shows that a concentric contraction occurs when the muscle contracts while shortening to produce movement.

In the middle row, the labeled example is eccentric contraction. The arm lowers the weight, the muscle becomes longer while still active, and the movement arrow curves downward. This row shows that an eccentric contraction occurs when the muscle elongates while controlling movement.

In the bottom row, the labeled example is isometric contraction. The arm position stays fixed while the muscle remains active, and the figure states no movement. This row shows that an isometric contraction occurs when the muscle contracts without changing overall length enough to move the joint.

All of these muscle activities are under the exquisite control of the nervous system. Neural control regulates concentric, eccentric and isometric contractions, muscle fiber recruitment, and muscle tone. A crucial aspect of nervous system control of skeletal muscles is the role of motor units.

Figure 10.3.2: The Ideal Length of a Sarcomere

This image shows the relationship between sarcomere length and muscle tension. The vertical axis is labeled Tension (percent of maximum) and ranges up to 100 percent. The horizontal axis is labeled Percentage sarcomere length. A single line rises from low tension at shorter sarcomere lengths, reaches a maximum plateau at intermediate lengths, and then declines back to zero at longer lengths.

The graph begins near 0 percent tension at a sarcomere length of about 60 percent. Tension rises steeply to about 80 percent near 80 percent sarcomere length, then reaches 100 percent tension around 95 to 110 percent sarcomere length. After that, tension decreases steadily as sarcomere length increases, reaching 0 percent tension again around 170 percent sarcomere length.

Below the graph are three labeled regions with small schematic drawings of filament overlap. The first region is Decreased length, showing excessive filament overlap at short sarcomere length. The second region is Increased length, showing more optimal overlap. The third region is No cross bridges, showing thin and thick filaments too far apart to interact.

Figure 10.3.3: The Phases of a Single Muscle Twitch

This image shows the time course of a single muscle twitch after one stimulus. The vertical axis is labeled Tension, and the horizontal axis is labeled Time (msec), extending from 0 to 100 milliseconds. A red arrow at time zero marks the single stimulus.

The graph divides the twitch into three labeled phases. The first is the latent period, shown at the far left over the first few milliseconds after the stimulus. During this phase, tension remains very low and has not yet risen significantly.

The second phase is the contraction period, shown from shortly after the latent period to about 25 to 30 milliseconds. During this interval, the curve rises steeply from near zero to its maximum tension. The peak occurs at approximately 28 to 30 milliseconds.

The third phase is the relaxation period, beginning after the peak and extending to about 100 milliseconds. During this phase, tension gradually declines back toward baseline. The decrease is more gradual than the earlier rise.

Figure 10.3.4: Two Tension-Versus-Time Graphs

This image compares wave summation and tetanus using two tension-versus-time graphs. In both graphs, the vertical axis is labeled Tension and the horizontal axis is labeled Time.

In graph (a), labeled Wave summation, the tension curve rises and falls in a repeating pattern, with each successive peak becoming higher than the one before it. The curve shows multiple contractions occurring before the muscle fully returns to baseline, so the overall tension builds in a step-like pattern. After the final and highest peak, the curve drops back down toward zero.

In graph (b), labeled Tetanus, the tension rises from zero to a high level and then remains elevated in a broad plateau for a period of time before falling back to baseline. This graph shows sustained contraction with little or no relaxation during the plateau.

Figure 10.3.5: Treppe

This image shows treppe on a graph of tension versus time. The vertical axis is labeled Tension, and the horizontal axis is labeled Time.

The curve shows a series of separate muscle twitches. Each twitch rises and falls back near baseline before the next twitch begins. Across the sequence, the peaks gradually become higher, showing that each successive twitch produces slightly greater tension than the one before it. Overall, the graph demonstrates that treppe is a staircase-like increase in tension during repeated, separate muscle twitches, with full or nearly full relaxation between contractions.

It is believed that treppe results from a higher concentration of Ca^{++} in the sarcoplasm resulting from the steady stream of signals from the motor neuron. It can only be maintained with adequate ATP.

Figure 10.5.1: Marathoners

This image shows several individuals running together in what appears to be a competitive road race. They are moving forward on a paved street, each wearing athletic clothing such as sleeveless tops, shorts, and running shoes. Visible race bibs display numbers including 20, 41, 42, and 43. Some runners wear brightly colored jerseys, and others wear shirts featuring the names of running clubs or event sponsors. In the background, a few bicycles and buildings can be seen, indicating an urban race setting. The runners are positioned close to one another, suggesting they are in the midst of the event rather than at the start or finish line.

Figure 10.5.2: Hypertrophy

This image shows the back view of an individual performing a double-biceps pose commonly seen in bodybuilding. The person is standing with both arms raised and bent at the elbows, fists clenched to showcase the upper arm muscles. Prominent definition is visible across the shoulders, upper arms, and back. The lighting emphasizes muscular contours, creating highlights across the shoulder blades, upper back, and arms. The background appears outdoors, with a large blurred structure or sign partially visible. The focus of the image is the muscular development displayed through the flexed pose.

Figure 10.5.3: Atrophy

This image shows two simplified side-view anatomical drawings of an upper arm and forearm. Both drawings include the same arm bones, but the muscle size differs to illustrate a comparison between normal muscle and atrophied muscle.

On the left, labeled Normal Muscle, the muscle has a larger, fuller belly and occupies more space along the upper arm. The muscle appears thicker between its attachment points.

On the right, labeled Atrophied Muscle, the muscle is thinner and narrower while keeping a similar general shape and attachment pattern. It occupies less space along the upper arm, illustrating a loss of muscle mass.

Sarco penia can be delayed to some extent by exercise, as training adds structural proteins and causes cellular changes that can offset the effects of atrophy. Increased exercise can produce greater numbers of cellular mitochondria, increase capillary density, and increase the mass and strength of connective tissue. The effects of age-related atrophy are especially pronounced in people who are sedentary, as the loss of muscle cells is displayed as functional impairments such as trouble with locomotion, balance, and posture. This can lead to a decrease in quality of life and medical problems, such as joint problems because the muscles that stabilize bones and joints are weakened. Problems with locomotion and balance can also cause various injuries due to falls.

Figure 10.6.1: Cardiac Muscle Tissue

This image is a microscopic view of muscle tissue. It shows many elongated, parallel muscle fibers running diagonally across the image. The fibers appear closely packed and separated by narrow spaces.

Multiple dark oval nuclei are visible within the fibers. The nuclei appear centrally located rather than pushed to the outer edge. The tissue does not appear arranged as broad bundles like a gross anatomy drawing; instead, it shows the fine cellular pattern seen in a histology image.

Figure 10.6.2: Cardiac Muscle

This image shows the structure of cardiac muscle tissue and highlights the specialized connections between cardiac muscle cells. The main image shows several cardiac muscle fibers arranged in branching bundles. Each fiber contains a central nucleus. A small capillary is shown near the muscle fibers, emphasizing the tissue's blood supply. The fibers branch and join with neighboring fibers rather than forming long parallel cylinders.

The figure labels intercalated discs where neighboring cardiac muscle cells meet. A magnified inset on the right enlarges one of these junctions. In that inset, the intercalated disc appears as a folded boundary between adjacent cells. The inset labels desmosomes and gap junctions within the intercalated disc.

The desmosomes are shown as anchoring connections that help hold adjacent cells together. The gap junctions are shown as communication channels between cells. Together, these structures allow cardiac muscle cells to remain connected mechanically and to coordinate activity across the tissue.

Figure 10.7.1: Smooth Muscle Tissue

This image has two labeled parts that show smooth muscle tissue in both diagram form and microscopic view.

In panel (a), the figure shows two illustrations of smooth muscle fibers with autonomic neurons. On the left, the smooth muscle cells are arranged in parallel bundles. The cells are elongated and spindle-shaped, tapering at both ends, and each cell contains a single central nucleus. Autonomic nerve fibers run between the muscle cells. On the right, a second illustration shows smooth muscle cells arranged in a less regular cluster. These cells are also spindle-shaped with central nuclei, and autonomic neurons branch among them. The two illustrations emphasize different arrangements of smooth muscle tissue and its autonomic nerve supply.

In panel (b), a micrograph shows smooth muscle tissue under the microscope. The tissue contains elongated cells with centrally located nuclei and lacks visible striations. The cells appear closely packed and aligned in the same general direction.

Figure 10.7.2: Muscle Contraction

This image compares a **r**elaxed smooth muscle cell on the left with a contracted smooth muscle cell on the right. The figure shows how dense bodies and intermediate filaments contribute to smooth muscle contraction.

Left Panel: Relaxed Smooth Muscle Cell

The smooth muscle cell is elongated and spindle shaped, with tapered ends. The cell contains many dense bodies, shown as small dark circular structures distributed throughout the cytoplasm and along the cell membrane. A network of intermediate filaments connects the dense bodies and extends across the cell. The cell is labeled relaxed muscle cell and has a long, narrow shape.

Right Panel: Contracted Smooth Muscle Cell

The same smooth muscle cell is shown in a contracted state. The cell is shorter, wider, and more rounded than in the relaxed state. The dense bodies are positioned closer together, and the network of intermediate filaments appears compressed as the cell shortens. Large arrows on both sides point inward, indicating contraction toward the center of the cell. The cell is labeled contracted muscle cell.

Structural Comparison

The figure shows that contraction in smooth muscle pulls the dense bodies toward one another through the intermediate filament network. As the distance between dense bodies decreases, the cell shortens and takes on a puckered or folded appearance instead of remaining long and spindle shaped.

Functional Overview

The figure illustrates how smooth muscle cells change shape during contraction. Dense bodies serve as anchoring points for the contractile apparatus, and intermediate filaments transmit the force generated within the cell. When contraction occurs, the dense bodies move closer together, causing the cell to shorten and thicken. This arrangement allows smooth muscle to generate force in multiple directions and supports functions such as moving food through the digestive tract, regulating blood vessel diameter, and controlling movement through hollow organs.

Figure 10.7.3: Motor Units

This image illustrates how autonomic neurons communicate with smooth muscle cells through multiple varicosities distributed along an axon rather than through a single specialized neuromuscular junction.

On the left side of the figure, an enlarged portion of an autonomic neuron is shown. The axon contains a series of rounded swellings called varicosities. Each varicosity contains numerous vesicles filled with neurotransmitters, depicted as small circular structures within the swelling. A gray arrow indicates that this enlarged structure corresponds to the neuron shown on the right side of the figure.

On the right side, elongated smooth muscle cells are arranged in parallel bundles. Running between the smooth muscle cells is an autonomic neuron, shown as a branching fiber. Along the length of the neuron are multiple varicosities, each appearing as a bulb-like enlargement of the axon. The varicosities are positioned close to the surrounding smooth muscle cells rather than being concentrated at a single contact point.

The figure demonstrates that autonomic neurons can release neurotransmitters from many varicosities distributed along the axon. This arrangement allows signals from a single neuron to influence multiple neighboring smooth muscle cells over a broad area, rather than at a single specialized synapse.

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11: THE MUSCULAR SYSTEM

Chapter Overview

Think about the things that you do each day—talking, walking, sitting, standing, and running—all of these activities require movement of particular skeletal muscles. Skeletal muscles are even used during sleep. The diaphragm is a sheet of skeletal muscle that has to contract and relax for you to breathe day and night. If you recall from your study of the skeletal system and joints, body movement occurs around the joints in the body. The focus of this chapter is reviewed below.



Figure 11.1: The muscular system allows us to move, flex, and contort our bodies. Practicing Crow Pose (Bakasana), shown here, demonstrates the voluntary control and coordination of skeletal muscles. (CC BY 4.0; via OpenStax).

The muscular system generates movement, maintains posture, and stabilizes joints. At the undergraduate level, the focus is on skeletal muscles: how they attach to bones, how their structure determines function, and how they work together to produce controlled motion.

Skeletal Muscle Function: Origins, Insertions, and Movement

Skeletal muscles move bones at joints by pulling, not pushing. Each muscle has an origin on the more fixed bone and an insertion on the bone that moves more during contraction. When a muscle contracts, it pulls its insertion toward its origin, producing movement that can be predicted if you know these attachment points.

Muscle Team Roles: Agonists, Antagonists, Synergists, Fixators

Muscles act in coordinated groups. The agonist, or prime mover, is the main muscle producing a movement. The antagonist has the opposite action and lengthens while the agonist shortens, helping control and brake the motion. Synergists assist the agonist by adding force or refining the movement. Fixators are stabilizing synergists that hold a bone or joint steady so the prime mover can act effectively.

Muscle Architecture and Fascicle Arrangement

Muscle fibers are organized into fascicles whose arrangement affects force and range of motion. Parallel and fusiform muscles (such as sartorius, biceps brachii) typically allow larger movements with moderate force. Circular muscles act as sphincters around openings. Convergent and triangular muscles (such as pectoralis major) offer versatile lines of pull. Pennate muscles (uni-, bi-, multipennate) pack many fibers into a small area and favor high force over large movement ranges. Recognizing these patterns

helps you predict whether a muscle is built more for strength or for speed and excursion.

Lever Systems and Biomechanics of Movement

Bones and joints form levers powered by muscle contractions. In these systems, the bone is the lever, the joint is the fulcrum, muscle tension is the effort, and the limb or object being moved is the load. First-class levers place the fulcrum between effort and load (for example, nodding at the atlanto-occipital joint) and can favor either force or speed. Second-class levers place the load between fulcrum and effort (such as standing on tiptoes) and favor force with limited range. Third-class levers place the effort between fulcrum and load (such as elbow flexion with biceps) and favor speed and range but require higher muscle forces. These principles link anatomy to performance and injury risk.

Lever principles connect structure to movement. They help you predict performance, tailor training, and reduce injury using a simple, physics-based lens. A lever is a rigid bar that turns around a pivot. In our body: bone = lever, joint = pivot (fulcrum), muscle pull (via tendon) = effort, and the thing being moved (limb, gravity, object) = load (resistance).

- First-class (E–F–L or L–F–E): fulcrum in the middle; example: nodding “yes” at the neck (atlanto-occipital joint). – Can favor force or speed depending on arm lengths.
- Second-class (F–L–E): load in the middle; strong, small range; example: plantarflexion - standing on tiptoes (calf muscles lift body; ankle is fulcrum). – Good for force (power), smaller movement range
- Third-class (F–E–L): effort in the middle; fast and large range; most common in the body. – Example: elbow flexion with the biceps. – Good for speed and large movement range, requires higher muscle force.

Naming Skeletal Muscles

Muscle names encode information about their anatomy. They may indicate location (temporalis, tibialis anterior), size (maximus, minimus, longus), shape (deltoid, trapezius), fiber direction (rectus, oblique), number of heads (biceps, triceps), attachments (sternocleidomastoid), primary action (flexor, extensor, adductor), or position and depth (medialis, lateralis, superficialis). For example, biceps brachii is a two-headed muscle of the arm, and flexor carpi radialis is a wrist flexor on the radial side. Learning these patterns allows you to infer structure and function from names.

Axial and Appendicular Muscles

Skeletal muscles are grouped as axial or appendicular. Axial muscles attach to and move the skull, vertebral column, and rib cage, supporting organs and posture. Appendicular muscles attach to the pectoral and pelvic girdles and the limbs, enabling locomotion, manipulation, and joint stabilization.

Axial Muscles: Head, Neck, and Trunk

Axial muscles include those of facial expression (orbicularis oris, zygomaticus), mastication (masseter, temporalis), tongue and swallowing (suprahyoid, infrahyoid), and extraocular muscles. Neck muscles such as sternocleidomastoid and the scalenes move and stabilize the head and assist in breathing. Along the spine, erector spinae and transversospinalis groups maintain posture, extend the vertebral column, and control rotation.

Thoracic muscles for breathing include the diaphragm and external and internal intercostals. Abdominal wall muscles (rectus abdominis, external and internal obliques, transversus abdominis) flex and rotate the trunk and compress abdominal contents. The pelvic floor (levator ani, coccygeus) supports pelvic organs and contributes to continence. Together, axial muscles maintain posture, drive ventilation, and protect and support internal organs.

Appendicular Muscles: Girdles and Limbs

Appendicular muscles move and stabilize the shoulder and pelvic girdles and the limbs. Shoulder girdle movers such as trapezius,

serratus anterior, and rhomboids position and stabilize the scapula. Shoulder joint movers, including deltoid, pectoralis major, latissimus dorsi, and the rotator cuff (supraspinatus, infraspinatus, teres minor, subscapularis), produce and control movements at the glenohumeral joint.

In the upper limb, biceps brachii, brachialis, and triceps brachii flex and extend the elbow, while forearm flexors, extensors, pronators, and supinators control wrist, hand, and rotational movements. In the lower limb, gluteal muscles, iliopsoas, adductors, and deep rotators control hip position and stability. The quadriceps extend the knee; the hamstrings extend the hip and flex the knee; medial thigh muscles adduct and stabilize the hip. In the leg, anterior muscles dorsiflex the ankle, lateral muscles evert the foot, and posterior muscles such as gastrocnemius and soleus plantarflex the ankle and provide propulsion in gait.

These appendicular muscle groups produce the powerful and precise movements required for walking, running, grasping, and fine motor tasks.

Integrating Structure and Function

This section of the textbook will help you connect muscle attachments, fascicle architecture, and lever mechanics with naming patterns and regional organization. By integrating these ideas, you move beyond memorizing lists and toward understanding why muscles are arranged and built as they are, and how this design supports human movement in health, exercise, and disease.

Chapter Objectives

To achieve the chapter objectives, you are expected to actively engage with the material. Learning the tissues is not a passive process - your understanding will grow as you interact with the content, peers, and instructor, regularly checking your thinking against feedback and revisiting concepts until you can explain and apply them on your own.

By the end of this chapter, students should be able to:

- Define and use movement-role terms in simple words: agonist (prime mover), antagonist (opposes), synergist (helper), and fixator (stabilizer). For a common action (e.g., elbow flexion, squat), identify which muscles play each role and explain why.
- Explain how muscle fascicles (fiber bundles) are arranged (parallel, fusiform, convergent, unipennate, bipennate, multipennate, circular) and relate each pattern to force and range of motion. Given a diagram or photo, classify the pattern and predict “more force” or “more movement.”
- Decode muscle names using clear criteria and examples: location (temporalis), shape (deltoid), size (maximus/minimus), fiber direction (rectus/oblique/transversus), number of heads (biceps/triceps), attachments (sternocleidomastoid), and action (flexor/extensor). Translate at least five Latin/Greek names into plain English meaning.
- Identify major axial muscles (face, mastication, tongue, neck, back extensors, abdominal wall, diaphragm/intercostals, pelvic floor) and state their main actions on the skeleton or soft tissues (e.g., compress abdomen, elevate ribs).
- Identify major appendicular muscles (shoulder girdle movers; rotator cuff; deltoid, pectoralis major, latissimus dorsi; arm/forearm flexors and extensors; gluteals, iliopsoas, adductors; quadriceps, hamstrings; gastrocnemius/soleus; tibialis anterior; peroneals) and state their primary joint actions.
- Locate and name the origin (fixed attachment) and insertion (moving attachment) of selected key muscles on models or diagrams. Use the line of pull to predict the prime movement at the joint in one sentence.
- Match a named movement to muscles and roles: given a functional task (push-up, sit-to-stand, stair climb, grip), list the main agonists, likely antagonists, and at least one stabilizer, with a brief reason.
- Apply simple lever ideas to muscle action: identify the fulcrum (joint), effort (muscle/tendon), and load; explain how a longer or shorter moment arm changes torque (strength) for a common movement (e.g., biceps curl, heel raise).
- Check understanding on images: label at least 40 key muscles on anterior and posterior views and pair each with its main action and one everyday example (e.g., gluteus maximus → hip extension → standing up)

11.1: Interactions of Skeletal Muscles

11.2: Naming Skeletal Muscles

11.3: Axial Muscles of the Head, Neck, and Back

11.4: Axial Muscles of the Abdominal Wall and Thorax

11.5: Muscles of the Pectoral Girdle and Upper Limbs
11.6: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
11.7: Terms and Definitions
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11.1: Interactions of Skeletal Muscles

Functional Organization of Skeletal Muscles

To move the skeleton, the tension created by the contraction of the fibers in most skeletal muscles is transferred to the tendons. The tendons are strong bands of dense, regular connective tissue that connect muscles to bones. The bone connection is why this muscle tissue is called skeletal muscle.

To pull on a bone, that is, to change the angle at its synovial joint, which essentially moves the skeleton, a skeletal muscle must also be attached to a fixed part of the skeleton. The moveable end of the muscle that attaches to the bone being pulled is called the muscle's insertion, and the end of the muscle attached to a fixed (stabilized) bone is called the origin. During forearm flexion—bending the elbow—the brachioradialis assists the brachialis.

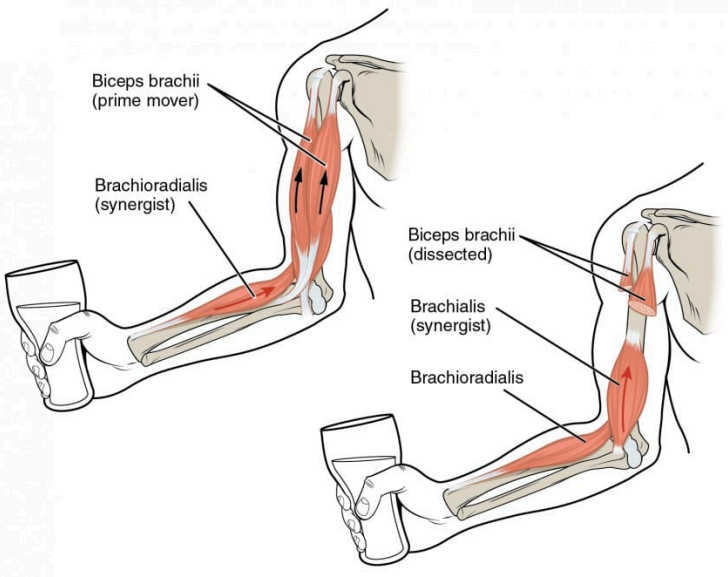


Figure 11.1.1: The biceps brachii flex the lower arm. The brachioradialis, in the forearm, and brachialis, located deep to the biceps in the upper arm, are both synergists that aid in this motion. (CC BY 4.0; via OpenStax). Alternate text description of the Figure 11.1.1.

Although a number of muscles may be involved in an action, the principal muscle involved is called the prime mover, or agonist. To lift a cup, a muscle called the biceps brachii is actually the prime mover; however, because it can be assisted by the brachialis, the brachialis is called a synergist in this action. A synergist can also be a fixator that stabilizes the bone that is the attachment for the prime mover's origin.

A muscle with the opposite action of the prime mover is called an antagonist. Antagonists play two important roles in muscle function:

1. they maintain body or limb position, such as holding the arm out or standing erect.
2. they control rapid movement, as in shadow boxing without landing a punch or the ability to check the motion of a limb.

For example, to extend the knee, a group of four muscles called the quadriceps femoris in the anterior compartment of the thigh are activated (and would be called the agonists of knee extension). However, to flex the knee joint, an opposite or antagonistic set of muscles called the hamstrings is activated.

As you can see, these terms would also be reversed for the opposing action. If you consider the first action as the knee bending, the hamstrings would be called the agonists and the quadriceps femoris would then be called the antagonists. See Table 11.1.1 for a list of some agonists and antagonists.

Table 11.1.1: Comparison of Agonist and Antagonist Skeletal Muscle Pairs

Agonist	Antagonist	Movement
Biceps brachii: in the anterior compartment of the arm	Triceps brachii: in the posterior compartment of the arm	The biceps brachii flexes the forearm, whereas the triceps brachii extends it.
Hamstrings: group of three muscles in the posterior compartment of the thigh	Quadriceps femoris: group of four muscles in the anterior compartment of the thigh	The hamstrings flex the leg, whereas the quadriceps femoris extend it.
Flexor digitorum superficialis and flexor digitorum profundus: in the anterior compartment of the forearm	Extensor digitorum: in the posterior compartment of the forearm	The flexor digitorum superficialis and flexor digitorum profundus flex the fingers and the hand at the wrist, whereas the extensor digitorum extends the fingers and the hand at the wrist.

There are also skeletal muscles that do not pull against the skeleton for movements. For example, there are the muscles that produce facial expressions. The insertions and origins of facial muscles are in the skin, so that certain individual muscles contract to form a smile or frown, form sounds or words, and raise the eyebrows. There also are skeletal muscles in the tongue, and the external urinary and anal sphincters that allow for voluntary regulation of urination and defecation, respectively. In addition, the diaphragm contracts and relaxes to change the volume of the pleural cavities but it does not move the skeleton to do this.

Note

When exercising, it is important to first warm up the muscles. Stretching pulls on the muscle fibers and it also results in an increased blood flow to the muscles being worked. Without a proper warm-up, it is possible that you may either damage some of the muscle fibers or pull a tendon. A pulled tendon, regardless of location, results in pain, swelling, and diminished function; if it is moderate to severe, the injury could immobilize you for an extended period.

Recall the discussion about muscles crossing joints to create movement. Most of the joints you use during exercise are synovial joints, which have synovial fluid in the joint space between two bones. Exercise and stretching may also have a beneficial effect on synovial joints. Synovial fluid is a thin, but viscous film with the consistency of egg whites. When you first get up and start moving, your joints feel stiff for a number of reasons. After proper stretching and warm-up, the synovial fluid may become less viscous, allowing for better joint function.

Patterns of Fascicle Organization

Skeletal muscle is enclosed in connective tissue scaffolding at three levels. Each muscle fiber (cell) is covered by endomysium and the entire muscle is covered by epimysium. When a group of muscle fibers is “bundled” as a unit within the whole muscle by an additional covering of a connective tissue called perimysium, that bundled group of muscle fibers is called a fascicle. Fascicle arrangement by perimysial is correlated to the force generated by a muscle; it also affects the range of motion of the muscle. Based on the patterns of fascicle arrangement, skeletal muscles can be classified in several ways. What follows are the most common fascicle arrangements.

Parallel muscles have fascicles that are arranged in the same direction as the long axis of the muscle (Figure 11.1.2). The majority of skeletal muscles in the body have this type of organization. Some parallel muscles are flat sheets that expand at the ends to make broad attachments. Other parallel muscles are rotund with tendons at one or both ends. Muscles that seem to be plump have a large mass of tissue located in the middle of the muscle, between the insertion and the origin, which is known as the central body. A more common name for this muscle is belly. When a muscle contracts, the contractile fibers shorten it to an even larger bulge. For example, extend and then flex your biceps brachii muscle; the large, middle section is the belly (Figure 11.1.3). When a parallel muscle has a central, large belly that is spindle-shaped, meaning it tapers as it extends to its origin and insertion, it sometimes is called fusiform.

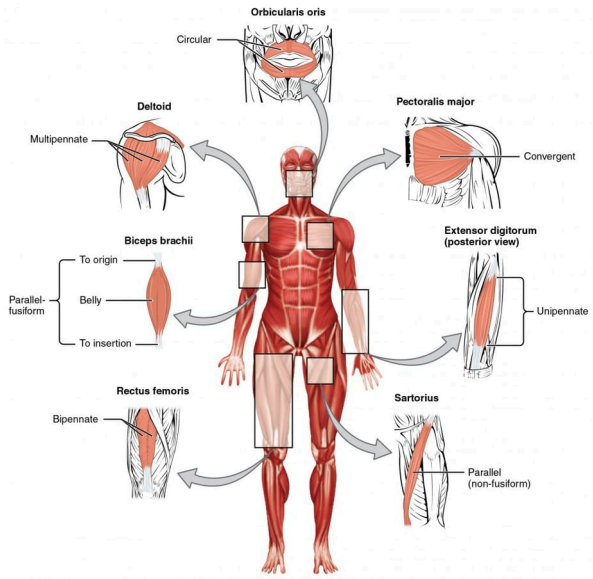


Figure 11.1.2: The skeletal muscles of the body typically come in seven different general shapes. (CC BY 4.0; via OpenStax). Alternate text description of the Figure 11.1.2.



Figure 11.1.3: The large mass at the center of a muscle is called the belly. Tendons emerge from both ends of the belly and connect the muscle to the bones, allowing the skeleton to move. The tendons of the bicep connect to the upper arm and the forearm. (CC BY 4.0; Victoria Garcia via OpenStax). Alternate text description of the Figure 11.1.3.

Circular muscles are also called sphincters. When they relax, the sphincters' concentrically arranged bundles of muscle fibers increase the size of the opening, and when they contract, the size of the opening shrinks to the point of closure. The orbicularis oris muscle is a circular muscle that goes around the mouth. When it contracts, the oral opening becomes smaller, as when puckering the lips for whistling. Another example is the orbicularis oculi, one of which surrounds each eye. Consider, for example, the names of the two orbicularis muscles (orbicularis oris and orbicularis oculi), where part of the first name of both muscles is the same. The first part of orbicularis, orb (orb = "circular"), is a reference to a round or circular structure; it may also make one think of orbit, such as the moon's path around the earth. The word oris (oris = "oral") refers to the oral cavity, or the mouth. The word oculi (ocular = "eye") refers to the eye.

There are other muscles throughout the body named by their shape or location. The deltoid is a large, triangular-shaped muscle that covers the shoulder. It is so-named because the Greek letter delta looks like a triangle. The rectus abdomis (rector = "straight") is the straight muscle in the anterior wall of the abdomen, while the rectus femoris is the straight muscle in the anterior compartment of the thigh.

When a muscle has a widespread expansion over a sizable area, but then the fascicles come to a single, common attachment

point, the muscle is called convergent. The attachment point for a convergent muscle could be a tendon, an aponeurosis (a flat, broad tendon), or a raphe (a very slender tendon). The large muscle on the chest, the pectoralis major, is an example of a convergent muscle because it converges on the greater tubercle of the humerus via a tendon. The temporalis muscle of the cranium is another.

Pennate muscles (penna = “feathers”) blend into a tendon that runs through the central region of the muscle for its whole length, somewhat like the quill of a feather with the muscle arranged similar to the feathers. Due to this design, the muscle fibers in a pennate muscle can only pull at an angle, and as a result, contracting pennate muscles do not move their tendons very far. However, because a pennate muscle generally can hold more muscle fibers within it, it can produce relatively more tension for its size. There are three subtypes of pennate muscles.

In a unipennate muscle, the fascicles are located on one side of the tendon. The extensor digitorum of the forearm is an example of a unipennate muscle. A bipennate muscle has fascicles on both sides of the tendon. In some pennate muscles, the muscle fibers wrap around the tendon, sometimes forming individual fascicles in the process. This arrangement is referred to as multipennate. A common example is the deltoid muscle of the shoulder, which covers the shoulder but has a single tendon that inserts on the deltoid tuberosity of the humerus.

Because of fascicles, a portion of a multipennate muscle like the deltoid can be stimulated by the nervous system to change the direction of the pull. For example, when the deltoid muscle contracts, the arm abducts (moves away from midline in the sagittal plane), but when only the anterior fascicle is stimulated, the arm will abduct and flex (move anteriorly at the shoulder joint).

The Lever System of Muscle and Bone Interactions

Skeletal muscles do not work by themselves. Muscles are arranged in pairs based on their functions. For muscles attached to the bones of the skeleton, the connection determines the force, speed, and range of movement. These characteristics depend on each other and can explain the general organization of the muscular and skeletal systems.

The skeleton and muscles act together to move the body. Have you ever used the back of a hammer to remove a nail from wood? The handle acts as a lever and the head of the hammer acts as a fulcrum, the fixed point that the force is applied to when you pull back or push down on the handle. The effort applied to this system is the pulling or pushing on the handle to remove the nail, which is the load, or “resistance” to the movement of the handle in the system. Our musculoskeletal system works in a similar manner, with bones being stiff levers and the articular endings of the bones—encased in synovial joints—acting as fulcrums. The load would be an object being lifted or any resistance to a movement (your head is a load when you are lifting it), and the effort, or applied force, comes from contracting skeletal muscle.

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11.2: Naming Skeletal Muscles

Skeletal Muscles Names: Latin and Greek Origins

The Greeks and Romans conducted the first studies done on the human body in Western culture. The educated class of subsequent societies studied Latin and Greek, and therefore the early pioneers of anatomy continued to apply Latin and Greek terminology or roots when they named the skeletal muscles. The large number of muscles in the body and unfamiliar words can make learning the names of the muscles in the body seem daunting, but understanding the etymology can help. Etymology is the study of how the root of a particular word entered a language and how the use of the word evolved over time. Taking the time to learn the root of the words is crucial to understanding the vocabulary of anatomy and physiology. When you understand the names of muscles it will help you remember where the muscles are located and what they do (Figure 11.2.1, Table 11.2.1, and Table 11.2.2). Pronunciation of words and terms will take a bit of time to master, but after you have some basic information; the correct names and pronunciations will become easier.

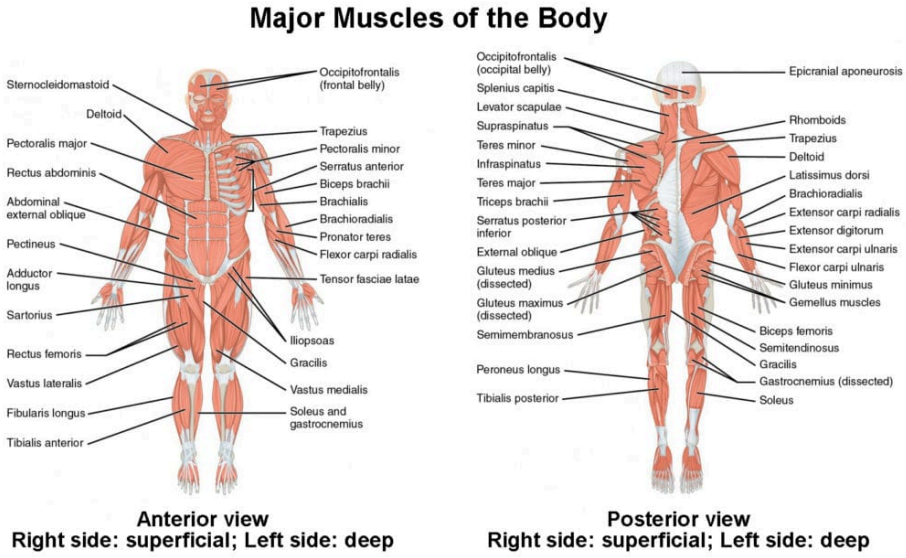


Figure 11.2.1: On the anterior and posterior views of the muscular system above, superficial muscles (those at the surface) are shown on the right side of the body while deep muscles (those underneath the superficial muscles) are shown on the left half of the body. For the legs, superficial muscles are shown in the anterior view while the posterior view shows both superficial and deep muscles. (CC BY 4.0; via OpenStax). Alternate text description of the Figure 11.2.1.

Table 11.2.1: Understanding a Muscle Name from the Latin

Example	Word	Latin Root 1	Latin Root 2	Meaning	Translation
abductor digiti minimi	abductor	*ab* = away from	*duct* = to move	a muscle that moves away from	A muscle that moves the little finger or toe away
	digiti	*digitus* = digit		refers to a finger or toe	
	minimi	*minimus* = mini, tiny		little	
adductor digiti minimi	adductor	*ad* = to, toward	*duct* = to move	a muscle that moves towards	A muscle that moves the little finger or toe toward
	digiti	*digitus* = digit		refers to a finger or toe	
	minimi	*minimus* = mini, tiny		little	

Table 11.2.2: Mnemonic Device for Latin Roots

Example	Latin or Greek Translation	Mnemonic Device
ad	to; toward	ADvance toward your goal
ab	away from	n/a
sub	under	SUBmarines move under water.
ductor	something that moves	A conDUCTOR makes a train move.
anti	against	If you are antisocial, you are against engaging in social activities.
epi	on top of	n/a
apo	to the side of	n/a
longissimus	longest	“Longissimus” is longer than the word “long.”
longus	long	long
brevis	short	brief
maximus	large	max
medius	medium	“Medius” and “medium” both begin with “med.”
minimus	tiny; little	mini
rectus	straight	To RECTify a situation is to straighten it out.
multi	many	If something is MULTIcolored, it has many colors.
uni	one	A UNIcorn has one horn.
bi/di	two	If a ring is DIcast, it is made of two metals.
tri	three	TRIple the amount of money is three times as much.
quad	four	QUADruplets are four children born at one birth.
externus	outside	EXternal
internus	inside	INternal

Characteristics Used in Muscle Naming

Anatomists name the skeletal muscles according to a number of criteria, each of which describes the muscle in some way. These include naming the muscle after its shape, its size compared to other muscles in the area, its location in the body or the location of its attachments to the skeleton, how many origins it has, or its action.

The skeletal muscle’s anatomical location or its relationship to a particular bone often determines its name. For example, the frontalis muscle is located on top of the frontal bone of the skull. Similarly, the shapes of some muscles are very distinctive and the names, such as orbicularis, reflect the shape. For the buttocks, the size of the muscles influences the names: gluteus maximus (largest), gluteus medius (medium), and the gluteus minimus (smallest). Names were given to indicate length— brevis (short), longus (long)—and to identify position relative to the midline: lateralis (to the outside away from the midline), and medialis (toward the midline). The direction of the muscle fibers and fascicles are used to describe muscles relative to the midline, such as the rectus (straight) abdominis, or the oblique (at an angle) muscles of the abdomen.

Some muscle names indicate the number of muscles in a group. One example of this is the quadriceps, a group of four muscles located on the anterior (front) thigh. Other muscle names can provide information as to how many origins a particular muscle has, such as the biceps brachii. The prefix bi indicates that the muscle has two origins and tri indicates three origins.

The location of a muscle’s attachment can also appear in its name. When the name of a muscle is based on the attachments, the origin is always named first. For instance, the sternocleidomastoid muscle of the neck has a dual origin on the sternum (sterno) and clavicle (cleido), and it inserts on the mastoid process of the temporal bone. The last feature by which to name a muscle is its action. When muscles are named for the movement they produce, one can find action words in their name. Some examples

are flexor (decreases the angle at the joint), extensor (increases the angle at the joint), abductor (moves the bone away from the midline), or adductor (moves the bone toward the midline).

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11.3: Axial Muscles of the Head, Neck, and Back

Organization of Axial Skeletal Muscles

The skeletal muscles are divided into axial (muscles of the trunk and head) and appendicular (muscles of the arms and legs) categories. This system reflects the bones of the skeleton system, which are also arranged in this manner. The axial muscles are grouped based on location, function, or both. Some of the axial muscles may seem to blur the boundaries because they cross over to the appendicular skeleton. The first grouping of the axial muscles you will review includes the muscles of the head and neck, then you will review the muscles of the vertebral column, and finally you will review the oblique and rectus muscles.

Muscles That Create Facial Expression

The origins of the muscles of facial expression are on the surface of the skull (remember, the origin of a muscle does not move). The insertions of these muscles have fibers intertwined with connective tissue and the dermis of the skin. Because the muscles insert in the skin rather than on bone, when they contract, the skin moves to create facial expression (Figure 11.3.1).

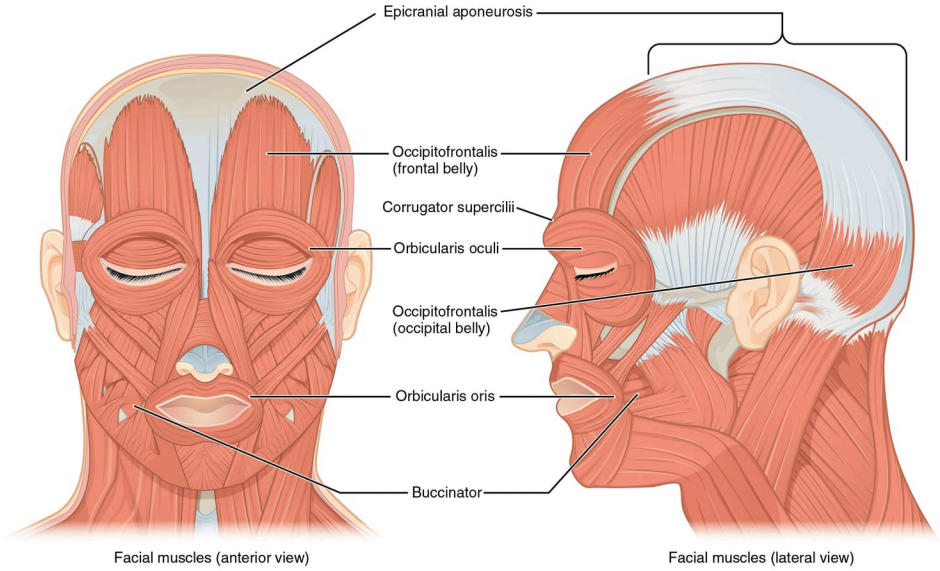


Figure 11.3.1: Many of the muscles of facial expression insert into the skin surrounding the eyelids, nose and mouth, producing facial expressions by moving the skin rather than bones. (CC BY 4.0; via Axial Muscles of the Head, Neck and Back). Alternate text description of the Figure 11.3.1.

The occipitofrontalis muscle moves up the scalp and eyebrows. The muscle has a frontal belly and an occipital (near the occipital bone on the posterior part of the skull) belly. In other words, there is a muscle on the forehead (frontalis) and one on the back of the head (occipitalis), but there is no muscle across the top of the head. Instead, the two bellies are connected by a broad tendon called the epicranial aponeurosis, or galea aponeurosis (galea = “helmet”). The physicians originally studying human anatomy thought the skull looked like a helmet.

A large portion of the face is composed of the buccinator muscle, which compresses the cheek. This muscle allows you to whistle, blow, and suck; and it contributes to the action of chewing. There are several small facial muscles, one of which is the corrugator supercilii, which is the prime mover of the eyebrows. Place your finger on your eyebrows at the point of the bridge of the nose. Raise your eyebrows as if you were surprised and lower your eyebrows as if you were frowning. With these movements, you can feel the action of the corrugator supercilii. Additional muscles of facial expression are presented in Figure 11.3.2.

Table 11.3.1: Origin and Insertion of the Muscles in Facial Expression

Action (Movement)	Prime mover	Origin	Insertion
Raising eyebrows (showing surprise)	Occipitofrontalis (frontal belly/ frontalis)	Epicranial aponeurosis	Skin of eyebrow
Retracts scalp	Occipitofrontalis (occipital belly/ occipitalis)	Occipital bone; mastoid process (temporal bone)	Epicranial aponeurosis
Closes eyelids (blinking, squinting, winking)	Orbicularis oculi	Medial wall of orbit	Skin surrounding eyelids
Elevates superior eyelid	Levator palpebrae superioris	Sphenoid bone	Skin of superior eyelid
Flaring nostrils	Nasalis	Maxilla	Skin of nostrils, nasal aponeurosis
Lateral movement of cheeks (e.g. sucking on a straw; also used to compress air in mouth while blowing)	Buccinator	Maxilla, mandible	Orbicularis oris
Draws corners of mouth inferior and lateral (e.g. frowning)	Depressor anguli oris	Mandible	Skin at corners of mouth
Lowering lower lip	Depressor labii inferioris	Mandible	Skin of lower lip
Raising upper lip	Levator labii superioris	Maxilla	Skin of the of upper lip; orbicularis oris
Protrusion of lower lip (e.g. pouting expression)	Mentalis	Mandible	Skin of chin
Compresses and purses lips (e.g. kiss)	Orbicularis oris	Maxilla, mandible; fibers of other facial muscles	Skin surrounding lips
Smiling	Zygomaticus major and minor	Zygomatic bone	Skin at superolateral corners of mouth and lip

Muscles That Move the Eyeball

The movement of the eyeball is under the control of the extrinsic eye muscles, which originate outside the eye and insert onto the outer surface of the white of the eye. These muscles are located inside the eye socket and cannot be seen on any part of the visible eyeball (Figure 11.3.2 and Table 11.3.1). If you have ever been to a doctor who held up a finger and asked you to follow it up, down, and to both sides, the doctor is checking to make sure your eye muscles are acting in a coordinated pattern.

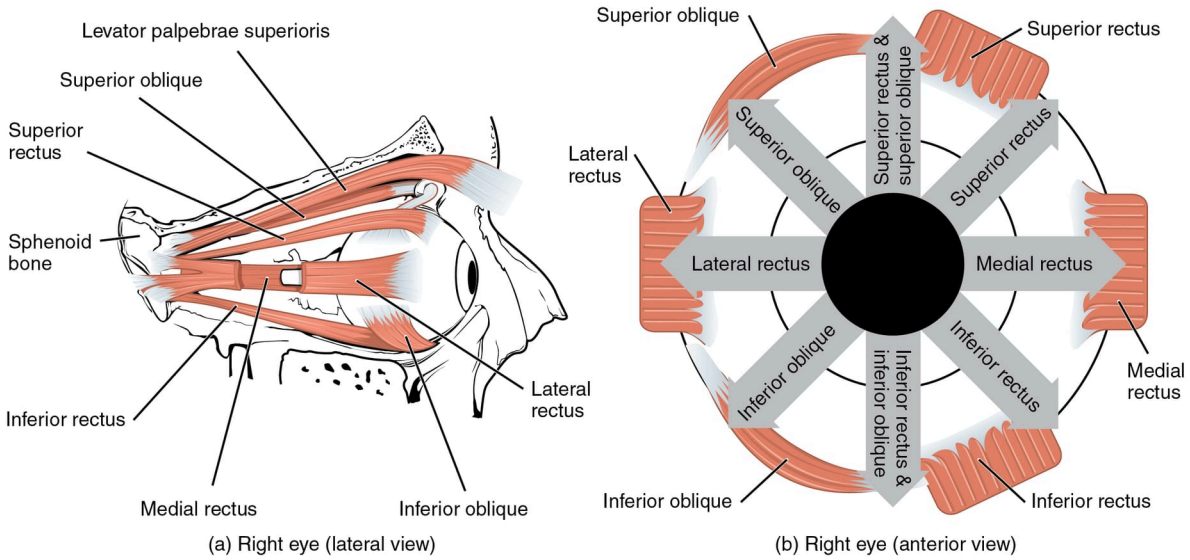


Figure 11.3.2: Muscles That Move the Eyeball (a) The extrinsic eye muscles originate outside of the eye on the skull. (b) Each muscle inserts onto the eyeball. (CC BY 4.0; via Axial Muscles of the Head, Neck and Back). Alternate text description of the Figure 11.3.2.

Table 11.3.2: Origin and Insertion of Muscles That Move the Eyeball

Action (Movement)	Prime Mover	Origin	Insertion
Moves eyes up and toward nose; rotates eyes from 1 o'clock to 3 o'clock	Superior rectus	Common tendinous ring (ring attaches to optic foramen)	Superior surface of eyeball
Moves eyes down and toward nose; rotates eyes from 6 o'clock to 3 o'clock	Inferior rectus	Common tendinous ring (ring attaches to optic foramen)	Inferior surface of eyeball
Moves eyes away from nose (abducts)	Lateral rectus	Common tendinous ring (ring attaches to optic foramen)	Superior surface of eyeball
Moves eyes toward nose	Medial rectus	Common tendinous ring (ring attaches to optic foramen)	Medial surface of eyeball
Extort (externally rotate) the eye, but it also assists in elevation (looking up) and abduction (moving the eye outward/away from the nose), creating an "up and out" movement	Inferior oblique	Floor of orbit (maxilla)	Posterior surface of the sclera (eyeball), between inferior rectus and lateral rectus
Intorsion (rotation of the eye inward), depression (downward movement), and abduction (outward movement)	Superior oblique	Body of Sphenoid bone	Posterior-lateral surface of the sclera
Raises the upper eyelid, opens the eyes	Levator palpabrae superioris	Roof of orbit (sphenoid bone)	Skin of upper eyelids
Closes the eyelids (blinking, sleeping)	Orbicularis oculi	Medial bones composing the orbit (nasal, maxilla, lacrimal)	Skin surrounding the eye (Circumference of orbit)

Muscles Controlling Jaw Motion

In anatomical terminology, chewing is called mastication. Muscles involved in chewing must be able to exert enough pressure to bite through and then chew food before it is swallowed (Figure 11.3.3 and Table 11.3.3). The masseter muscle is the main muscle used for chewing because it elevates the mandible (lower jaw) to close the mouth, and it is assisted by the temporalis muscle, which retracts the mandible. You can feel the temporalis move by putting your fingers to your temple as you chew.

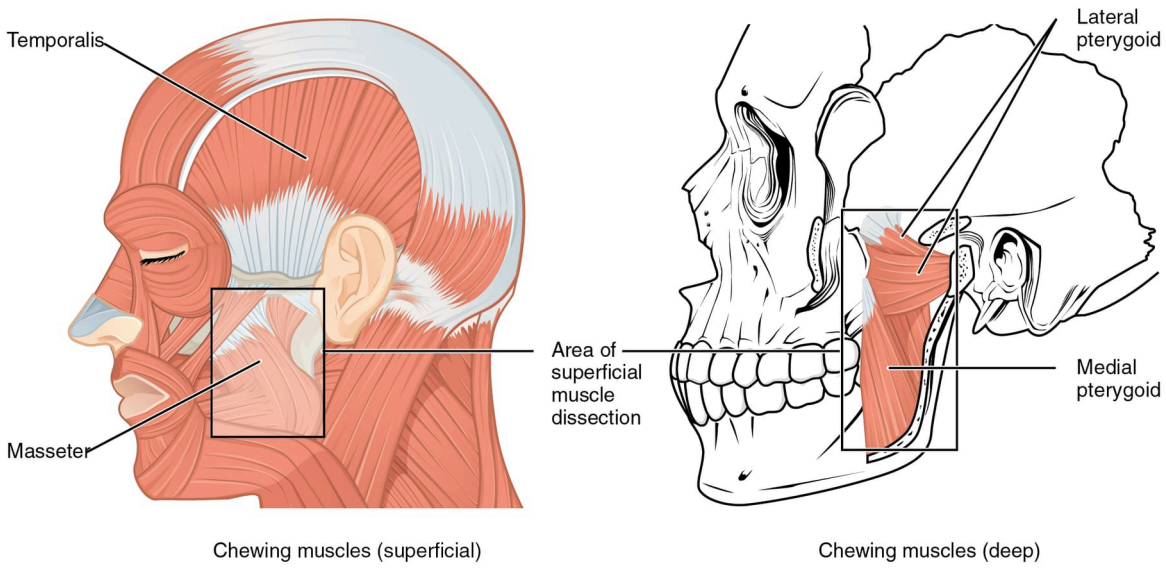


Figure 11.3.3: The muscles that move the lower jaw are typically located within the cheek and originate from processes in the skull. This provides the jaw muscles with the large amount of leverage needed for chewing. (CC BY 4.0; via Axial Muscles of the Head, Neck and Back). Alternate text description of the Figure 11.3.3.

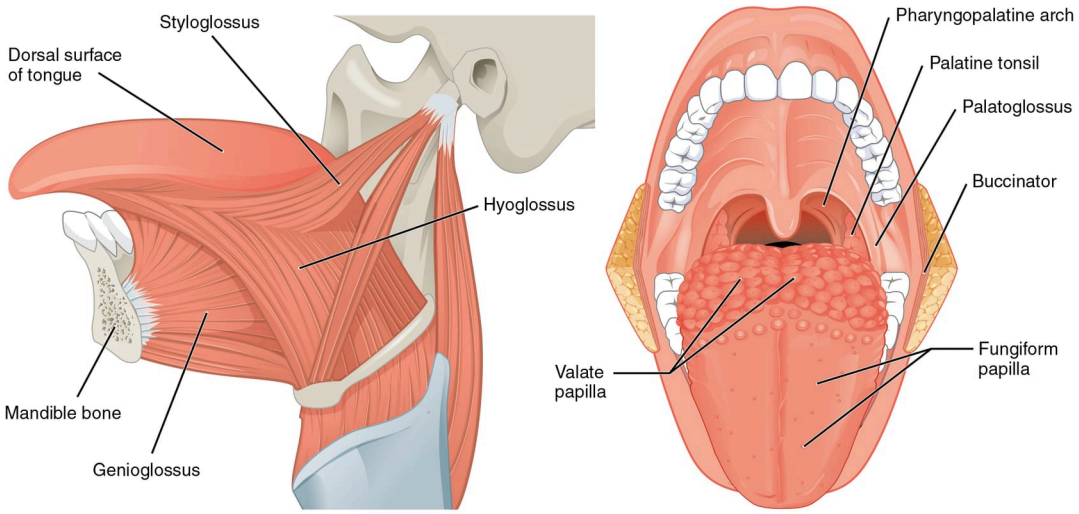
Table 11.3.3: Origin and Insertion of Muscles that Move the Lower Jaw at the Temporomandibular Joint

Movement	Prime mover	Origin	Insertion
Closes mouth; aids chewing	Masseter	Maxilla arch; zygomatic arch (for masseter)	Mandible
Closes mouth; pulls lower jaw in under upper jaw	Temporalis	Temporal bone	Mandible
Opens mouth; pushes lower jaw out under upper jaw; moves lower jaw side-to-side	Lateral pterygoid	Pterygoid process of sphenoid bone	Mandible
Closes mouth; pushes lower jaw out under upper jaw; moves lower jaw side-to-side	Medial pterygoid	Sphenoid bone; maxilla	Mandible; temporo-mandibular joint

Although the masseter and temporalis are responsible for elevating and closing the jaw to break food into digestible pieces, the medial pterygoid and lateral pterygoid muscles provide assistance in chewing and moving food within the mouth.

Muscles That Move the Tongue

Although the tongue is obviously important for tasting food, it is also necessary for mastication, deglutition (swallowing), and speech (Figure 11.3.4 and Table 11.3.4). Because it is so moveable, the tongue facilitates complex speech patterns and sounds.



(a) Extrinsic tongue muscles

(b) Palatoglossus and surface of tongue

Figure 11.3.4: Extrinsic muscles of the tongue and surface features of the oral cavity. (CC BY 4.0; via Axial Muscles of the Head, Neck and Back). Alternate text description of the Figure 11.3.4.

Tongue muscles can be extrinsic or intrinsic. Extrinsic tongue muscles insert into the tongue from outside origins, and the intrinsic tongue muscles insert into the tongue from origins within it. The extrinsic muscles move the whole tongue in different directions, whereas the intrinsic muscles allow the tongue to change its shape (such as, curling the tongue in a loop or flattening it).

The extrinsic muscles all include the word root glossus (glossus = “tongue”), and the muscle names are derived from where the muscle originates. The genioglossus (genio = “chin”) originates on the mandible and allows the tongue to move downward and forward. The styloglossus originates on the styloid bone, and allows upward and backward motion. The palatoglossus originates on the soft palate to elevate the back of the tongue, and the hyoglossus originates on the hyoid bone to move the tongue downward and flatten it.

Muscles of the Anterior Neck that Assist in Deglutition and Speech

The muscles of the anterior neck assist in deglutition (swallowing) and speech by controlling the positions of the larynx (voice box), and the hyoid bone, a horseshoe-shaped bone that functions as a solid foundation on which the tongue can move. The muscles of the neck are categorized according to their position relative to the hyoid bone (Figure 11.3.5). Suprahyoid muscles are superior to it, and the infrahyoid muscles are located inferiorly.

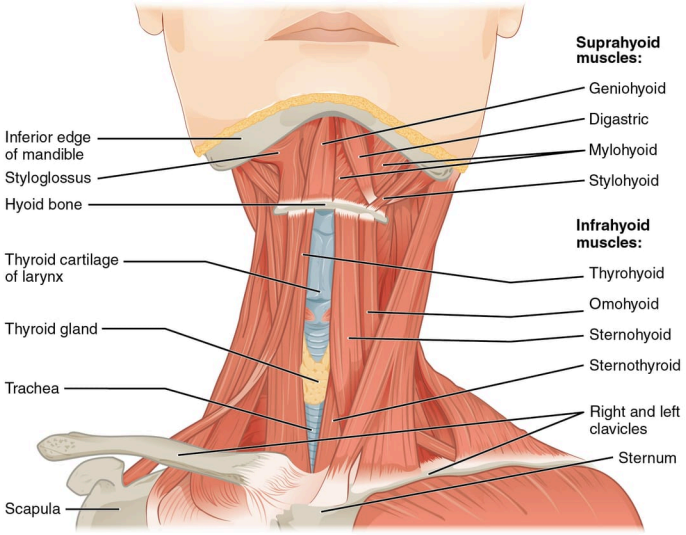


Figure 11.3.5: The anterior muscles of the neck facilitate swallowing and speech. The suprahyoid muscles originate from above the hyoid bone in the chin region. The infrahyoid muscles originate below the hyoid bone in the lower neck. (CC BY 4.0; via Axial Muscles of the Head, Neck and Back). Alternate text description of the Figure 11.3.5.

Table 11.3.4: Origin and Insertion of Muscles for Tongue Movement, Swallowing, and Speech

Action (Movement)	Prime mover	Origin	Insertion
Moves tongue down; sticks tongue out of mouth	Genioglossus	Mandible	Tongue undersurface; hyoid bone
Flattens tongue	Hyoglossus	Hyoid Bone	Sides of tongue
Moves tongue up; retracts tongue back into mouth	Styloglossus	Styloid process of temporal bone	Tongue undersurface and sides
Raises hyoid bone in a way that also raises the larynx, allowing the epiglottis to cover the glottis during deglutition; also assists in opening the mouth by depressing the mandible	Digastric	Mandible; temporal bone	Hyoid bone
Raises hyoid bone in a way that presses the tongue against the roof of the mouth, pushing food back into the pharynx during deglutition	Mylohyoid	Mandible	Hyoid bone; median raphe
Depresses the hyoid bone during swallowing and speaking	Sternohyoid	Clavicle	Hyoid bone

Muscles That Move the Head

The head, attached to the top of the vertebral column, is balanced, moved, and rotated by the neck muscles (Table 11.3.5). When these muscles act unilaterally, the head rotates. When they contract bilaterally, the head flexes or extends. The major muscle that laterally flexes and rotates the head is the sternocleidomastoid. In addition, both muscles working together are the flexors of the head. Place your fingers on both sides of the neck and turn your head to the left and to the right. You will feel the movement originate there. This muscle divides the neck into anterior and posterior triangles when viewed from the side (Figure 11.3.6).

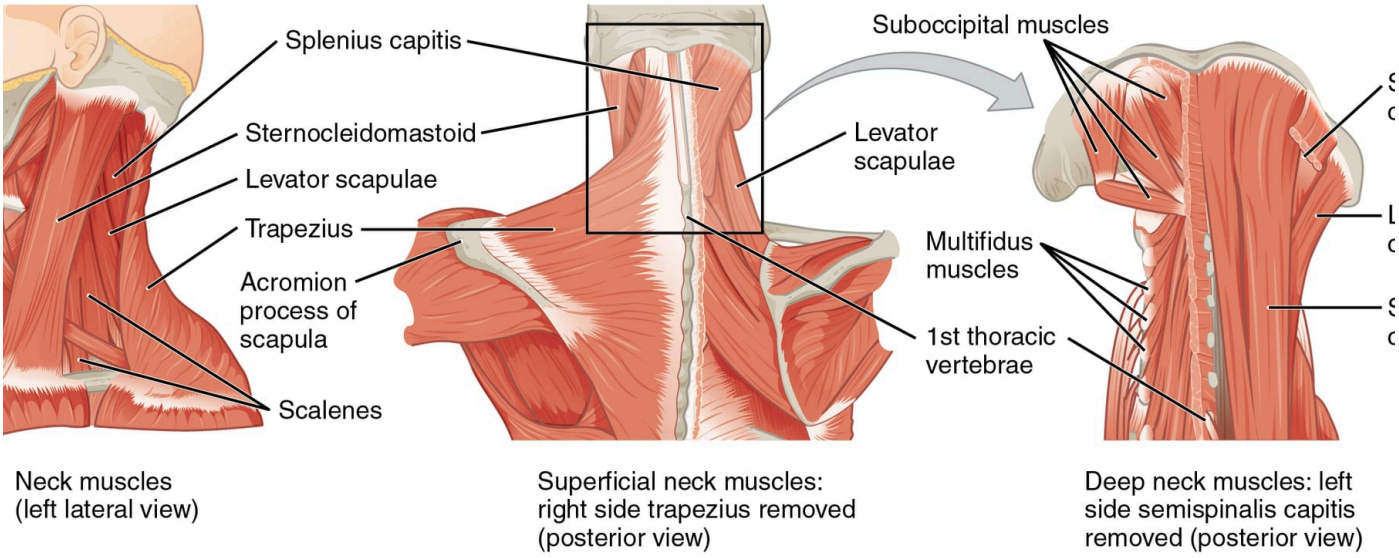


Figure 11.3.6: The superficial and deep muscles of the neck are responsible for moving the head, cervical vertebrae, and scapulars. (CC BY 4.0; via Axial Muscles of the Head, Neck and Back). Alternate text description of the Figure 11.3.6.

Muscles of the Posterior Neck and the Back

The posterior muscles of the neck are primarily concerned with head movements, like extension. The back muscles stabilize and move the vertebral column, and are grouped according to the lengths and direction of the fascicles.

The splenius muscles originate at the midline and run laterally and superiorly to their insertions. From the sides and the back of the neck, the splenius capitis inserts onto the head region, and the splenius cervicis extends onto the cervical region. These muscles can extend the head, laterally flex it, and rotate it (Figure 11.3.7).

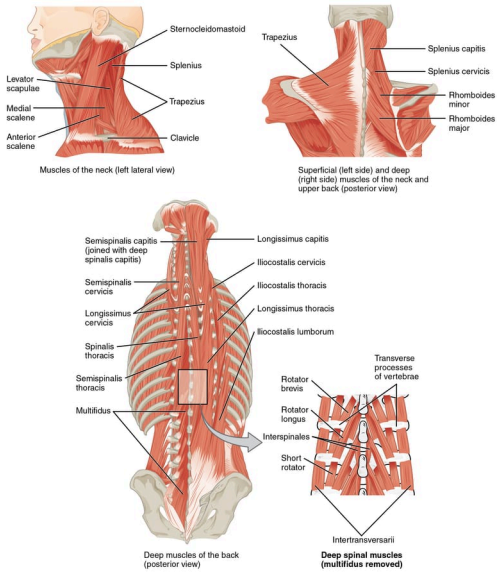


Figure 11.3.7: The large, complex muscles of the neck and back move the head, shoulders, and vertebral column. (CC BY 4.0; via Axial Muscles of the Head, Neck and Back). Alternate text description of the Figure 11.3.7.

The erector spinae group forms the majority of the muscle mass of the back and it is the primary extensor of the vertebral column. It controls flexion, lateral flexion, and rotation of the vertebral column, and maintains the lumbar curve. The erector spinae comprises the iliocostalis (laterally placed) group, the longissimus (intermediately placed) group, and the spinalis (medially

placed) group.

The iliocostalis group includes the iliocostalis cervicis, associated with the cervical region; the iliocostalis thoracis, associated with the thoracic region; and the iliocostalis lumborum, associated with the lumbar region. The three muscles of the longissimus group are the longissimus capitis, associated with the head region; the longissimus cervicis, associated with the cervical region; and the longissimus thoracis, associated with the thoracic region. The third group, the spinalis group, comprises the spinalis capitis (head region), the spinalis cervicis (cervical region), and the spinalis thoracis (thoracic region).

The transversospinals muscles run from the transverse processes to the spinous processes of the vertebrae. Similar to the erector spinae muscles, the semispinalis muscles in this group are named for the areas of the body with which they are associated. The semispinalis muscles include the semispinalis capitis, the semispinalis cervicis, and the semispinalis thoracis. The multifidus muscle of the lumbar region helps extend and laterally flex the vertebral column.

Important in the stabilization of the vertebral column is the segmental muscle group, which includes the interspinales and intertransversarii muscles. These muscles bring together the spinous and transverse processes of each consecutive vertebra. Finally, the scalene muscles work together to flex, laterally flex, and rotate the head. They also contribute to deep inhalation. The scalene muscles include the anterior scalene muscle (anterior to the middle scalene), the middle scalene muscle (the longest, intermediate between the anterior and posterior scalenes), and the posterior scalene muscle (the smallest, posterior to the middle scalene).

Table 11.3.5: Muscles That Move the Head

Action (Movement)	Prime mover	Origin	Insertion
Rotates and tilts head to the side; tilts head forward	Sternocleidomastoid	Sternum; clavicle	Temporal bone (mastoid process); occipital bone
Rotates and tilts head backward	Semispinalis capitis	Transverse and articular processes of cervical and thoracic vertebra	Occipital bone
Rotates and tilts head to the side; tilts head backward	Splenius capitis	Spinous processes of cervical and thoracic vertebra	Temporal bone (mastoid process); occipital bone
Rotates and tilts head to the side; tilts head backward	Longissimus capitis	Transverse and articular processes of cervical and thoracic vertebra	Temporal bone (mastoid process)

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11.4: Axial Muscles of the Abdominal Wall and Thorax

Axial Muscles Supporting Posture and Respiration

It is a complex job to balance the body on two feet and walk upright. The muscles of the vertebral column, thorax, and abdominal wall extend, flex, and stabilize different parts of the body's trunk. The deep muscles of the core of the body help maintain posture as well as carry out other functions. The brain sends out electrical impulses to these various muscle groups to control posture by alternate contraction and relaxation. This is necessary so that no single muscle group becomes fatigued too quickly. If any one group fails to function, body posture will be compromised.

Muscles of the Abdomen

There are four pairs of abdominal muscles that cover the anterior and lateral abdominal region and meet at the anterior midline. These muscles of the anterolateral abdominal wall can be divided into four groups: the external obliques, the internal obliques, the transversus abdominis, and the rectus abdominis (Figure 11.4.1 and Table 11.4.1.

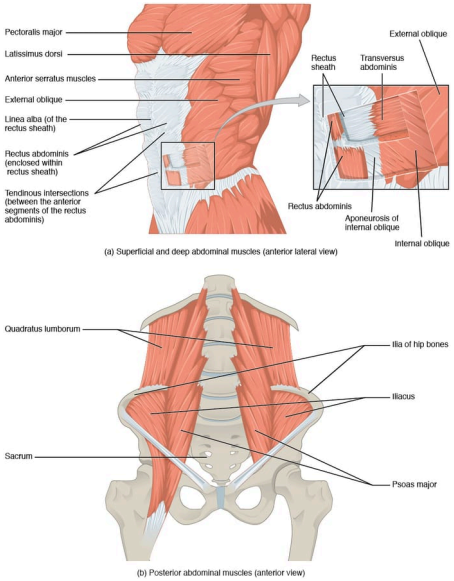


Figure 11.4.1: Superficial, deep, and posterior abdominal muscles shown from anterior and posterior views, highlighting major muscle layers and their anatomical relationships. (CC BY 4.0 ; via Axial Muscles of the Abdominal Wall and Thorax). Alternate text description of the Figure 11.4.1.

Table 11.4.1: Muscles of the Abdomen

Action (Movement)	Prime mover	Origin	Insertion
Twisting at waist; also bending to the side	External obliques; internal obliques	Ribs 5–12; ilium	Ribs 7–10; linea alba; ilium
Squeezing abdomen during forceful exhalations, defecation, urination, and childbirth	Transversus abdominis	Ilium; ribs 5–10	Sternum; linea alba; pubis
Sitting up	Rectus abdominis	Pubis	Sternum; ribs 5 and 7
Bending to the side	Quadratus lumborum	Ilium; ribs 5–10	Rib 12; vertebrae L1–L4

There are three flat skeletal muscles in the antero-lateral wall of the abdomen. The external oblique, closest to the surface, extend inferiorly and medially, in the direction of sliding one's four fingers into pants pockets. Perpendicular to it is the intermediate

internal oblique, extending superiorly and medially, the direction the thumbs usually go when the other fingers are in the pants pocket. The deep muscle, the transversus abdominis, is arranged transversely around the abdomen, similar to the front of a belt on a pair of pants. This arrangement of three bands of muscles in different orientations allows various movements and rotations of the trunk. The three layers of muscle also help to protect the internal abdominal organs in an area where there is no bone.

The linea alba is a white, fibrous band that is made of the bilateral rectus sheaths that join at the anterior midline of the body. These enclose the rectus abdominis muscles (a pair of long, linear muscles, commonly called the "sit-up" muscles) that originate at the pubic crest and symphysis, and extend the length of the body's trunk. Each muscle is segmented by three transverse bands of collagen fibers called the tendinous intersections. This results in the look of "six-pack abs," as each segment hypertrophies on individuals at the gym who do many sit-ups.

The posterior abdominal wall is formed by the lumbar vertebrae, parts of the ilia of the hip bones, psoas major and iliacus muscles, and quadratus lumborum muscle. This part of the core plays a key role in stabilizing the rest of the body and maintaining posture.

Career Connection

Physical Therapists

Those who have a muscle or joint injury will most likely be sent to a physical therapist (PT) after seeing their regular doctor. PTs have a master's degree or doctorate, and are highly trained experts in the mechanics of body movements. Many PTs also specialize in sports injuries.

If you injured your shoulder while you were kayaking, the first thing a physical therapist would do during your first visit is to assess the functionality of the joint. The range of motion of a particular joint refers to the normal movements the joint performs. The PT will ask you to abduct and adduct, circumduct, and flex and extend the arm. The PT will note the shoulder's degree of function, and based on the assessment of the injury, will create an appropriate physical therapy plan.

The first step in physical therapy will probably be applying a heat pack to the injured site, which acts much like a warm-up to draw blood to the area, to enhance healing. You will be instructed to do a series of exercises to continue the therapy at home, followed by icing, to decrease inflammation and swelling, which will continue for several weeks. When physical therapy is complete, the PT will do an exit exam and send a detailed report on the improved range of motion and return of normal limb function to your doctor. Gradually, as the injury heals, the shoulder will begin to function correctly. A PT works closely with patients to help them get back to their normal level of physical activity.

Muscles of the Thorax that Supports Respiration

The muscles of the chest serve to facilitate breathing by changing the size of the thoracic cavity (Table 11.4.2). When you inhale, your chest rises because the cavity expands. Alternately, when you exhale, your chest falls because the thoracic cavity decreases in size.

The Diaphragm

The change in volume of the thoracic cavity during breathing is due to the alternate contraction and relaxation of the diaphragm (Figure 11.4.2). It separates the thoracic and abdominal cavities, and is dome-shaped at rest. The superior surface of the diaphragm is convex, creating the elevated floor of the thoracic cavity. The inferior surface is concave, creating the curved roof of the abdominal cavity.

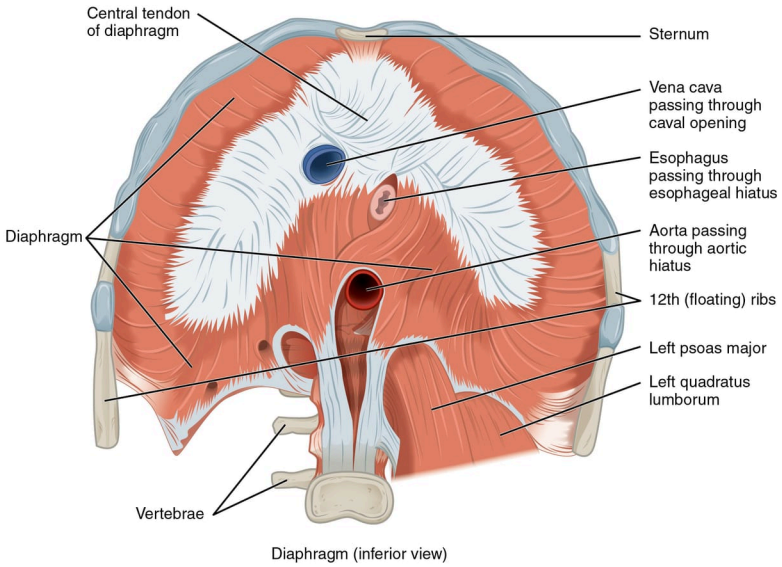


Figure 11.4.2: Inferior anatomical view of the diaphragm displaying its central tendon, muscular regions, and passageways for the vena cava, esophagus, and aorta, along with surrounding ribs, vertebrae, and posterior abdominal muscles. (CC BY 4.0 ; via Axial Muscles of the Abdominal Wall and Thorax). Alternate text description of the Figure 11.4.2.

The Intercostal Muscles

There are three sets of muscles, called intercostal muscles, which span each of the intercostal spaces. The principal role of the intercostal muscles is to assist in breathing by changing the dimensions of the rib cage (Figure 11.4.3).

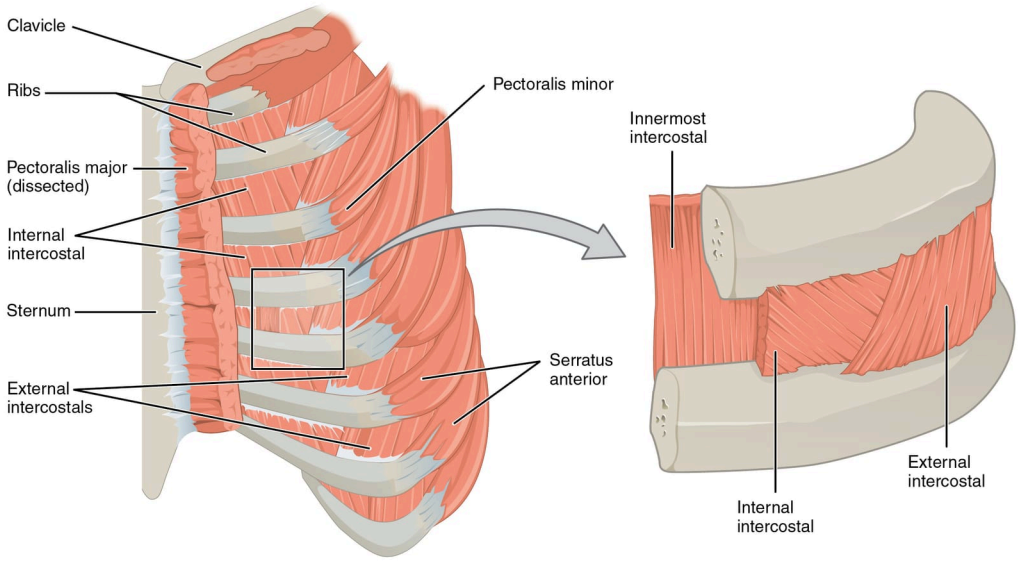


Figure 11.4.3: Lateral and cross-sectional views of the thoracic wall highlighting the external, internal, and innermost intercostal muscles, along with the pectoralis major, pectoralis minor, serratus anterior, ribs, and sternum. (CC BY 4.0 ; via Axial Muscles of the Abdominal Wall and Thorax). Alternate text description of the Figure 11.4.3.

The 11 pairs of superficial external intercostal muscles aid in inspiration of air during breathing because when they contract, they raise the rib cage, which expands it. The 11 pairs of internal intercostal muscles, just under the externals, are used for expiration because they draw the ribs together to constrict the rib cage. The innermost intercostal muscles are the deepest, and they act as synergists for the action of the internal intercostals.

Table 11.4.2: Muscles of the Thorax That Supports Respiration

Action (Movement)	Prime mover	Origin	Insertion
Inhalation; exhalation	Diaphragm	Sternum; ribs 6–12; lumbar vertebrae	Central tendon
Inhalation;exhalation	External intercostals	Rib superior to each intercostal muscle	Rib inferior to each intercostal muscle
Forced exhalation	Internal intercostals	Rib inferior to each intercostal muscle	Rib superior to each intercostal muscle
Elevate 1st and 2nd rib during forced inhalation	Scalanes	Transverse processes of cervical vertebrae	Superior surface of 1st and 2nd rib

Muscles of the Pelvic Floor and Perineum

The pelvic floor is a muscular sheet that defines the inferior portion of the pelvic cavity. The pelvic diaphragm, spanning anteriorly to posteriorly from the pubis to the coccyx, comprises the levator ani and the ischiococcygeus. Its openings include the anal canal and urethra, and the vagina in females.

The large levator ani consists of two skeletal muscles, the pubococcygeus and the iliococcygeus (Figure 11.4.4). The levator ani is considered the most important muscle of the pelvic floor because it supports the pelvic viscera. It resists the pressure produced by contraction of the abdominal muscles so that the pressure is applied to the colon to aid in defecation and to the uterus to aid in childbirth (assisted by the ischiococcygeus, which pulls the coccyx anteriorly). This muscle also creates skeletal muscle sphincters at the urethra and anus.

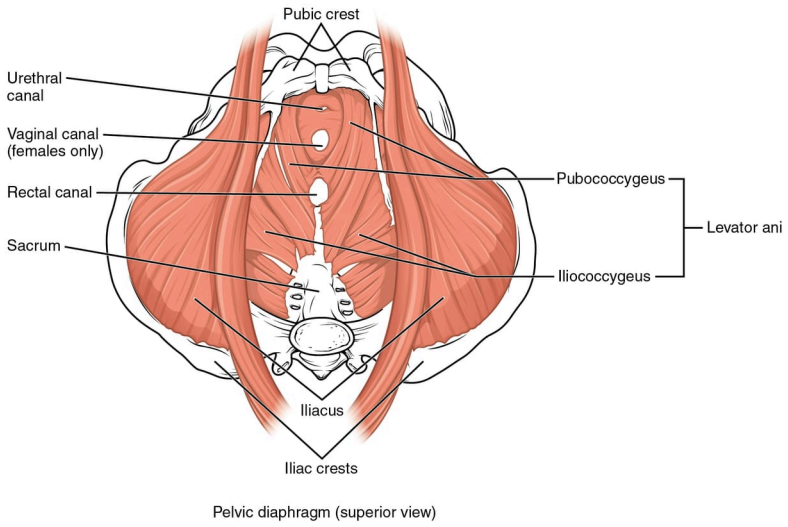


Figure 11.4.4: Superior anatomical view of the pelvic diaphragm, highlighting the levator ani group, coccygeus, and the urethral, vaginal, and rectal canals along with surrounding bony landmarks. (CC BY 4.0 ; via Axial Muscles of the Abdominal Wall and Thorax). Alternate text description of the Figure 11.4.4.

The perineum is the diamond-shaped space between the pubic symphysis (anteriorly), the coccyx (posteriorly), and the ischial tuberosities (laterally), lying just inferior to the pelvic diaphragm (levator ani and coccygeus). Divided transversely into triangles, the anterior is the urogenital triangle, which includes the external genitals. The posterior is the anal triangle, which contains the anus. The perineum is also divided into superficial and deep layers with some of the muscles common to people of any sex. Females also have the compressor urethrae and the sphincter urethrovaginals, which function to close the vagina. In males, there is the deep transverse perineal muscle that plays a role in ejaculation.

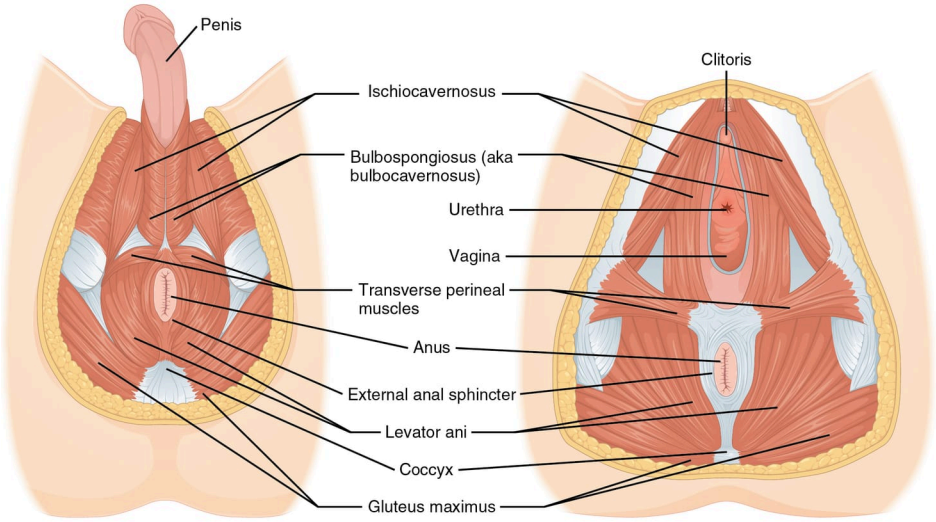


Figure 11.4.5: The perineum muscles play roles in urination in both sexes, ejaculation in men, and vaginal contraction in women. (CC BY 4.0 ; via Axial Muscles of the Abdominal Wall and Thorax). Alternate text description of the Figure 11.4.5.

Table 11.4.3 shows a structured table that organizes information about movements and muscles of the perineal region. The table is divided into sections for superficial and deep muscles. The columns list movement, target structure, direction of the intended motion, the prime mover involved, the muscle's origin point, and its insertion. Examples include muscles that support the perineal body, compress the urethra or surrounding tissues, assist erectile structures, or close the anal opening. The table also identifies muscles like the superficial transverse perineal, bulbospongiosus, ischiocavernosus, external urethral sphincter, and external anal sphincter. Additional rows describe associated targets such as the urethra, veins of erectile tissues, the anus, and the abdominal cavity.

Table 11.4.3: Summary table detailing superficial and deep perineal muscles

Muscle Group	Muscle Name	Primary Function (Movement)	Target Structure	Type/Direction of Action	Origin	Insertion
Pelvic floor (levator ani)	Pubococcygeus and Iliococcygeus	Supports pelvic organs during defecation, urination, childbirth, and coughing	Abdominal cavity	Lifts superiorly to resist increased abdominal pressure	Pubis and ischium	Urethra, anal canal, perineal body, coccyx
Superficial perineal muscles	Superficial transverse perineal	Supports the perineal body and stabilizes the anus in the center of the perineum	Perineal body	Stabilization (no movement)	Ischium	Perineal body
Superficial perineal muscles	Bulbospongiosus	Compresses the urethra during urination; assists ejaculation and erection	Urethra	Compression	Perineal body	Perineal membrane; corpus spongiosum of penis; deep fascia of penis; clitoris
Superficial perineal muscles	Ischiocavernosus	Compresses veins to maintain erection of the penis or clitoris	Veins of penis and clitoris	Compression	Ischium, ischial rami, pubic rami	Pubic symphysis; corpus cavernosum of penis; clitoris
Deep perineal muscles	External urethral sphincter	Voluntarily controls urination by compressing the urethra	Urethra	Compression	Ischial rami and pubic rami	Median raphe (male); vaginal wall (female)
Deep perineal muscles	External anal sphincter	Closes the anus to control defecation	Anus	Sphincter	Anococcygeal ligament	Perineal body

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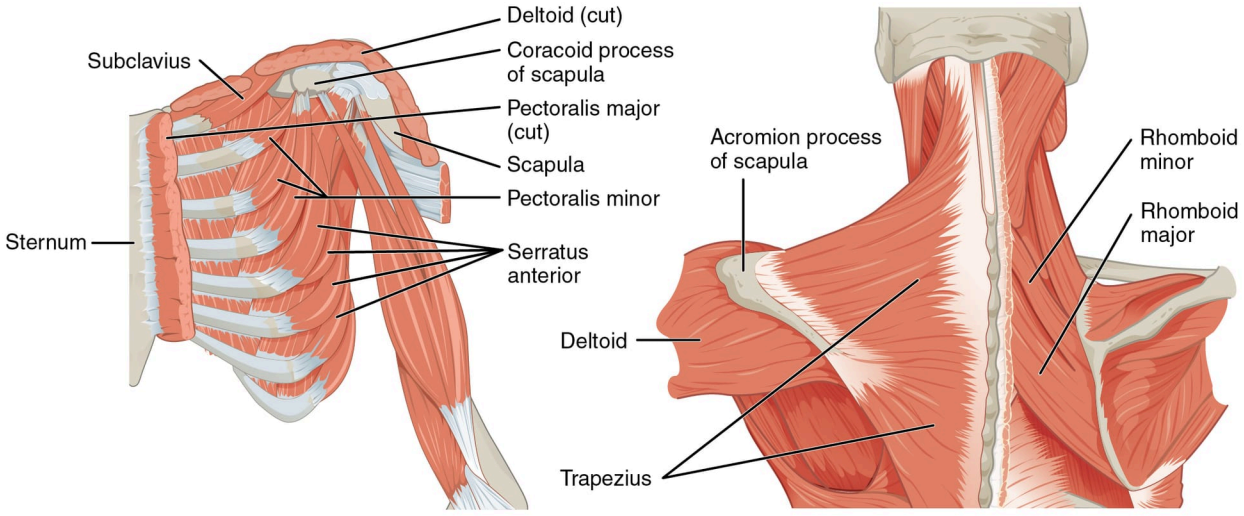
11.5: Muscles of the Pectoral Girdle and Upper Limbs

Muscles of the Shoulder, Arm, Forearm, and Hand

Muscles of the shoulder and upper limb can be divided into four groups: muscles that stabilize and position the pectoral girdle, muscles that move the arm, muscles that move the forearm, and muscles that move the wrists, hands, and fingers. The pectoral girdle, or shoulder girdle, consists of the lateral ends of the clavicle and scapula, along with the proximal end of the humerus, and the muscles covering these three bones to stabilize the shoulder joint. The girdle creates a base from which the head of the humerus, in its ball-and-socket joint with the glenoid fossa of the scapula, can move the arm in multiple directions.

Pectoral Girdle Positioning Muscles

Muscles that position the pectoral girdle are located either on the anterior thorax or on the posterior thorax (Figure 11.5.1 and Table 11.5.1). The anterior muscles include the subclavius, pectoralis minor, and serratus anterior. The posterior muscles include the trapezius, rhomboid major, and rhomboid minor. When the rhomboids are contracted, your scapula moves medially, which can pull the shoulder and upper limb posteriorly.



Pectoral girdle muscle (left anterior lateral view)

Pectoral girdle muscles (posterior view)

Figure 11.5.1: The muscles that stabilize the pectoral girdle make it a steady base on which other muscles can move the arm. Note that the pectoralis major and deltoid, which move the humerus, are cut here to show the deeper positioning muscles. (CC BY 4.0 ; via Muscles of the Pectoral Girdle and Upper Limbs). Alternate text description of the Figure 11.5.1.

Table 11.5.1: Muscles that Position the Pectoral Girdle

Action (Movement)	Prime mover	Origin	Insertion
Stabilizes clavicle during movement by depressing it	Subclavius	First rib	Inferior surface of clavicle
Rotates shoulder anteriorly (throwing motion); assists with inhalation	Pectoralis minor	Anterior surfaces of certain ribs (2–4 or 3–5)	Coracoid process of scapula
Moves arm from side of body to front of body; assists with inhalation	Serratus anterior	Muscle slips from certain ribs (1–8 or 1–9)	Anterior surface of vertebral border of scapula
Elevates shoulders (shrugging); pulls shoulder blades together; tilts head backwards	Trapezius	Skull; vertebral column	Acromion and spine of scapula; clavicle

Action (Movement)	Prime mover	Origin	Insertion
Stabilizes scapula during pectoral girdle movement	Rhomboid major	Thoracic vertebrae (T2–T5)	Medial border of scapula
Stabilizes scapula during pectoral girdle movement	Rhomboid minor	Cervical and thoracic vertebrae (C7 and T1)	Medial border of scapula

Muscles That Move the Humerus at Shoulder Joint

Similar to the muscles that position the pectoral girdle, muscles that cross the shoulder joint and move the humerus bone of the arm include both axial and scapular muscles. The two axial muscles are the pectoralis major and the latissimus dorsi. The pectoralis major is thick and fan-shaped, covering much of the superior portion of the anterior thorax. The broad, triangular latissimus dorsi is located on the inferior part of the back, where it inserts into a thick connective tissue sheath called an aponeurosis.

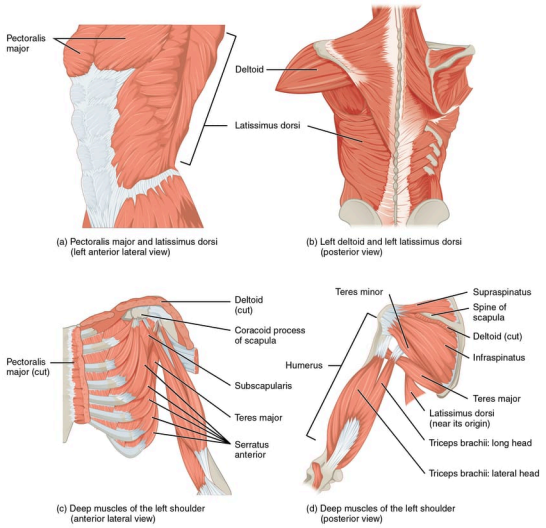


Figure 11.5.2: Anterior, lateral, and posterior diagrams illustrating major shoulder muscles, including the pectoralis major, latissimus dorsi, deltoid, serratus anterior, and the deep rotator cuff group—supraspinatus, infraspinatus, teres minor, and subscapularis. (CC BY 4.0 ; via Muscles of the Pectoral Girdle and Upper Limbs). Alternate text description of the Figure 11.5.2.

Table 11.5.2: Muscles That Move the Humerus at Shoulder Joint

Action (Movement)	Muscle	Origin	Insertion
Extends, adducts, and internally rotates shoulder	Latissimus dorsi	Thoracic vertebrae (T7-T12); lumbar vertebrae; lower ribs (9-12); iliac crest	Intertubercular sulcus of humerus
Flex, adduct, and internally rotate shoulder	Pectoralis major	Clavicle; sternum; cartilage of certain ribs (1-6 or 1-7); aponeurosis of external oblique muscle	Greater tubercle of humerus
Flex and adduct shoulder	Coracobrachialis	Coracoid process of scapula	Medial surface of humerus shaft
	Deltoid	Trapezius; clavicle; acromion and spine of scapula	Deltoid tuberosity of humerus

Action (Movement)	Muscle	Origin	Insertion
Adduct and internally rotate shoulder; stabilizes shoulder joint during movement of the pectoral girdle	Subscapularis (part of rotator cuff)	Subscapular fossa of scapula	Lesser tubercle of humerus
Externally rotate shoulder	Infraspinatus (part of rotator cuff)	Infraspinous fossa of scapula	Greater tubercle of humerus
Abduct shoulder	Supraspinatus (part of rotator cuff)	Supraspinous fossa of scapula	Greater tubercle of humerus
Adduct and internally rotate shoulder	Teres major	Posterior surface of scapula	Intertubercular sulcus of humerus
Externally rotate shoulder	Teres minor (part of rotator cuff)	Lateral border of dorsal scapular surface	Greater tubercle of humerus

The rest of the shoulder muscles originate on the scapula. The anatomical and ligamental structure of the shoulder joint and the arrangements of the muscles covering it, allows the arm to carry out different types of movements. The deltoid, the thick muscle that creates the rounded lines of the shoulder is the major abductor of the arm, but it also facilitates flexing and medial rotation, as well as extension and lateral rotation. The subscapularis originates on the anterior scapula and medially rotates the arm. Named for their locations, the supraspinatus (superior to the spine of the scapula) and the infraspinatus (inferior to the spine of the scapula) abduct the arm, and laterally rotate the arm, respectively. The thick and flat teres major is inferior to the teres minor and extends the arm, and assists in adduction and medial rotation of it. The long teres minor laterally rotates and extends the arm. Finally, the coracobrachialis flexes and adducts the arm.

The tendons of the deep subscapularis, supraspinatus, infraspinatus, and teres minor connect the scapula to the humerus, forming the rotator cuff (musculotendinous cuff), the circle of tendons around the shoulder joint. When baseball pitchers undergo shoulder surgery it is usually on the rotator cuff, which becomes pinched and inflamed, and may tear away from the bone due to the repetitive motion of bring the arm overhead to throw a fast pitch.

Muscles That Move the Forearm at the Elbow Joint

The forearm, made of the radius and ulna bones, has four main types of action at the hinge of the elbow joint: flexion, extension, pronation, and supination. The forearm flexors include the biceps brachii, brachialis, and brachioradialis. The extensors are the triceps brachii and anconeus. The pronators are the pronator teres and the pronator quadratus, and the supinator is the only one that turns the forearm anteriorly. When the forearm faces anteriorly, it is supinated. When the forearm faces posteriorly, it is pronated.

The biceps brachii, brachialis, and brachioradialis flex the forearm. The two-headed biceps brachii crosses the shoulder and elbow joints to flex the forearm, also taking part in supinating the forearm at the radioulnar joints and flexing the arm at the shoulder joint. Deep to the biceps brachii, the brachialis provides additional power in flexing the forearm. Finally, the brachioradialis can flex the forearm quickly or help lift a load slowly. These muscles and their associated blood vessels and nerves form the anterior compartment of the arm (anterior flexor compartment of the arm) (Figure 11.5.4 and Figure 11.5.5).

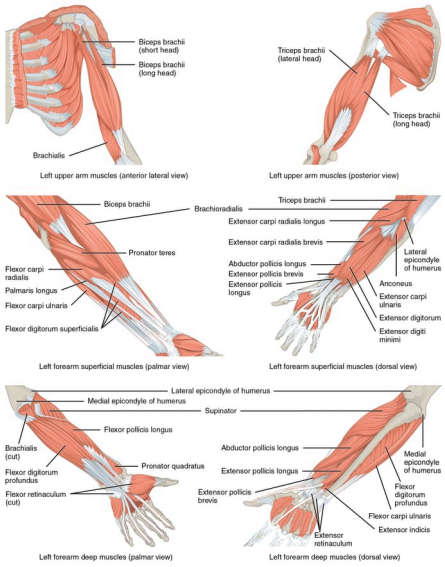


Figure 11.5.3: Anterior, posterior, and lateral diagrams of upper-arm and forearm musculature, comparing superficial layers such as the biceps brachii, triceps brachii, and flexor–extensor groups with deeper muscles including pronator teres, flexor digitorum profundus, and the supinator. (CC BY 4.0 ; via Muscles of the Pectoral Girdle and Upper Limbs). Alternate text description of the Figure 11.5.3.

Table 11.5.3: Muscles that Move the Forearm at the Elbow Joint

Action (Movement)	Prime Mover	Origin	Insertion
	Anterior Muscles (Flexion)		
• Flexion of elbow joint • Pronation of radioulnar joint • Flexion of shoulder joint	Biceps brachii	Coracoid process; tubercle above glenoid cavity	Radial tuberosity
Elbow flexion	Brachialis	Front of distal humerus	Coronoid process of ulna
Assists in elbow flexion (synergist)	Brachioradialis	Lateral supracondylar ridge at distal end of humerus	Base of styloid process of radius
	Posterior Muscles (Extension)		
Assists in extending elbow joint	Anconeus	Lateral epicondyle of humerus	Lateral aspect of olecranon process of ulna
Extends elbow and shoulder	Triceps brachii	Infraglenoid tubercle of scapula; posterior shaft of humerus; posterior humeral shaft distal to the radial groove	Olecranon process of ulna

Muscles That Move the Forearm at the Radioulnar Joints

The pronators are the pronator teres and the pronator quadratus, and the supinator is the only one that turns the forearm anteriorly. When the forearm faces anteriorly, it is supinated. When the forearm faces posteriorly, it is pronated.

Table 11.5.4: Muscles that Move the Forearm at the Radioulnar Joint

Action (Movement)	Prime Mover	Origin	Insertion
	Anterior Muscles (Pronation)		
Assists in turning hand palm posterior (pronation of radioulnar joint)	Pronator quadratus	Distal portion of anterior ulnar shaft	Distal surface of anterior radius
Turns hand palm posterior (pronation of radioulnar joint)	Pronator teres	Medial epicondyle of humerus; coronoid process of ulna	Lateral radius
	Posterior Muscles (Supination)		
Turns hand palm anterior (supinator of radioulnar joint)	Supinator	Lateral epicondyle of humerus; proximal ulna	Proximal end of radius

Muscles of the Arm That Move the Wrists, Hands, and Fingers

Wrist, hand, and finger movements are facilitated by two groups of muscles. The forearm is the origin of the extrinsic muscles of the hand. The palm is the origin of the intrinsic muscles of the hand.

The muscles in the anterior compartment of the forearm (anterior flexor compartment of the forearm) originate on the humerus and insert onto different parts of the hand. These make up the bulk of the forearm. From lateral to medial, the superficial anterior compartment of the forearm includes the flexor carpi radialis, palmaris longus, flexor carpi ulnaris, and flexor digitorum superficialis. The flexor digitorum superficialis flexes the hand as well as the digits at the knuckles, which allows for rapid finger movements, as in typing or playing a musical instrument. However, poor ergonomics can irritate the tendons of these muscles as they slide back and forth with the carpal tunnel of the anterior wrist and pinch the median nerve, which also travels through the tunnel, causing Carpal Tunnel Syndrome. The deep anterior compartment produces flexion and bends fingers to make a fist. These are the flexor pollicis longus and the flexor digitorum profundus.

The muscles in the superficial posterior compartment of the forearm (superficial posterior extensor compartment of the forearm) originate on the humerus. These are the extensor radialis longus, extensor carpi radialis brevis, extensor digitorum, extensor digiti minimi, and the extensor carpi ulnaris.

The muscles of the deep posterior compartment of the forearm (deep posterior extensor compartment of the forearm) originate on the radius and ulna. These include the abductor pollicis longus, extensor pollicis brevis, extensor pollicis longus, and extensor indicis.

Table 11.5.5: Muscles That Move the Wrists, Hands, and Fingers

Action (Movement)	Prime Mover	Origin	Insertion
Assists in bending hand up toward shoulder; tilts hand to side away from body; stabilizes wrist	Flexor carpi ulnaris	Medial epicondyle of humerus; olecranon process; posterior surface of ulna	Pisiform bone; hamate bone; base of fifth metacarpal
Flexes (bends) wrist toward body; tilts hand to side away from body	Flexor carpi radialis	Medial epicondyle of humerus	Base of second and third metacarpals
Flexes (bends) fingers to make fist	Flexor digitorum superficialis	Medial epicondyle of humerus; coronoid process of ulna; shaft of radius	Middle phalanges of fingers 2 - 5
Assists in bending hand up toward shoulder	Palmaris longus	Medical epicondyle of humerus	Palmar aponeurosis; skin and fascia of palm
	Deep Anterior Compartment of Forearm		
Flexes (bends) fingers to make a fist; also bends wrist toward body	Flexor digitorum profundus	Coronoid process; anteromedial surface of ulna; interosseous membrane	Distal phalanges of fingers 2 - 5

Action (Movement)	Prime Mover	Origin	Insertion
Flexes (bends) tip of thumb	Flexor pollicus longus	Anterior surface of radius; interosseous membrane	Distal phalanx of thumb
Assists extensor radialis longus in extending and abducting wrist; also stabilizes hand during finger flexion	Extensor carpi radialis brevis	Lateral epicondyle of humerus	Base of third metacarpal
Straightens wrist away from body; tilts hand to side toward body	Extensor carpi ulnaris	Lateral epicondyle of humerus; posterior border of ulna	Base of fifth metacarpal
Extends finger 5 (little finger)	Extensor digiti minimi	Lateral epicondyle of humerus	Extensor expansion; distal phalanx of finger 5 (little finger)
Opens fingers and moves them sideways away from the body	Extensor digitorum	Lateral epicondyle of humerus	Extensor expansions; distal phalanges of fingers
Straightens wrist away from body	Extensor radialis longus	Lateral supracondylar ridge of humerus	Base of second metacarpal
Moves thumb sideways toward body; extends thumb; moves hand sideways toward body	Abductor pollicis longus	Posterior surface of radius and ulna; interosseous membrane	Base of first metacarpal; trapezium
Extends finger 2 (index finger); straightens wrist away from body	Extensor indicis	Posterior surface of distal ulna; interosseous membrane	Tendon of extensor digitorum of finger 2 (index finger)
Extends thumb	Extensor pollicis brevis	Dorsal shaft of radius and ulna; interosseous membrane	Base of proximal phalanx of thumb
Extends thumb	Extensor pollicis longus	Dorsal shaft of radius and ulna; interosseous membrane	Base of distal phalanx of thumb

The tendons of the forearm muscles attach to the wrist and extend into the hand. Fibrous bands called retinacula sheath the tendons at the wrist. The flexor retinaculum extends over the palmar surface of the hand while the extensor retinaculum extends over the dorsal surface of the hand.

Intrinsic Muscles of the Hand

The intrinsic muscles of the hand both originate and insert within it. These muscles allow your fingers to also make precise movements for actions, such as typing or writing. These muscles are divided into three groups. The thenar muscles are on the radial aspect of the palm. The hypothenar muscles are on the medial aspect of the palm, and the intermediate muscles are midpalmar.

The thenar muscles include the abductor pollicis brevis, opponens pollicis, flexor pollicis brevis, and the adductor pollicis. These muscles form the thenar eminence, the rounded contour of the base of the thumb, and all act on the thumb. The movements of the thumb play an integral role in most precise movements of the hand.

The hypothenar muscles include the abductor digiti minimi, flexor digiti minimi brevis, and the opponens digiti minimi. These muscles form the hypothenar eminence, the rounded contour of the little finger, and as such, they all act on the little finger. Finally, the intermediate muscles act on all the fingers and include the lumbrical, the palmar interossei, and the dorsal interossei.

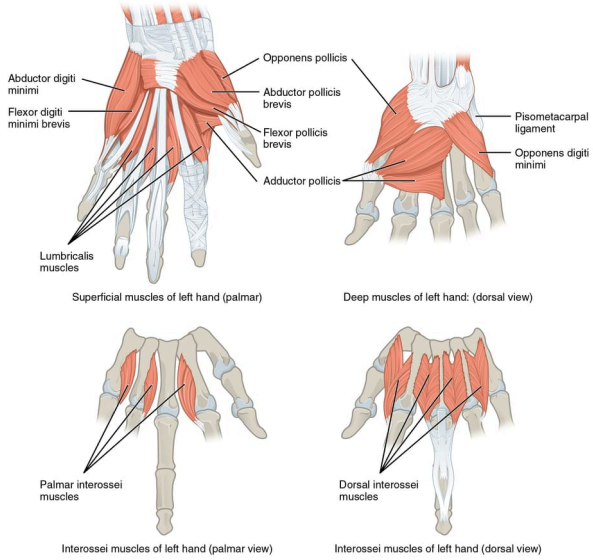


Figure 11.5.4: The intrinsic muscles of the hand both originate and insert within the hand. These muscles provide the fine motor control of the fingers by flexing, extending, abducting, and adducting the more distal finger and thumb segments. (CC BY 4.0 ; via Muscles of the Pectoral Girdle and Upper Limbs). Alternate text description of the Figure 11.5.4.

Table 11.5.6: Intrinsic Muscles of the Hand

Movement	Prime mover	Origin	Insertion
Abduction (Moves thumb toward body)	Abductor pollicis brevis	Flexor retinaculum; and nearby carpals	Lateral base of proximal phalanx of thumb
Opposition (Moves thumb across palm to touch other fingers)	Opponens pollicis	Flexor retinaculum; trapezium	Anterior of first metacarpal
Flexion (Flexes thumb)	Flexor pollicis brevis	Flexor retinaculum; trapezium	Lateral base of proximal phalanx of thumb
Adduction (Moves thumb away from body)	Adductor pollicis	Capitate bone; bases of metacarpals 2–4; front of metacarpal 3	Medial base of proximal phalanx of thumb
Adduction (Moves little finger toward bod	Abductor digiti minimi	Pisiform bone	Medial side of proximal phalanx of little finger
(Flexion) Flexes little finger	Flexor digiti minimi brevis	Hamate bone; flexor retinaculum	Medial side of proximal phalanx of little finger
Opposition (Moves little finger across palm to touch thumb)	Opponens digiti minimi	Hamate bone; flexor retinaculum	Medial side of fifth metacarpal
Flexion (Flexes each finger at metacarpo-phalangeal joints; extends each finger at interphalangeal joints)	Lumbricals	Palm (lateral sides of tendons in flexor digitorum profundus)	Fingers 2–5 (lateral edges of extensional expansions on first phalanges)

Movement	Prime mover	Origin	Insertion
Adducts and flexes each finger at metacarpo-phalangeal joints; extends each finger at interphalangeal joints	Palmar interossei	Side of each metacarpal that faces metacarpal 3 (absent from metacarpal 3)	Extensor expansion on first phalanx of each finger (except finger 3) on side facing finger 3
Abducts and flexes the three middle fingers at metacarpo-phalangeal joints; extends the three middle fingers at interphalangeal joints	Dorsal interossei	Sides of metacarpals	Both sides of finger 3; for each other finger, extensor expansion over first phalanx on side opposite finger 3

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11.6: Appendicular Muscles of the Pelvic Girdle and Lower Limbs

Overview of Pelvic Girdle

The appendicular muscles of the lower body position and stabilize the pelvic girdle, which serves as a foundation for the lower limbs. Comparatively, there is much more movement at the pectoral girdle than at the pelvic girdle. There is very little movement of the pelvic girdle because of its connection with the sacrum at the base of the axial skeleton. The pelvic girdle is less range of motion because it was designed to stabilize and support the body.

Muscles of the Thigh

What would happen if the pelvic girdle, which attaches the lower limbs to the torso, were capable of the same range of motion as the pectoral girdle? For one thing, walking would expend more energy if the heads of the femurs were not secured in the acetabula of the pelvis. The body's center of gravity is in the area of the pelvis. If the center of gravity were not to remain fixed, standing up would be difficult as well. Therefore, what the leg muscles lack in range of motion and versatility, they make up for in size and power, facilitating the body's stabilization, posture, and movement.

Gluteal Region Muscles That Move the Femur

Most muscles that insert on the femur (the thigh bone) and move it, originate on the pelvic girdle. The psoas major and iliacus make up the iliopsoas group. Some of the largest and most powerful muscles in the body are the gluteal muscles or gluteal group. The gluteus maximus is the largest; deep to the gluteus maximus is the gluteus medius, and deep to the gluteus medius is the gluteus minimus, the smallest of the trio (Figure 11.6.1 and Figure 11.6.2).

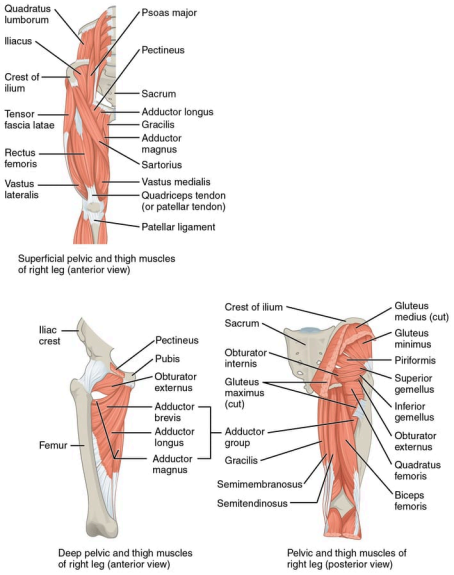


Figure 11.6.1: Comparative anterior and posterior illustrations of the right pelvic and thigh regions, highlighting superficial and deep muscles including the iliacus, psoas major, quadriceps group, adductors, gluteal muscles, and hamstring group. (CC BY 4.0; via Appendicular Muscles of the Pelvic Girdle and Lower Limbs). Alternate text description of the Figure 11.6.1.

Table 11.6.1 : Muscles that Move the Hip Joint

Action (Movement)	Prime Mover	Origin	Insertion
Flexes hip	Iliacus	Iliac fossa; iliac crest; lateral sacrum	Lesser trochanter of femur

Action (Movement)	Prime Mover	Origin	Insertion
Flexes hip	Psoas major	Lumbar vertebrae (L_1 - L_5); thoracic vertebrae (T_{12})	Lesser trochanter of femur
Extend and laterally rotates hip	Gluteus maximus	Dorsal ilium; sacrum; coccyx	Gluteal tuberosity of femur; iliotibial tract
Abducts and medially rotates hip	Gluteus medius	Lateral surface of ilium	Greater trochanter of femur
Abducts and medially rotates hip	Gluteus minimus	External surface of ilium	Greater trochanter of femur
Abducts and medially rotates hip	Tensor fascia lata	Anterior aspect of iliac crest; anterior superior iliac spine	Iliotibial tract
Laterally rotates hip; maintains posture by stabilizing hip joint	Inferior gemellus	Ischial tuberosity	Greater trochanter of femur
Laterally rotates hip; maintains posture by stabilizing hip joint	Obturator externus	Outer surfaces of obturator membrane, pubis, and ischium; margins of obturator foramen	Trochanteric fossa of posterior femur
Laterally rotates hip; maintains posture by stabilizing hip joint	Obturator internus	Inner surface of obturator membrane; greater sciatic notch; margins of obturator foramen	Greater trochanter in front of piriformis
Laterally rotates hip; maintains posture by stabilizing hip joint	Piriformis	Anterolateral surface of sacrum	Greater trochanter of femur
Laterally rotates hip; maintains posture by stabilizing hip joint	Quadratus femoris	Ischial tuberosity	Trochanteric crest of femur
Laterally rotates hip; maintains posture by stabilizing hip joint	Superior gemellus	Ischial spine	Greater trochanter of femur
Adducts and flexes hip	Adductor brevis	Body of pubis; inferior ramus of pubis	Linea aspera above adductor longus
Adducts and flexes hip	Adductor longus	Pubis near pubic symphysis	Linea aspera
Adducts hip Posterior fibers: extends and laterally rotates hip Anterior fibers: flex hip	Adductor magnus	Ischial rami; pubic rami; ischial tuberosity	Linea aspera; adductor tubercle of femur
Adducts and flexes hip; flexes knee	Gracilis	Inferior ramus; body of pubis; ischial ramus	Medial surface of tibia
Adducts and flexes hip	Pectineus	Pectineal line of pubis	Lesser trochanter to linea aspera of posterior aspect of femur

The tensor fascia latae is a thick, squarish muscle in the superior aspect of the lateral thigh. It acts as a synergist of the gluteus medius and iliopsoas in flexing and abducting the thigh. It also helps stabilize the lateral aspect of the knee by pulling on the iliotibial tract (band), making it taut. Deep to the gluteus maximus, the piriformis, obturator internus, obturator externus, superior gemellus, inferior gemellus, and quadratus femoris laterally rotate the femur at the hip.

The adductor longus, adductor brevis, and adductor magnus can both medially and laterally rotate the thigh depending on the placement of the foot. The adductor longus flexes the thigh, whereas the adductor magnus extends it. The pectineus adducts and flexes the femur at the hip as well. The pectineus is located in the femoral triangle, which is formed at the junction between the

hip and the leg and also includes the femoral nerve, the femoral artery, the femoral vein, and the deep inguinal lymph nodes.

Thigh Muscles That Move the Femur, Tibia, and Fibula

Deep fascia in the thigh separates it into medial, anterior, and posterior compartments. The muscles in the medial compartment of the thigh are responsible for adducting the femur at the hip. Along with the adductor longus, adductor brevis, adductor magnus, and pectineus, the strap-like gracilis adducts the thigh in addition to flexing the leg at the knee.

Table 11.6.2: Thigh Muscles That Move the Femur, Tibia, and Fibula

Action (Movement)	Prime Mover	Origin	Insertion
Moves lower leg out in front of body, as when kicking; assists in raising knee	Rectus femoris	Anterior inferior iliac spine; superior margin of acetabulum	Patella; tibial tuberosity
Moves back of lower legs up and back toward the buttocks, as when kneeling; assists in moving thigh diagonally upward and outward as when mounting a bike	Sartorius	Anterior superior iliac spine	Medial aspect of proximal tibia
Moves lower leg out in front of body, as when kicking	Vastus intermedius	Proximal femur shaft	Patella; tibial tuberosity
Moves lower leg out in front of body, as when kicking	Vastus lateralis	Greater trochanter; intertrochanteric line; linea apera	Patella; tibial tuberosity
Moves lower leg out in front of body, as when kicking	Vastus medialis	Linea aspera; intertrochanteric line	Patella; tibial tuberosity
Moves back of lower legs up and back toward the buttocks, as when kneeling; moves thigh down and back; twists the thigh (and lower leg) outward	Biceps femoris	Ischial tuberosity; linea aspera; distal femur	Head of fibula; lateral condyle of tibia
Moves back of lower legs up and back toward the buttocks, as when kneeling; moves thigh down and back; twists the thigh (and lower leg) outward	Semimembranosus	Ischial tuberosity	Medial condyle of tibia; lateral condyle of femur
Moves back of lower legs up and back toward the buttocks, as when kneeling; moves thigh down and back; twists the thigh (and lower leg) outward	Semitendinosus	Ischial tuberosity	Upper tibial shaft

The muscles of the anterior compartment of the thigh flex the thigh and extend the leg. This compartment contains the quadriceps femoris group, which actually comprises four muscles that extend and stabilize the knee. The rectus femoris is on the anterior aspect of the thigh, the vastus lateralis is on the lateral aspect of the thigh, the vastus medialis is on the medial aspect of the thigh, and the vastus intermedius is between the vastus lateralis and vastus medialis and deep to the rectus femoris. The tendon common to all four is the quadriceps tendon (patellar tendon), which inserts into the patella and continues below it as the patellar ligament. The patellar ligament attaches to the tibial tuberosity. In addition to the quadriceps femoris, the sartorius is a band-like muscle that extends from the anterior superior iliac spine to the medial side of the proximal tibia. This versatile muscle flexes the leg at the knee and flexes, abducts, and laterally rotates the leg at the hip. This muscle allows us to sit cross-legged.

The posterior compartment of the thigh includes muscles that flex the leg and extend the thigh. The three long muscles on the back of the knee are the hamstring group, which flexes the knee. These are the biceps femoris, semitendinosus, and semimembranosus. The tendons of these muscles form the popliteal fossa, the diamond-shaped space at the back of the knee.

Muscles That Move the Feet and Toes

Similar to the thigh muscles, the muscles of the leg are divided by deep fascia into compartments, although the leg has three: anterior, lateral, and posterior (Figure 11.6.2).

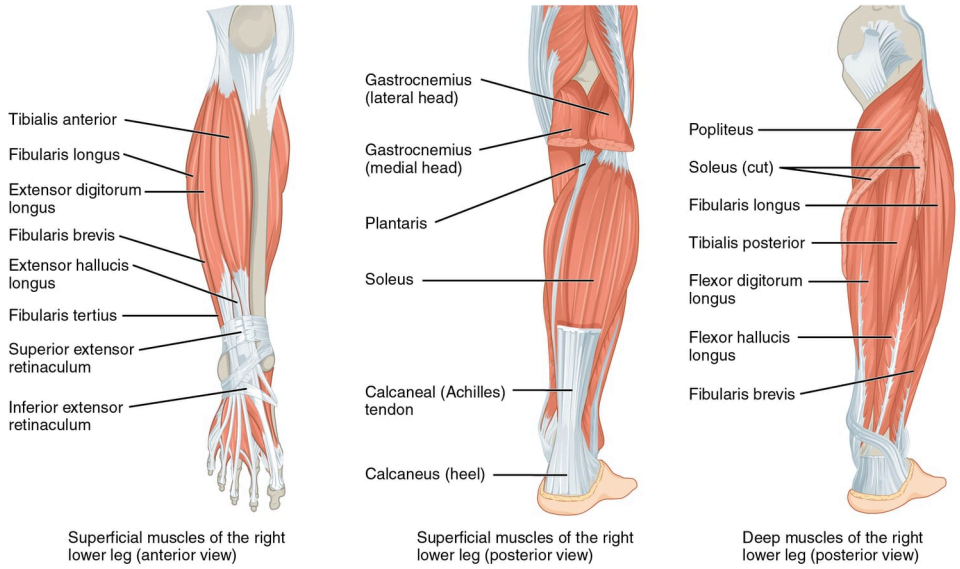


Figure 11.6.2: The muscles of the anterior compartment of the lower leg are generally responsible for dorsiflexion, and the muscles of the posterior compartment of the lower leg are generally responsible for plantar flexion. The lateral and medial muscles in both compartments invert, evert, and rotate the foot. (CC BY 4.0; via Appendicular Muscles of the Pelvic Girdle and Lower Limbs). Alternate text description of the Figure 11.6.2.

Table 11.6.3: Muscles That Move the Feet and Toes (includes Intrinsic Muscles in the Foot)

Action (Movement)	Prime Mover	Origin	Insertion
	Anterior Compartment of Leg		
Extends toes 2-4; dorsiflexion of ankle	Extensor digitorum longus	Lateral condyle of tibia; proximal portion of fibula; interosseous membrane	Middle and distal phalanges of toes 2 - 5
Extends the big toe; dorsiflexion of ankle	Extensor hallucis longus	Anteromedial fibula shaft; interosseous membrane	Distal phalanx hallux (big toe)
Dorsiflexion of ankle; inversion of intertarsal	Tibialis anterior	Lateral condyle and upper tibial shaft; interosseous membrane	Interior surface of medial cuneiform; first metatarsal bone
	Lateral Compartment of Leg		
Eversion of intertarsal; plantarflexion of ankle	Fibularis (peroneus) brevis	Distal fibula shaft	Proximal end of fifth metatarsal
Eversion of intertarsal, plantarflexion of ankle	Fibularis (peroneus) longus	Upper portion of lateral fibula	First metatarsal; medial cuneiform
	Posterior Compartment of Leg: Superficial Muscles		
Plantarflexion of ankle; flexion of knee	Gastrocnemius	Medial and lateral condyles of femur	Posterior calcaneus
Plantarflexion of ankle	Soleus	Superior tibia; fibula; interosseous membrane	Posterior calcaneus
	Posterior Compartment of Leg: Deep Muscles		
Flexion of digits 2-5; plantarflexion of ankle	Flexor digitorum longus	Posterior tibia	Distal phalanges of toes 2 - 5

Action (Movement)	Prime Mover	Origin	Insertion
Flexes big toe; plantarflexion of ankle	Flexor hallucis longus	Midshaft of fibula; interosseous membrane	Distal phalanx of hallux (big toe)
Plantarflexion of ankle; inversion of intertarsal	Tibialis posterior	Superior tibia; fibula; interosseous membrane	Tarsals and metatarsals 2 - 4

The muscles in the anterior compartment of the leg are the tibialis anterior, a long and thick muscle on the lateral surface of the tibia, the extensor hallucis longus, deep under it, and the extensor digitorum longus, lateral to it, all contribute to raising the front of the foot when they contract. The fibularis tertius, a small muscle that originates on the anterior surface of the fibula, is associated with the extensor digitorum longus and sometimes fused to it, but is not present in all people. Thick bands of connective tissue called the superior extensor retinaculum (transverse ligament of the ankle) and the inferior extensor retinaculum, hold the tendons of these muscles in place during dorsiflexion.

The lateral compartment of the leg includes two muscles are the fibularis longus (peroneus longus) and the fibularis brevis (peroneus brevis). The superficial muscles in the posterior compartment of the leg all insert onto the calcaneal tendon (Achilles tendon), a strong tendon that inserts into the calcaneal bone of the ankle. The muscles in this compartment are large and strong and keep humans upright. The most superficial and visible muscle of the calf is the gastrocnemius. Deep to the gastrocnemius is the wide, flat soleus. The plantaris runs obliquely between the two; some people may have two of these muscles, whereas no plantaris is observed in about seven percent of other cadaver dissections. The plantaris tendon is a desirable substitute for the fascia lata in hernia repair, tendon transplants, and repair of ligaments. There are four deep muscles in the posterior compartment of the leg as well: the popliteus, flexor digitorum longus, flexor hallucis longus, and tibialis posterior.

The foot also has intrinsic muscles, which originate and insert within it (similar to the intrinsic muscles of the hand). These muscles primarily provide support for the foot and its arch, and contribute to movements of the toes (Figure 11.6.3). The principal support for the longitudinal arch of the foot is a deep fascia called plantar aponeurosis, which runs from the calcaneus bone to the toes (inflammation of this tissue is the cause of “plantar fasciitis,” which can affect runners). The intrinsic muscles of the foot consist of two groups. The dorsal group includes only one muscle, the extensor digitorum brevis. The second group is the plantar group, which consists of four layers, starting with the most superficial.

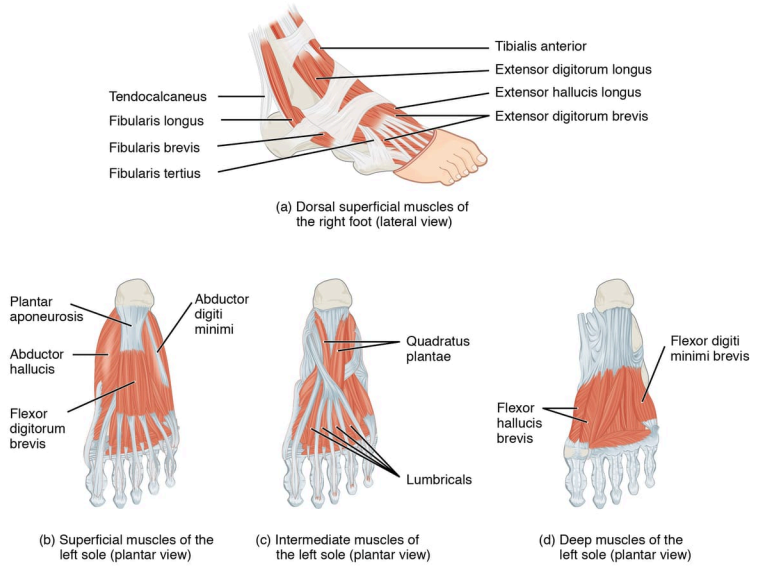


Figure 11.6.3: Lateral, plantar, and layered plantar views illustrating superficial, intermediate, and deep muscles of the foot, including dorsal extensors, plantar flexors, intrinsic sole muscles, and intermuscular structures. (CC BY 4.0; via Appendicular Muscles of the Pelvic Girdle and Lower Limbs). Alternate text description of the Figure 11.6.3.

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11.7: Terms and Definitions

Key Terms

Select to view definitions

Abduct
move away from midline in the sagittal plane

Abductor
moves the bone away from the midline

Abductor digiti minimi
muscle that abducts the little finger

Abductor pollicis brevis
muscle that abducts the thumb

Abductor pollicis longus
muscle that inserts into the first metacarpal

Adductor
moves the bone toward the midline

Adductor brevis
muscle that adducts and medially rotates the thigh

Adductor longus
muscle that adducts, medially rotates, and flexes the thigh

Adductor magnus
muscle with an anterior fascicle that adducts, medially rotates and flexes the thigh, and a posterior fascicle that assists in thigh extension

Adductor pollicis
muscle that adducts the thumb

Agonist
(also, prime mover) muscle whose contraction is responsible for producing a particular motion

Anal triangle
posterior triangle of the perineum that includes the anus

Anconeus
small muscle on the lateral posterior elbow that extends the forearm

Antagonist
muscle that opposes the action of an agonist

Anterior compartment of the arm
(anterior flexor compartment of the arm) the biceps brachii, brachialis, brachioradialis, and their associated blood vessels and nerves

Anterior compartment of the forearm
(anterior flexor compartment of the forearm) deep and superficial muscles that originate on the humerus and insert into the hand

Anterior compartment of the leg
region that includes muscles that dorsiflex the foot

Anterior compartment of the thigh
region that includes muscles that flex the thigh and extend the leg

Anterior scalene
a muscle anterior to the middle scalene

Appendicular
of the arms and legs

Axial
of the trunk and head

Belly
bulky central body of a muscle

Bi
two

Biceps brachii
two-headed muscle that crosses the shoulder and elbow joints to flex the forearm while assisting in supinating it and flexing the arm at the shoulder

Biceps femoris
hamstring muscle

Bipennate
pennate muscle that has fascicles that are located on both sides of the tendon

Brachialis
muscle deep to the biceps brachii that provides power in flexing the forearm.

Brachioradialis
muscle that can flex the forearm quickly or help lift a load slowly

Brevis
short

Buccinator
muscle that compresses the cheek

Calcaneal tendon
(also, Achilles tendon) strong tendon that inserts into the calcaneal bone of the ankle

Caval opening
opening in the diaphragm that allows the inferior vena cava to pass through; foramen for the vena cava

Circular
(also, sphincter) fascicles that are concentrically arranged around an opening

Compressor urethrae
deep perineal muscle in females

Convergent
fascicles that extend over a broad area and converge on a common attachment site

Coracobrachialis
muscle that flexes and adducts the arm

Corrugator supercilii
prime mover of the eyebrows

Deep anterior compartment
flexor pollicis longus, flexor digitorum profundus, and their associated blood vessels and nerves

Deep posterior compartment of the forearm
(deep posterior extensor compartment of the forearm) the abductor pollicis longus, extensor pollicis brevis, extensor pollicis longus, extensor indicis, and their associated blood vessels and nerves

Deep transverse perineal
deep perineal muscle in males

Deglutition
swallowing

Deltoid
shoulder muscle that abducts the arm as well as flexes and medially rotates it, and extends and laterally rotates it

Diaphragm
skeletal muscle that separates the thoracic and abdominal cavities and is dome-shaped at rest

Digastric
muscle that has anterior and posterior bellies and elevates the hyoid bone and larynx when one swallows; it also depresses the mandible

Dorsal group
region that includes the extensor digitorum brevis

Dorsal interossei
muscles that abduct and flex the three middle fingers at the metacarpophalangeal joints and extend them at the interphalangeal joints

Epicranial aponeurosis
(also, galea aponeurosis) flat broad tendon that connects the frontalis and occipitalis

Erector spinae group
large muscle mass of the back; primary extensor of the vertebral column

Extensor
muscle that increases the angle at the joint

Extensor carpi radialis brevis
muscle that extends and abducts the hand at the wrist

Extensor carpi ulnaris
muscle that extends and adducts the hand

Extensor digiti minimi
muscle that extends the little finger

Extensor digitorum
muscle that extends the hand at the wrist and the phalanges

Extensor digitorum brevis
muscle that extends the toes

Extensor digitorum longus
muscle that is lateral to the tibialis anterior

Extensor hallucis longus
muscle that is partly deep to the tibialis anterior and extensor digitorum longus

Extensor indicis
: muscle that inserts onto the tendon of the extensor digitorum of the index finger

Extensor pollicis brevis
: muscle that inserts onto the base of the proximal phalanx of the thumb

Extensor pollicis longus
: muscle that inserts onto the base of the distal phalanx of the thumb

Extensor radialis longus
: muscle that extends and abducts the hand at the wrist

Extensor retinaculum
: band of connective tissue that extends over the dorsal surface of the hand

External intercostal
: superficial intercostal muscles that raise the rib cage

External oblique
: superficial abdominal muscle with fascicles that extend inferiorly and medially

Extrinsic eye muscles
: originate outside the eye and insert onto the outer surface of the white of the eye, and create eyeball movement

Extrinsic muscles of the hand
: muscles that move the wrists, hands, and fingers and originate on the arm

Fascicle
: muscle fibers bundled by perimysium into a unit

Fibularis brevis
: (also, peroneus brevis) muscle that plantar flexes the foot at the ankle and everts it at the intertarsal joints

Fibularis longus
: (also, peroneus longus) muscle that plantar flexes the foot at the ankle and everts it at the intertarsal joints

Fixator
: synergist that assists an agonist by preventing or reducing movement at another joint, thereby stabilizing the origin of the agonist

Flexion
: movement that decreases the angle of a joint

Flexor
: muscle that decreases the angle at the joint

Flexor carpi radialis
: muscle that flexes and abducts the hand at the wrist

Flexor carpi ulnaris
: muscle that flexes and adducts the hand at the wrist

Flexor digiti minimi brevis
: muscle that flexes the little finger

Flexor digitorum longus
: muscle that flexes the four small toes

Flexor digitorum profundus
: muscle that flexes the phalanges of the fingers and the hand at the wrist

Flexor digitorum superficialis
: muscle that flexes the hand and the digits

Flexor hallucis longus
: muscle that flexes the big toe

Flexor pollicis brevis
: muscle that flexes the thumb

Flexor pollicis longus
: muscle that flexes the distal phalanx of the thumb

Fleor retinaculum
: band of connective tissue that extends over the palmar surface of the hand

Frontalis
: front part of the occipitofrontalis muscle

Fusiform
: muscle that has fascicles that are spindle-shaped to create large bellies

Gastrocnemius
: most superficial muscle of the calf

Genioglossus
: muscle that originates on the mandible and allows the tongue to move downward and forward

Geniohyoid
: muscle that depresses the mandible, and raises and pulls the hyoid bone anteriorly

Gluteal group
: muscle group that extends, flexes, rotates, adducts, and abducts the femur

Gluteus maximus
: largest of the gluteus muscles that extends the femur

Gluteus medius
: muscle deep to the gluteus maximus that abducts the femur at the hip

Gluteus minimus
: smallest of the gluteal muscles and deep to the gluteus medius

Gracilis
: muscle that adducts the thigh and flexes the leg at the knee

Hmstring group
: three long muscles on the back of the leg

Hyoglossus
: muscle that originates on the hyoid bone to move the tongue downward and flatten it

Hypothenar
: group of muscles on the medial aspect of the palm

Hypothenar eminence
: rounded contour of muscle at the base of the little finger

Iliacus
: muscle that, along with the psoas major, makes up the iliopsoas

Iliococcygeus
: muscle that makes up the levator ani along with the pubococcygeus

iIiopsoas group
: muscle group consisting of iliacus and psoas major muscles, that flexes the thigh at the hip, rotates it laterally, and flexes the trunk of the body onto the hip

Iliotibial (IT) tract
: muscle that inserts onto the tibia; made up of the gluteus maximus and connective tissues of the tensor fasciae latae

Inferior extensor retinaculum
: cruciate ligament of the ankle

Infraspinatus
: muscle that laterally rotates the arm

Insertion
: end of a skeletal muscle that is attached to the structure (usually a bone) that is moved when the muscle contracts

Intercostal muscles
: muscles that span the spaces between the ribs

Internal intercostal
: muscles the intermediate intercostal muscles that draw the ribs together

Internal oblique
: flat, intermediate abdominal muscle with fascicles that run perpendicular to those of the external oblique

Intrinsic muscles of the hand
: muscles that move the wrists, hands, and fingers and originate in the palm

Lateral compartment of the leg
: region that includes the fibularis (peroneus) longus and the fibularis (peroneus) brevis and their associated blood vessels and nerves

Lateral pterygoid
: muscle that moves the mandible from side to side

Lateralis
: to the outside

Latissimus dorsi
: broad, triangular axial muscle located on the inferior part of the back

Levator ani
: pelvic muscle that resists intra-abdominal pressure and supports the pelvic viscera

Linea alba
: white, fibrous band that runs along the midline of the trunk

Longus
: long

Masseter
: main muscle for chewing that elevates the mandible to close the mouth

Mastication
: chewing

Maximus
: largest

Medial compartment of the thigh
: a region that includes the adductor longus, adductor brevis, adductor magnus, pectineus, gracilis, and their

associated blood vessels and nerves

Medial pterygoid
muscle that moves the mandible from side to side

Medialis
to the inside

Medius
medium

Middle scalene
longest scalene muscle, located between the anterior and posterior scalenes

Minimus
smallest

Multipennate
pennate muscle that has a tendon branching within it

Mylohyoid
muscle that lifts the hyoid bone and helps press the tongue to the top of the mouth

Oblique
at an angle

Obturator externus
muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

Obturator internus
muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

Occipitalis
posterior part of the occipitofrontalis muscle

Occipitofrontalis
muscle that makes up the scalp with a frontal belly and an occipital belly

Omohyoid
muscle that has superior and inferior bellies and depresses the hyoid bone

Opponens digiti minimi
muscle that brings the little finger across the palm to meet the thumb

Opponens pollicis
muscle that moves the thumb across the palm to meet another finger

Orbicularis oculi
circular muscle that closes the eye

Orbicularis oris
circular muscle that moves the lips

Origin
end of a skeletal muscle that is attached to another structure (usually a bone) in a fixed position

Palatoglossus
muscle that originates on the soft palate to elevate the back of the tongue

Palmaris longus
muscle that provides weak flexion of the hand at the wrist

Parallel
fascicles that extend in the same direction as the long axis of the muscle

Patellar ligament
extension of the quadriceps tendon below the patella

Pectineus
muscle that abducts and flexes the femur at the hip

Pectoral girdle
shoulder girdle, made up of the clavicle and scapula

Ppectoralis major
thick, fan-shaped axial muscle that covers much of the superior thorax

Pectoralis minor
muscle that moves the scapula and assists in inhalation

Pelvic diaphragm
muscular sheet that comprises the levator ani and the ischiococcygeus

Pelvic girdle
hips, a foundation for the lower limb

Pennate
fascicles that are arranged differently based on their angles to the tendon

Perineum
diamond-shaped region between the pubic symphysis, coccyx, and ischial tuberosities

Piriformis
muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

Plantar aponeurosis
muscle that supports the longitudinal arch of the foot

Plantar group
four-layered group of intrinsic foot muscles

Plantaris
muscle that runs obliquely between the gastrocnemius and the soleus

Popliteal fossa
diamond-shaped space at the back of the knee

Popliteus
muscle that flexes the leg at the knee and creates the floor of the popliteal fossa

Posterior compartment of the leg
region that includes the superficial gastrocnemius, soleus, and plantaris, and the deep popliteus, flexor digitorum longus, flexor hallucis longus, and tibialis posterior

Posterior compartment of the thigh
region that includes muscles that flex the leg and extend the thigh

Posterior scalene
smallest scalene muscle, located posterior to the middle scalene

Prime mover
(also, agonist) principle muscle involved in an action

Pronator quadratus
pronator that originates on the ulna and inserts on the radius

Pronator teres
pronator that originates on the humerus and inserts on the radius

Psoas major
muscle that, along with the iliacus, makes up the iliopsoas

Quadratus femoris
muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

Quadriceps femoris group
four muscles, that extend and stabilize the knee

Quadriceps tendon
(also, patellar tendon) tendon common to all four quadriceps muscles, inserts into the patella

Rectus
straight

Rectus abdominis
long, linear muscle that extends along the middle of the trunk

Rectus femoris
quadricep muscle on the anterior aspect of the thigh

Rectus sheaths
tissue that makes up the linea alba

Retinacula
fibrous bands that sheath the tendons at the wrist

Rhomboid major
muscle that attaches the vertebral border of the scapula to the spinous process of the thoracic vertebrae

Rhomboid minor
muscle that attaches the vertebral border of the scapula to the spinous process of the thoracic vertebrae

Rotator cuff
(also, musculotendinous cuff) the circle of tendons around the shoulder joint

Sartorius
band-like muscle that flexes, abducts, and laterally rotates the leg at the hip

Scalene muscles
flex, laterally flex, and rotate the head; contribute to deep inhalation

Semimembranosus
hamstring muscle

Semitendinosus
hamstring muscle

Serratus anterior
large and flat muscle that originates on the ribs and inserts onto the scapula

Soleus
wide, flat muscle deep to the gastrocnemius

Splenius
posterior neck muscles; includes the splenius capitis and splenius cervicis

Sternocleidomastoid
major muscle that laterally flexes and rotates the head

Sternohyoid
muscle that depresses the hyoid bone

Sternothyroid
muscle that depresses the larynx's thyroid cartilage

Styloglossus
muscle that originates on the styloid bone, and allows upward and backward motion of the tongue

Stylohyoid
muscle that elevates the hyoid bone posteriorly

Subclavius
muscle that stabilizes the clavicle during movement

Subscapularis
muscle that originates on the anterior scapula and medially rotates the arm

Superficial anterior compartment of the forearm
flexor carpi radialis, palmaris longus, flexor carpi ulnaris, flexor digitorum superficialis, and their associated blood vessels and nerves

Superficial posterior compartment of the forearm
extensor radialis longus, extensor carpi radialis brevis, extensor digitorum, extensor digiti minimi, extensor carpi ulnaris, and their associated blood vessels and nerves

Superior extensor retinaculum
transverse ligament of the ankle

Ssupinator
muscle that moves the palm and forearm anteriorly

Suprahyoid muscles
neck muscles that are superior to the hyoid bone

Supraspinatus
muscle that abducts the arm

Synergist
muscle whose contraction helps a prime mover in an action

Temporalis
muscle that retracts the mandible

Tendinous intersections
three transverse bands of collagen fibers that divide the rectus abdominis into segments

Tensor fascia lata
muscle that flexes and abducts the thigh

Teres major
muscle that extends the arm and assists in adduction and medial rotation of it

Teres minor
muscle that laterally rotates and extends the arm

Thenar
group of muscles on the lateral aspect of the palm

Thenar eminence
rounded contour of muscle at the base of the thumb

Thyrohyoid
muscle that depresses the hyoid bone and elevates the larynx's thyroid cartilage

Tibialis anterior
muscle located on the lateral surface of the tibia

Tibialis posterior
muscle that plantar flexes and inverts the foot

Transversus abdominis
deep layer of the abdomen that has fascicles arranged transversely around the abdomen

Trapezius
muscle that stabilizes the upper part of the back

Tri
three

Triceps brachii
three-headed muscle that extends the forearm

Unipennate
pennate muscle that has fascicles located on one side of the tendon

Vastus intermedius
quadricep muscle that is between the vastus lateralis and vastus medialis and is deep to the rectus femoris

Vastus lateralis
quadricep muscle on the lateral aspect of the thigh

Vastus medialis
quadricep muscle on the medial aspect of the thigh

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11.8: Chapter Review Questions

Multiple-Choice Section

- Use the end-of-chapter multiple-choice section as a regular self-check tool, not just before exams.
- Read each item carefully, think about what is really being tested (concept, definition, application, or calculation), and choose the option (A, B, C, or D) that best reflects what you have learned in this chapter.
  - After you read through the chapter, attempt all items without looking at your notes; then return to the chapter to review any you missed or felt unsure about.
  - Afterward, explain to yourself why the correct option is right and why the others are not. Finally, repeat the multiple-choice section a few days later to see what you truly remember and understand.
- Students who consistently use these prompts in this way typically perform better across the course because they turn reading into active practice.

1. Which characteristic is unique to most muscles of facial expression compared with other skeletal muscles?
   A. They all originate from the scalp musculature.
   B. They insert onto cartilage around the face.
   C. They insert only onto the facial bones.
   D. They insert into the skin of the face.
2. Which type of muscle acts to assist the agonist in producing a specific movement?
   A. Synergist
   B. Fixator
   C. Insertion
   D. Antagonist
3. During flexion at a typical synovial joint, which of the following best describes the change in joint position?
   A. The angle between the articulating bones is increased.
   B. The angle between the articulating bones is decreased.
   C. The bone moves away from the body's midline regardless of angle.
   D. The bone moves toward the body's midline regardless of angle.
4. During contraction of a skeletal muscle acting on a joint, which structure is usually displaced the least?
   A. The origin
   B. The insertion
   C. The ligaments
   D. The joint capsule
5. Which named muscle is a classic example of a convergent fascicle arrangement?
   A. Biceps brachii
   B. Gluteus maximus
   C. Pectoralis major
   D. Rectus femoris
6. Which description best characterizes the architecture of a bipennate muscle?
   A. Muscle fibers insert into a central tendon from one side only.
   B. Muscle fibers insert into a central tendon from both sides at an angle.
   C. Muscle fibers insert into a central tendon from multiple directions around it.
   D. Muscle fibers insert along the entire length of bone on one side only.
7. What can be predicted from the relative positions of a muscle's origin and insertion across a joint?
   A. The muscle's specific action at that joint
   B. The exact maximum force the muscle can generate
   C. The precise name assigned to the muscle
   D. The total body mass the muscle can lift
8. The temporalis muscle is located primarily in which region of the head?
   A. On the forehead, over the frontal bone
   B. In the anterior neck, below the mandible
   C. On the lateral side of the skull, above the zygomatic arch

D. On the chin, over the mental protuberance

9. Which term is most likely to appear in the name of a muscle that moves a limb away from the midline of the body?
   A. Flexor
   B. Adductor
   C. Extensor
   D. Abductor
10. Which muscle is considered the primary agonist for flexion of the head and neck when acting bilaterally?
   A. Occipitofrontalis
   B. Corrugator supercilii
   C. Sternocleidomastoid
   D. Masseter
11. What is the primary action of the masseter muscle?
   A. Swallowing
   B. Chewing by elevating the mandible
   C. Moving the lips during speech
   D. Closing the eyelids
12. The names of the extrinsic muscles of the tongue most commonly share which ending?
   A. Glottis
   B. Glossus
   C. Gluteus
   D. Hyoid

13. What is the primary function of the erector spinae muscle group?
   A. Producing powerful movements of the arms
   B. Stabilizing the pelvic girdle during gait
   C. Maintaining upright posture and extending the vertebral column
   D. Rotating the vertebral column only
14. Which of the following muscles is not part of the anterior abdominal wall musculature?
   A. Quadratus lumborum
   B. Rectus abdominis
   C. Internal oblique
   D. External oblique
15. The linea alba is best described as which of the following?
   A. A small paired muscle that compresses abdominal organs
   B. A midline band of connective tissue separating the right and left rectus abdominis
   C. A long band of collagen fibers that connects the iliac crest to the lateral knee
   D. Another name for the tendinous inscriptions within the rectus abdominis
16. The rhomboid major and minor muscles lie deep to which superficial back muscle?
   A. Rectus abdominis
   B. Scalene muscles
   C. Trapezius
   D. Latissimus dorsi
17. Which muscle is the principal extensor of the forearm at the elbow joint?
   A. Biceps brachii
   B. Triceps brachii
   C. Brachialis
   D. Deltoid
18. Most wrist flexor muscles share which proximal origin?
   A. Lateral epicondyle of the humerus
   B. Medial epicondyle of the humerus
   C. Carpal bones of the wrist
   D. Deltoid tuberosity of the humerus
19. Which combination of muscle groups is primarily responsible for stabilizing the pectoral girdle on the thoracic cage?
   A. Axial and scapular muscles
   B. Axial muscles only
   C. Appendicular muscles only
   D. Axial and appendicular muscles
20. The large muscle group that anchors the lower limb to the pelvic girdle and produces powerful extension at the hip joint is

which group?
A. Gluteal group
B. Obturator group
C. Adductor group
D. Abductor group

21. Which muscle is best known for enabling the cross-legged sitting position due to its combined actions at the hip and knee?
A. Gluteus maximus
B. Piriformis
C. Gracilis
D. Sartorius

22. Which of the following is generally considered the largest superficial muscle in the posterior compartment of the lower leg?
A. Soleus
B. Gastrocnemius
C. Tibialis anterior
D. Tibialis posterior

23. The vastus intermedius muscle of the quadriceps femoris group lies deep to which muscle?
A. Biceps femoris
B. Rectus femoris
C. Vastus medialis
D. Vastus lateralis

24. Which statement correctly compares pennate and parallel muscle arrangements in terms of force production and range of motion?
A. Pennate muscles produce less force and greater range of motion than parallel muscles.
B. Parallel muscles produce more force but less range of motion than pennate muscles.
C. Pennate muscles produce greater force but have less range of motion than parallel muscles.
D. Parallel and pennate muscles produce equal force and equal range of motion.

25. A circular (sphincter) muscle fascicle arrangement is especially suited to which functional role?
A. Generating maximal force over a short distance
B. Stabilizing a single large joint
C. Opening and closing body orifices
D. Producing very fine, precise finger movements

26. When the sternocleidomastoid muscles on the right and left sides contract simultaneously, the primary movement produced is which of the following?
A. Rotation of the head to the same side
B. Lateral flexion of the neck to the same side
C. Flexion of the neck and head anteriorly
D. Extension of the neck and head posteriorly

27. Which muscle is a primary agonist for abduction of the arm at the glenohumeral (shoulder) joint from 15 to about 90 degrees?
A. Supraspinatus
B. Pectoralis major
C. Deltoid
D. Latissimus dorsi

28. Which of the following muscle pairs is correctly matched as antagonist and agonist at the same joint?
A. Biceps brachii and brachialis during elbow flexion
B. Quadriceps femoris and tibialis anterior during knee extension
C. Triceps brachii and biceps brachii during elbow extension
D. Gastrocnemius and soleus during plantar flexion

29. Contraction of both the rectus abdominis and the external oblique muscles on both sides of the body at the same time primarily results in which movement?
A. Trunk extension
B. Trunk flexion
C. Lateral flexion of the spine to one side
D. Pure rotation of the trunk without flexion

30. Which muscle group acts as a powerful antagonist to the hamstring muscles during extension of the knee?
A. Gastrocnemius–soleus complex
B. Quadriceps femoris
C. Gluteal group
D. Adductor group of the thigh

31. Which muscle is most directly responsible for dorsiflexion of the foot at the ankle joint during the swing phase of gait?
    A. Gastrocnemius
    B. Soleus
    C. Tibialis anterior
    D. Fibularis (peroneus) longus
32. Which head and neck movement would be most impaired if both sternocleidomastoid muscles were paralyzed?
    A. Extension of the head
    B. Lateral flexion of the neck to one side
    C. Flexion of the neck so the chin moves toward the chest
    D. Elevation of the scapula
33. Which of the following best explains why the gluteus medius is clinically important in maintaining a normal gait pattern?
    A. It extends the hip during push-off.
    B. It flexes the hip during swing phase.
    C. It abducts the thigh and stabilizes the pelvis in the frontal plane during single-leg stance.
    D. It laterally rotates the thigh to initiate walking.

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11.9: Applied Thinking Self-Check

Challenge Yourself

a. Critical thinking is essential in a time of endless information and AI, helping students evolve from passive memorizers into active learners.
b. How to answer (per question):
   - Direct answer: 1 clear sentence that answers the prompt.
   - Mechanism: 3–5 short sentences linking structure to function (cause → effect).
   - Example or small diagram: 1 sentence or a simple labeled sketch.
   - Assumption (if needed): 1 short phrase (e.g., “Assume right limb”).
c. Length: 100–150 words. Short sentences are fine. Use precise terms.
d. Sentence starters you can use:
   - The key idea is … because …
   - This structure allows … by …
   - If … happens, then … because …
   - For example, …

Word bank (use as needed)

fascicle, parallel, fusiform, convergent, unipennate, bipennate, multipennate, circular, origin, insertion, agonist, antagonist, synergist, fixator, lever, fulcrum, moment arm, torque, naming (location, shape, size, fiber direction, heads, attachments, action), axial, appendicular, suprahyoid, infrahyoid, sternocleidomastoid, facial nerve (CN VII), aponeurosis, linea alba, diaphragm, pelvic floor, rotator cuff (supraspinatus, infraspinatus, teres minor, subscapularis), scapulohumeral rhythm, hamstrings, quadriceps, patella.

Questions

1. What effect does fascicle arrangement have on a muscle’s action?
   - Include: force vs range/speed trade-off (pennate = more force; parallel/fusiform = more range/speed) and one example (e.g., deltoid vs sartorius).
2. Movements of the body occur at joints. Describe how muscles are arranged around joints.
   - Include: agonist–antagonist pairs, synergists, fixators; how crossing a joint and line of pull determine action.
3. Explain how a synergist assists an agonist by being a fixator.
   - Include: stabilizing origin/nearby bone to improve the prime mover’s line of pull; example (scapular stabilizers helping biceps curl)
4. Why are the muscles of the face different from typical skeletal muscle?
   - Include: many insert into skin (not bone) to move skin for expression; innervation by facial nerve (CN VII); example (orbicularis oris closes lips).
5. What are some similarities and differences between the diaphragm and the pelvic diaphragm?
   - Include: both form muscular floors; diaphragm = breathing (inspiration), pelvic diaphragm = organ support/continence; different actions/innervation and clinical roles.
6. The tendons of which muscles form the rotator cuff? Why is the rotator cuff important?
   - Include: SITS (supraspinatus, infraspinatus, teres minor, subscapularis); cuff compresses/stabilizes the humeral head and guides rotation; common injury risk.
7. Which muscles form the hamstrings? How do they function together?
   - Include: biceps femoris (long head), semitendinosus, semimembranosus; hip extension + knee flexion; role in gait and deceleration.
8. Which muscles form the quadriceps? How do they function together?
   - Include: rectus femoris, vastus lateralis, vastus medialis, vastus intermedius; knee extension (rectus also flexes hip); patella improves moment arm.

9. How does lever class and moment arm affect muscle performance at a joint?
    - Include: bones as levers, joint as fulcrum, tendon as effort; third-class levers favor speed/range, second-class favor force; example (biceps curl vs heel raise).

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11.10: Alternative Text Descriptions

Figure 11.1.1: Prime Movers and Synergists

This image shows elbow flexion during a lifting movement. Two views of the arm are presented.

In the first view, the biceps brachii is labeled as the prime mover, and the brachioradialis is labeled as a synergist. Arrows within the upper arm indicate the direction of muscle action during flexion.

In the second view, the biceps brachii is shown dissected or removed from the surface to reveal deeper structures. In this view, the brachialis is labeled as a synergist, and the brachioradialis is also labeled. An arrow indicates muscle action contributing to elbow flexion.

The instructional purpose of the image is to show that multiple muscles work together during elbow flexion, with the biceps brachii serving as the main agonist and the brachialis and brachioradialis assisting as synergists.

Figure 11.1.2: Muscle Shapes and Fiber Alignment

This image illustrates common skeletal muscle fascicle arrangements using a central human muscular figure and multiple labeled examples positioned around the body. Arrows connect each example muscle to its anatomical location.

At the center is a full-body anterior view of a human muscular system with selected regions outlined to indicate example locations. Surrounding the central figure are detailed muscle drawings that demonstrate specific fascicle patterns.

At the top of the figure, a circular muscle labeled orbicularis oris surrounds the mouth. The muscle fibers form concentric rings, illustrating a circular (sphincter) arrangement that allows an opening to close when the muscle contracts.

On one side of the shoulder region, the deltoid muscle is shown with fibers arranged in multiple angles around a central tendon. This arrangement is labeled multipennate, indicating several sets of fibers inserting into a single tendon to produce strong contractions.

Near the upper arm, the biceps brachii is displayed as a parallel fusiform muscle. The illustration labels the origin, insertion, and the enlarged central region called the belly, showing fibers running parallel to the length of the muscle.

On the chest, the pectoralis major is shown as a convergent muscle. The fibers spread broadly across the chest and narrow toward a single tendon attaching to the upper arm.

Along the forearm, the extensor digitorum, shown from a posterior view, is identified as a unipennate muscle, with muscle fibers attached at an angle on one side of a central tendon.

In the thigh, the rectus femoris is illustrated as a bipennate muscle, with muscle fibers attaching on both sides of a central tendon, increasing force production.

Along the length of the thigh, the sartorius muscle is depicted as a parallel non-fusiform muscle, with long fibers running parallel without a pronounced belly.

Together, these examples demonstrate how different fascicle arrangements relate to muscle shape, force generation, and range of motion across the human body.

Figure 11.1.3: Biceps Brachii Muscle Contraction

This image is a black-and-white photograph showing a close-up of a flexed arm from the side. The focus is on the upper arm,

which is bent at the elbow with the hand forming a fist near the shoulder. The biceps region is prominently contracted, creating a visible muscle contour along the upper arm. The shoulder and part of the upper torso are partially visible on the right side of the frame. The background is plain and dark, highlighting the shape and definition of the flexed muscles.

Figure 11.2.1: Overview of the Muscular System

This image presents a comprehensive overview of the major skeletal muscles of the human body in two full-body views: an anterior view on the left and a posterior view on the right. In each figure, the right half shows superficial muscles and the left half shows deeper muscles exposed beneath the superficial layer. Labels identify muscles throughout the head, trunk, upper limbs, and lower limbs.

The figure contains two upright human figures. The left figure shows the front of the body, and the right figure shows the back of the body. Each figure is divided into superficial and deep muscle layers, allowing comparison between outer and inner muscle groups. Label lines point to specific muscles in each region of the body.

1. Anterior view
    a. Head and neck muscles: The anterior view includes the occipitofrontalis (frontal belly) and sternocleidomastoid. These muscles help control facial expression, head movement, and neck flexion and rotation.
    b. Chest and shoulder muscles: The anterior view includes pectoralis major, pectoralis minor, deltoid, and serratus anterior. These muscles move the shoulder and upper limb, and serratus anterior also contributes to movements associated with breathing.
    c. Arm muscles: The anterior view includes biceps brachii, brachialis, brachioradialis, pronator teres, and flexor carpi radialis. These muscles help produce elbow flexion, forearm rotation, and wrist movement.
    d. Abdominal muscles: The anterior view includes rectus abdominis and external oblique. These muscles support posture, allow trunk flexion and rotation, and help compress abdominal contents.
    e. Hip and thigh muscles: The anterior view includes iliopsoas, adductor longus, gracilis, sartorius, rectus femoris, vastus lateralis, and vastus medialis. These muscles support hip flexion, hip adduction, and knee extension.
    f. Lower leg muscles: The anterior view includes tibialis anterior, fibularis (peroneus) longus, and parts of soleus and gastrocnemius. These muscles control foot dorsiflexion, plantarflexion, and ankle stability.
2. Posterior view
    a. Head and neck muscles: The posterior view includes the occipitofrontalis (occipital belly) and splenius capitis. These muscles help extend and rotate the head and neck.
    b. Upper back and shoulder muscles: The posterior view includes trapezius, levator scapulae, rhomboids, supraspinatus, infraspinatus, teres major, and teres minor. These muscles control movement of the scapula and shoulder joint and provide postural support.
    c. Posterior arm muscles: The posterior view includes triceps brachii, brachioradialis, extensor carpi radialis, extensor carpi ulnaris, and extensor digitorum. These muscles produce elbow extension and help extend the wrist and fingers.
    d. Back and trunk muscles: The posterior view includes latissimus dorsi and serratus posterior inferior. These muscles assist in upper limb movement, respiration, and posture.
    e. Hip and gluteal muscles: The posterior view includes gluteus maximus shown dissected, along with gluteus medius, gluteus minimus, and gemellus muscles. These muscles support hip extension, hip abduction, and stabilization during walking.
    f. Posterior thigh muscles: The posterior view includes biceps femoris and semitendinosus. These muscles support knee flexion and hip extension.
    g. Lower leg muscles: The posterior view includes gastrocnemius shown dissected, soleus, tibialis posterior, and peroneus longus. These muscles control ankle movement and help with push-off during walking.

Figure 11.3.1: Muscles of Facial Expression

This image presents the major muscles of facial expression in two views: an anterior view of the face on the left and a lateral view of the head on the right. Both views show labeled facial muscles with leader lines, highlighting structures involved in facial expression, eye movement, and control of the mouth and cheeks.

The figure is divided into two panels. The left panel shows the front of the face, and the right panel shows the side of the head. The muscles are shown as layered structures over the skull, and labels identify muscles of the forehead and scalp, the eyes, and the mouth and cheeks. The main purpose of the image is to show the muscles responsible for facial expression and facial movement.

1. Anterior view
    a. Epicranial aponeurosis - The epicranial aponeurosis is a broad, flat connective tissue sheet at the top of the head. Its function is to connect the frontal and occipital muscle bellies and allow coordinated movement of the scalp.
    b. Occipitofrontalis, frontal belly - The frontal belly of the occipitofrontalis lies across the forehead. Its functions are to raise the eyebrows and wrinkle the forehead.
    c. Corrugator supercilii - The corrugator supercilii is a small muscle above the inner part of the eyebrows. Its functions are to draw the eyebrows downward and medially and produce vertical forehead wrinkles.
    d. Orbicularis oculi - The orbicularis oculi is a circular muscle surrounding each eye. Its functions are to close the eyelids and enable blinking and squinting.
    e. Orbicularis oris - The orbicularis oris is a circular muscle surrounding the mouth. Its functions are to close and protrude the lips and to support speech and facial expression.
    f. Buccinator - The buccinator is a muscle of the cheek. Its functions are to compress the cheek and help with chewing by keeping food between the teeth.
2. Lateral view
    a. Epicranial aponeurosis - In the lateral view, the epicranial aponeurosis is shown extending across the scalp. Its function is to act as a connective layer between muscle groups of the scalp.
    b. Occipitofrontalis, occipital belly - The occipital belly of the occipitofrontalis is located at the back of the head. Its functions are to pull the scalp backward and assist with coordinated forehead and scalp movement.
    c. Occipitofrontalis, frontal belly - The frontal belly continues into the forehead region. Its functions are to elevate the eyebrows and wrinkle the forehead.
    d. Orbicularis oculi - The orbicularis oculi encircles the eye and functions to close the eyelids.
    e. Orbicularis oris - The orbicularis oris surrounds the mouth and controls opening and closing of the lips.
    f. Buccinator - The buccinator lies in the cheek region and helps with chewing and facial expression.

Figure 11.3.2: Muscles That Move the Eyeball

This image shows the extraocular muscles of the right eye in two views. Panel (a) presents a lateral view of the eye within the orbit, while panel (b) presents an anterior view showing the directions of eye movement produced by the muscles.

In panel (a), six muscles attach to and surround the eyeball. Four rectus muscles approach the eye from behind. The superior rectus lies above the eyeball, the inferior rectus lies below it, the medial rectus runs along the side nearest the nose, and the lateral rectus runs along the side nearest the temple. Most of these muscles originate near the sphenoid bone at the back of the orbit and extend forward to the eyeball. The superior oblique travels along the upper portion of the orbit before changing direction and attaching to the eye, while the inferior oblique follows a curved path beneath the eyeball. Above the superior rectus, the levator palpebrae superioris extends forward to the upper eyelid and functions to elevate the eyelid rather than move the eyeball.

In panel (b), the right eye is viewed from the front with the extraocular muscles arranged around it. The medial rectus on the nasal side pulls the eye inward toward the midline, while the lateral rectus on the temporal side pulls the eye outward. The superior rectus and inferior rectus lie above and below the eye and contribute primarily to upward and downward movement, respectively. The superior oblique arches across the superior aspect of the eye and contributes to downward and lateral movement, whereas the inferior oblique curves beneath the eye and contributes to upward and lateral movement. Arrows indicate that some movements result from the combined actions of multiple muscles. Upward movement involves the superior rectus and inferior oblique working together, while downward movement involves the inferior rectus and superior oblique working together.

The figure demonstrates how the six extraocular muscles are positioned around the eyeball and how their coordinated actions produce the full range of eye movements.

Figure 11.3.3: Muscles That Move the Lower Jaw

This image shows the major muscles involved in mastication, or chewing, in two side views of the head and jaw. The left panel shows the superficial chewing muscles, or outer layer, and the right panel shows the deep chewing muscles, which are visible after removing superficial layers. A boxed region on the left highlights the area of dissection, indicating where deeper muscles are exposed in the right panel.

In the superficial view, the labeled muscles are the temporalis and masseter. The temporalis is a large, fan-shaped muscle covering the side of the skull above the ear. Its functions are to elevate the mandible, closing the jaw, and to retract the mandible,

pulling it backward. The masseter is a thick muscle along the side of the jaw that extends from the cheekbone to the lower jaw. Its functions are to elevate the mandible and generate strong force for biting and chewing. The boxed area on the cheek indicates where superficial tissues have been removed to reveal deeper chewing muscles in the next panel.

In the deep view, the labeled muscles are the lateral pterygoid and medial pterygoid. The lateral pterygoid lies deep in the face near the jaw joint and runs horizontally between the skull and mandible. Its functions are to protract the mandible, moving it forward, assist in opening the jaw, and contribute to side-to-side movements. The medial pterygoid lies on the inner side of the mandible and runs diagonally from the skull to the mandibular angle. Its functions are to elevate the mandible and assist in side-to-side grinding movements.

Together, the figure shows that the muscles of mastication include the temporalis, masseter, lateral pterygoid, and medial pterygoid. These muscles work together to move the mandible during biting, chewing, and grinding. The temporalis and masseter are especially important for jaw closure, while the pterygoid muscles contribute to forward movement, side-to-side motion, and coordinated chewing.

Figure 11.3.4: Anatomy of the Tongue

This image has two panels that show the muscles and surface anatomy of the tongue. The left panel focuses on the extrinsic tongue muscles, and the right panel shows the surface of the tongue and nearby oral structures.

In the left panel, the tongue is shown in side view with the dorsal surface of the tongue labeled along the top. The styloglossus, hyoglossus, and genioglossus are identified as extrinsic muscles that attach the tongue to surrounding structures. The styloglossus extends from the styloid region toward the tongue, the hyoglossus extends upward from the hyoid region, and the genioglossus fans forward from the mandible into the tongue. The mandible bone is also labeled. Together, these muscles help move the tongue in different directions, including retraction, depression, and protrusion.

In the right panel, the open oral cavity is shown from above. The palatoglossus is labeled near the back of the tongue where it forms part of the arch between the tongue and soft palate. Nearby, the pharyngopalatine arch and palatine tonsil are identified. The buccinator is labeled laterally in the cheek region. On the tongue surface, the figure labels vallate papillae near the posterior dorsal surface and fungiform papillae distributed more anteriorly. These surface structures help distinguish different regions of the tongue and highlight visible papilla types.

Figure 11.3.5: Muscles of the Anterior Neck

The image shows the muscles and supporting structures of the anterior neck. The hyoid bone lies near the center of the neck beneath the mandible and serves as a landmark that separates the suprahyoid muscles above from the infrahyoid muscles below.

In the upper portion of the figure, the inferior edge of the mandible forms the superior boundary of the neck region. Above the hyoid bone are the suprahyoid muscles. The geniohyoid and mylohyoid occupy the floor of the mouth and extend between the mandible and hyoid bone. The digastric spans from the mandible toward the hyoid region as a two-bellied muscle, while the stylohyoid extends from the skull to the hyoid bone along the side of the upper neck. The styloglossus is positioned superior to the hyoid region and extends toward the tongue. Together, these muscles elevate the hyoid bone and floor of the mouth and assist with swallowing and jaw movements.

Below the hyoid bone are the infrahyoid muscles, which form strap-like bands running vertically along the front of the neck. The thyrohyoid extends between the thyroid cartilage and the hyoid bone. Inferior to it, the sternohyoid runs from the sternum to the hyoid bone, while the sternothyroid extends from the sternum to the thyroid cartilage. The omohyoid follows an angled course from the shoulder region toward the hyoid bone. These muscles depress and stabilize the hyoid bone and larynx during swallowing and speech.

Deep to the muscular layers, the thyroid cartilage forms the prominent anterior portion of the larynx immediately below the hyoid bone. Inferior to the larynx, the thyroid gland wraps around the upper portion of the trachea. The trachea continues downward in the midline of the neck. At the base of the figure, the clavicles extend laterally from the sternum, and part of the scapula is visible near the shoulder region.

The figure demonstrates how the muscles of the anterior neck are arranged around the hyoid bone and surrounding structures to support swallowing, speech, jaw movement, and stabilization of the larynx and hyoid.

Figure 11.3.6: Posterior and Lateral Views of the Neck

This image compares superficial and deep neck muscles across three related views. The left panel shows a left lateral view of the neck, the middle panel shows a posterior view with the right trapezius removed, and the right panel shows a deeper posterior view with the left semispinalis capitis removed.

In the left lateral view, the sternocleidomastoid forms a prominent band running obliquely along the side of the neck from behind the ear toward the sternum and clavicle. Posterior to it, the splenius capitis extends upward toward the skull. The levator scapulae runs from the upper cervical region to the superior border of the scapula. The trapezius forms a broad superficial muscle covering the posterior neck and upper shoulder region. Inferior and deeper in the neck, the scalene muscles extend between the cervical vertebrae and upper ribs. The acromion process of the scapula is visible at the shoulder as a bony landmark.

In the middle posterior view, the left side retains the superficial trapezius muscle, while the trapezius has been removed from the right side to reveal deeper structures. Beneath the removed trapezius, the levator scapulae is visible extending from the cervical vertebrae to the scapula. The splenius capitis occupies the upper posterior neck and extends toward the skull. A highlighted region at the upper neck indicates the area enlarged in the third panel.

In the right posterior view, additional deeper muscles are exposed after removal of the semispinalis capitis on the left side. The suboccipital muscles occupy the region immediately beneath the base of the skull and surround the upper cervical vertebrae. Inferior to these are the multifidus muscles, which run between adjacent vertebrae along the posterior vertebral column. The longissimus capitis extends superiorly along the side of the neck toward the skull. The semispinalis capitis remains visible on one side and has been cut away on the other to reveal deeper layers. The levator scapulae continues laterally toward the scapula, and the first thoracic vertebra serves as an inferior vertebral landmark.

Together, the three panels demonstrate the layered organization of the neck muscles, progressing from superficial muscles visible at the body surface to deeper muscles located near the cervical vertebrae and base of the skull.

Figure 11.3.7: Muscles of the Neck and Back

This image presents multiple views of the muscles of the neck and deep back. The top left panel shows a left lateral view of the neck, the top right panel shows a posterior view comparing superficial muscles on one side with deeper muscles on the other, the large lower panel shows the deep muscles of the back in posterior view, and the inset at lower right shows the smallest deep spinal muscles after the multifidus has been removed.

In the lateral neck view, the sternocleidomastoid forms a prominent band running along the side of the neck from behind the ear toward the clavicle and sternum. Posterior to it, the splenius muscle extends upward toward the skull. The levator scapulae runs from the upper cervical vertebrae to the scapula, while the anterior and medial scalene muscles descend from the cervical vertebrae toward the upper ribs. The trapezius forms a broad superficial sheet across the posterior neck and shoulder region. The clavicle is visible at the base of the neck as a bony landmark.

In the upper posterior comparison view, the left side retains the superficial trapezius muscle, which covers much of the upper back and neck. On the right side, the trapezius has been removed to reveal deeper muscles. The splenius capitis and splenius cervicis extend from the upper thoracic and cervical regions toward the skull and upper neck. Inferior and lateral to these muscles, the rhomboid minor and rhomboid major span between the vertebral column and the medial border of the scapula. This comparison demonstrates how deeper muscles become visible when superficial layers are removed.

The large posterior view focuses on the deep muscles of the back. Near the neck, the semispinalis capitis and semispinalis cervicis lie close to the vertebral column and extend superiorly toward the skull. Lateral to them are the longissimus capitis and longissimus cervicis. Farther down the thoracic and lumbar regions, the erector spinae columns form longitudinal bands on either side of the vertebral column, including the spinalis thoracis nearest the midline, the longissimus thoracis in the intermediate position, and the iliocostalis muscles farther laterally. The iliocostalis cervicis, iliocostalis thoracis, and iliocostalis lumborum extend upward through the cervical, thoracic, and lumbar regions. Deep to these muscles, the multifidus runs between vertebrae along much of the vertebral column. Together, these muscle groups support posture, extend the vertebral column, and stabilize the spine.

The inset shows the deepest spinal muscles after removal of the multifidus. Small muscles span between adjacent vertebrae and their processes. The rotator brevis and rotator longus connect vertebrae across short distances, the interspinales extend between neighboring spinous processes, and the intertransversarii run between adjacent transverse processes. A short rotator muscle is

also shown connecting nearby vertebrae. The transverse processes are visible as bony landmarks. These deepest muscles provide fine control and stabilization of vertebral movements.

Together, the panels demonstrate the layered organization of the neck and back muscles, progressing from superficial muscles visible at the body surface to the deepest muscles that act directly on individual vertebrae.

Figure 11.4.1: Abdominal and Lower Trunk Musculature

This image presents two views of the abdominal and lower trunk musculature to illustrate the organization of superficial and deep muscle layers.

The instructional purpose of the image is to show how abdominal muscles are arranged in layers, how they connect through connective tissue structures, and how deeper muscles support the spine and pelvis.

Part (a): Superficial and Deep Abdominal Muscles (Anterior–Lateral View) - The first portion of the figure focuses on the front and side of the torso. It identifies major abdominal muscles and connective structures:

- The rectus abdominis is a vertical muscle located in the midline of the abdomen. It is enclosed within the rectus sheath, a connective tissue covering.
- The linea alba runs along the center of the abdomen and serves as a connective seam that joins muscles from both sides.
- The tendinous intersections divide the rectus abdominis into segments, which contribute to its characteristic segmented structure.

Muscle layers on the side of the abdomen include:

- The external oblique, which is the outermost muscle layer.
- The internal oblique, located beneath the external oblique.
- The transversus abdominis, the deepest layer, which wraps horizontally around the abdomen.

An inset highlights deeper structures and connective tissue:

- The aponeurosis of the internal oblique, a flat tendon, contributes to the formation of the rectus sheath.
- This layered arrangement demonstrates how muscles and connective tissues work together to stabilize and compress the abdominal wall.

Additional labeled muscles such as the pectoralis major, latissimus dorsi, and anterior serratus muscles are included to provide context for how abdominal muscles connect to the upper body.

Part (b): Posterior Abdominal Muscles (Anterior View of Deep Structures): The second portion of the figure shows deeper muscles associated with the posterior abdominal wall and pelvis. Key structures include:

- The psoas major, which extends from the spine to the femur and plays a role in hip flexion and spinal stability.
- The iliacus, which works with the psoas major to flex the hip.
- The quadratus lumborum, located on either side of the spine, which stabilizes the lower back and assists with lateral flexion.
- The iliac crest (ilia of the hip bones) provides attachment points for muscles.
- The sacrum, a large triangular bone at the base of the spine, serves as a central anchor for muscle attachments.

Figure 11.4.2: The Diaphragm

This image shows the diaphragm from an inferior view, looking upward toward the thoracic cavity. The diaphragm appears as a broad dome-shaped muscle with a large pale central tendon surrounded by muscular fibers that radiate outward toward its attachments.

The central tendon occupies the middle of the diaphragm and is surrounded by the muscular portion of the diaphragm. Anteriorly, the diaphragm attaches to the sternum. Laterally, it attaches to the lower ribs, including the twelfth (floating) ribs visible on either side of the figure. Posteriorly, muscular extensions attach to the vertebral column. Adjacent to the posterior attachments are the left psoas major and left quadratus lumborum muscles, which lie beneath the diaphragm along the posterior abdominal wall.

Three major openings pass through the diaphragm. Near the central tendon is the caval opening, through which the vena cava passes. Slightly inferior and anterior to the aortic opening is the esophageal hiatus, where the esophagus passes between the thoracic and abdominal cavities. More posteriorly, near the vertebral column, is the aortic hiatus, through which the aorta descends from the thorax into the abdomen.

The figure demonstrates how the diaphragm forms a muscular partition between the thoracic and abdominal cavities while providing passageways for major blood vessels and the esophagus.

Figure 11.4.3: The Intercostal Muscles

This image compares the muscles of the thoracic wall and emphasizes the layered arrangement of the intercostal muscles between the ribs. The main panel shows a lateral view of the chest wall with portions of the superficial musculature removed to expose deeper structures. An inset enlarges a single intercostal space to show the organization of the muscle layers between adjacent ribs.

In the main image, the clavicle lies superiorly at the shoulder region, while the sternum forms the anterior midline of the thoracic wall. Multiple ribs extend laterally from the sternum toward the side of the chest. Much of the pectoralis major has been removed, revealing deeper structures beneath it. Deep to the pectoralis major, the pectoralis minor extends from several upper ribs toward the scapular region. Along the lateral thoracic wall, the serratus anterior forms a series of finger-like muscular slips attaching to the ribs.

Between adjacent ribs are the intercostal muscles. The external intercostals form the more superficial layer and span the spaces between ribs. Deep to them are the internal intercostals, whose muscle fibers run in a different direction. Together these layers occupy the intercostal spaces and contribute to movements of the thoracic wall during breathing.

The inset focuses on a single space between two ribs. Three distinct muscular layers are visible. The external intercostal occupies the most superficial position, the internal intercostal lies immediately beneath it, and the innermost intercostal forms the deepest layer adjacent to the inner thoracic wall. The differing fiber orientations of these layers are visible, illustrating the layered construction of the intercostal musculature.

Together, the figure demonstrates how the thoracic wall is organized around the ribs and how the three intercostal muscle layers are arranged between adjacent ribs to support respiration.

Figure 11.4.4: The Pelvic Diaphragm

This image shows the pelvic diaphragm from a superior view. The main purpose of the diagram is to identify the levator ani muscle group and the openings that pass through the pelvic floor. The figure also labels nearby bony landmarks to show how the pelvic diaphragm is positioned within the pelvis.

The levator ani is identified as the main pelvic floor muscle group and is subdivided into the pubococcygeus and iliococcygeus. These muscles extend across the pelvic outlet and form a supportive muscular floor. The diagram labels the urethral canal, the vaginal canal (females only), and the rectal canal as openings passing through the pelvic diaphragm. These openings show that the pelvic floor provides support while allowing passage for urinary, reproductive, and digestive structures.

Surrounding landmarks include the pubic crest anteriorly, the sacrum posteriorly, and the iliac crests laterally. The iliacus is also labeled along the lateral pelvic region. Together, these structures help orient the pelvic diaphragm within the bony pelvis.

Figure 11.4.5: Muscles of the Perineum

This image compares the perineal muscles in male and female inferior views.

Both sides label several common muscles, including the ischiocavernosus, bulbospongiosus, transverse perineal muscles, external anal sphincter, and levator ani. The anus, coccyx, and gluteus maximus are also labeled in both views. These labels show that both perineal regions share a common arrangement of muscles that support the pelvic floor and surround the anal region.

In the left panel, the male view labels the penis anteriorly. In the right panel, the female view labels the clitoris, urethra, and vagina. These labels specify the different external openings and associated structures while preserving the overall comparison of

muscle placement.

Figure 11.5.1: Muscles That Position the Pectoral Girdle

This image presents muscles of the pectoral girdle and upper trunk, shown in two views to compare anterior (front) and posterior (back) muscle groups.

Left Image: Pectoral Girdle Muscles (Anterior–Lateral View) - This portion highlights muscles located on the front and side of the chest and shoulder. Key structures include:

- The pectoralis major (partially removed) is a large superficial chest muscle that contributes to arm movement such as flexion and adduction.
- Beneath it, the pectoralis minor connects the ribs to the scapula and helps stabilize the shoulder.
- The serratus anterior runs along the ribs and plays a key role in holding the scapula against the thoracic wall and assisting with upward rotation of the arm.
- The subclavius lies beneath the clavicle and helps stabilize that bone.
- The scapula (shoulder blade) serves as an attachment site for several muscles.
- The coracoid process of the scapula is a bony projection that provides attachment for muscles including the pectoralis minor.
- The deltoid (cut in this view) normally covers the shoulder and is responsible for arm elevation.
- The sternum provides a central attachment point for chest muscles.

Right Image: Pectoral Girdle Muscles (Posterior View) - This portion shows muscles on the back of the shoulder and upper torso. Key structures include:

- The trapezius, a large surface muscle, supports posture and moves the scapula.
- The deltoid covers the shoulder joint and is involved in arm lifting and rotation.
- The rhomboid major and rhomboid minor connect the spine to the scapula and help retract and stabilize the shoulder blade.
- The acromion process of the scapula is a bony projection that forms the top of the shoulder and serves as an attachment site for muscles.

Figure 11.5.2: Muscles of the Neck and Deep Back

This image presents four related views of the neck and back musculature, progressing from superficial muscles visible at the body surface to the deepest muscles that act directly on the vertebral column. The top left panel shows a left lateral view of the neck, the top right panel shows a posterior view comparing superficial and deep muscle layers, the large lower panel shows the deep muscles of the back in posterior view, and the lower right inset shows the deepest spinal muscles after removal of the multifidus.

In the left lateral view of the neck, the sternocleidomastoid forms a prominent band running obliquely from the region behind the ear toward the clavicle and sternum. Posterior to it, the splenius muscle extends upward toward the skull. The levator scapulae descends from the upper cervical vertebrae toward the superior border of the scapula. Inferior and deeper in the neck, the anterior and medial scalene muscles extend from the cervical vertebrae toward the upper ribs. The trapezius forms a broad superficial sheet covering the posterior neck and upper shoulder region. The clavicle is visible at the base of the neck as a bony landmark.

In the upper posterior comparison view, the left side retains the superficial trapezius muscle, which covers much of the posterior neck and upper back. On the right side, the trapezius has been removed to expose deeper structures. The splenius capitis extends from the upper thoracic and lower cervical region toward the skull, while the splenius cervicis lies inferior to it and attaches to the cervical vertebrae. Deep to these muscles, the rhomboid minor and rhomboid major extend from the vertebral column to the medial border of the scapula. This panel demonstrates how removal of a superficial muscle reveals deeper muscles involved in movement and stabilization of the neck and scapula.

The large posterior view of the back focuses on the deep muscles adjacent to the vertebral column. Near the head and neck, the semispinalis capitis extends upward toward the skull and is shown blended with the deep spinalis capitis. Inferior to it, the semispinalis cervicis occupies the posterior cervical region. Lateral to the semispinalis muscles are the longissimus capitis and longissimus cervicis, which run superiorly along the side of the neck. In the thoracic region, the spinalis thoracis lies closest to the midline, while the semispinalis thoracis occupies a deeper position between the vertebrae and the more superficial muscle columns. The multifidus forms a series of deep muscular bundles running between vertebrae along much of the spinal column.

Farther laterally are the muscles of the erector spinae group. The longissimus thoracis occupies the intermediate column, while the iliocostalis muscles form the most lateral column. The iliocostalis cervicis extends through the cervical region, the iliocostalis thoracis spans the thoracic region, and the iliocostalis lumborum occupies the lumbar region. Together, these longitudinal muscle columns support posture, extend the vertebral column, and assist in controlling movements of the trunk and neck.

The inset view enlarges a portion of the spinal column after the multifidus has been removed. The transverse processes of the vertebrae are visible on each side as bony landmarks. Between adjacent vertebrae are several small deep muscles. The rotator brevis and rotator longus connect vertebrae across short distances. The interspinales extend between neighboring spinous processes near the midline. A short rotator connects adjacent vertebrae, and the intertransversarii extend between neighboring transverse processes. These muscles are the deepest muscles of the back and contribute primarily to fine adjustments, stabilization, and precise control of vertebral movements.

Overall, the figure demonstrates the layered organization of the neck and back musculature, from large superficial muscles involved in major movements of the head, neck, and shoulders to the deepest muscles that stabilize and control individual vertebrae.

Figure 11.5.3: Muscles of the Left Upper Arm and Forearm

This figure presents six views of the left upper arm and forearm to compare muscle groups by location, depth, and viewing direction. The top row shows the upper arm in anterior lateral and posterior views. The middle row shows the superficial muscles of the forearm in palmar and dorsal views. The bottom row shows deeper forearm muscles after removal of some superficial structures.

- Upper Left Panel: Anterior Lateral View of the Left Upper Arm
  - An anterior lateral view of the left upper arm is shown. The biceps brachii occupies the front of the arm and is visible as two heads that converge into a common tendon near the elbow. Deep to the biceps brachii is the brachialis, which lies against the humerus and becomes more visible near the distal arm. Together these muscles form the major flexor region of the upper arm.
- Upper Right Panel: Posterior View of the Left Upper Arm
  - A posterior view of the left upper arm is shown. The triceps brachii occupies most of the posterior arm. The long head extends from the scapular region along the medial side of the arm, while the lateral head occupies the lateral and posterior surface of the humerus. These muscles form the primary extensor region of the arm.
- Middle Left Panel: Superficial Palmar View of the Forearm
  - The superficial muscles of the forearm are shown from the palmar side. The brachioradialis forms a prominent muscle along the lateral side of the forearm near the elbow. Medially, the pronator teres crosses obliquely from the medial elbow toward the radius. Several long flexor muscles extend from the elbow toward the wrist and hand, including the flexor carpi radialis, palmaris longus, and flexor carpi ulnaris. The flexor digitorum superficialis occupies much of the central forearm and sends tendons toward the fingers. These muscles form the superficial flexor compartment of the forearm.
- Middle Right Panel: Superficial Dorsal View of the Forearm
  - The superficial muscles of the forearm are shown from the dorsal side. The triceps brachii is visible proximally near the elbow, while the brachioradialis remains visible along the lateral forearm. The extensor carpi radialis longus and extensor carpi radialis brevis run along the lateral aspect of the forearm toward the wrist. The extensor digitorum occupies the center of the posterior forearm and gives rise to multiple tendons that extend to the fingers. Medially, the extensor carpi ulnaris extends toward the wrist. Near the thumb are the abductor pollicis longus, extensor pollicis brevis, and extensor pollicis longus. The extensor digiti minimi extends toward the little finger. The anconeus occupies a small region near the posterior elbow. The lateral epicondyle of the humerus serves as a bony landmark at the elbow.
- Lower Left Panel: Deep Palmar View of the Forearm
  - Deeper structures of the forearm are shown from the palmar side after removal of some superficial tissues. The brachialis and flexor retinaculum are shown cut to expose underlying anatomy. The flexor digitorum profundus occupies much of the deep forearm and gives rise to tendons that extend to the fingers. The flexor pollicis longus extends toward the thumb. Near the distal forearm, the pronator quadratus spans between the radius and ulna. The medial epicondyle of the humerus serves as a landmark near the elbow.
- Lower Right Panel: Deep Dorsal View of the Forearm
  - Deeper structures of the dorsal forearm are shown. The supinator wraps around the proximal radius near the elbow. The abductor pollicis longus and the tendons of the extensor pollicis longus and extensor pollicis brevis extend toward the thumb. The extensor indicis provides a tendon to the index finger. The extensor retinaculum crosses the posterior wrist and holds the extensor tendons in place. Portions of the flexor digitorum profundus and flexor carpi ulnaris remain visible from this view. The medial and lateral epicondyles of the humerus mark the sides of the elbow region.

- Together, the six panels demonstrate the organization of the muscles of the upper arm and forearm, showing the differences between anterior and posterior compartments, superficial and deep layers, and flexor and extensor muscle groups.

Figure 11.5.4: Intrinsic Muscles of the Hand

This image presents four views of the left hand to compare superficial and deep muscle groups and to distinguish muscles on the palmar side from those associated with the dorsal interossei.

In the upper left panel, the superficial muscles of the left hand in palmar view are shown. Labeled muscles include the abductor digiti minimi, flexor digiti minimi brevis, lumbrical muscles, opponens pollicis, abductor pollicis brevis, flexor pollicis brevis, and adductor pollicis. This panel emphasizes the intrinsic muscles visible from the palm, including muscles associated with the little finger and thumb, as well as the lumbricals that extend toward the fingers.

In the upper right panel, the deep muscles of the left hand are shown with labels including opponens pollicis, adductor pollicis, pisometacarpal ligament, and opponens digiti minimi. This panel highlights deeper intrinsic structures associated with thumb and little finger movement.

In the lower left panel, the palmar interossei muscles are shown in palmar view. In the lower right panel, the dorsal interossei muscles are shown in dorsal view. These lower panels focus specifically on the interosseous muscles located between the metacarpals and show how the palmar and dorsal interossei occupy different positions in the hand.

Figure 11.6.1: Superficial and Deep Muscles of the Right Pelvis and Thigh

This figure presents three views of the right pelvic and thigh region to compare superficial and deep muscle groups from anterior and posterior perspectives. The upper panel shows superficial muscles in anterior view, the lower left panel shows deeper anterior muscles after removal of some superficial structures, and the lower right panel shows the posterior muscles of the pelvis and thigh.

In the upper anterior view, the iliac crest forms the superior border of the pelvis, and the sacrum is visible near the midline. The quadratus lumborum and psoas major extend downward from the trunk toward the pelvis, while the iliacus occupies the inner surface of the ilium. Near the upper medial thigh, the pectineus lies adjacent to the pelvis. On the lateral side of the hip, the tensor fascia latae descends into the thigh. The long sartorius crosses diagonally from the lateral hip to the medial knee. The rectus femoris occupies the center of the anterior thigh, with the vastus lateralis on the lateral side and the vastus medialis on the medial side. Along the medial thigh are the adductor longus, gracilis, and adductor magnus. At the knee, the quadriceps tendon continues across the patella and into the patellar ligament. This view emphasizes the superficial muscles involved in hip flexion, thigh movement, and knee extension.

In the lower left anterior view, deeper muscles of the medial thigh are exposed. The iliac crest and pubis serve as pelvic landmarks, while the femur forms the bony framework of the thigh. The pectineus occupies the upper medial thigh near the pubis. Deep to the superficial adductor muscles, the obturator externus extends from the pelvis toward the femur. The adductor brevis lies between the adductor longus and adductor magnus. Together, the adductor longus, adductor brevis, and adductor magnus form much of the medial thigh and contribute to movement of the thigh toward the body's midline.

In the lower right posterior view, the gluteus maximus has been cut and partially removed to reveal deeper structures of the hip. Superiorly, the gluteus medius has also been cut to expose the gluteus minimus beneath it. Deep lateral rotator muscles are visible below the gluteus minimus, including the piriformis, superior gemellus, inferior gemellus, obturator internus, and quadratus femoris. The iliac crest and sacrum provide bony orientation for the pelvis. Along the posterior thigh, the hamstring muscles are visible, including the biceps femoris laterally and the semitendinosus and semimembranosus medially. The gracilis remains visible along the medial thigh, and the adductor group occupies the medial and posterior portion of the thigh. This view highlights the layered organization of the gluteal region, deep hip rotators, and posterior thigh muscles.

Together, the three panels demonstrate the arrangement of superficial and deep muscles of the pelvis and thigh, showing how the anterior and posterior muscle groups are organized around the hip joint and femur.

Figure 11.6.2: Superficial and Deep Muscles of the Right Lower Leg

This figure presents three views of the right lower leg to compare muscle groups by position and depth. The left panel shows the superficial muscles in anterior view, the middle panel shows the superficial muscles in posterior view, and the right panel shows the deep muscles in posterior view after removal of part of the soleus.

In the left panel, the anterior surface of the right lower leg is shown. The tibialis anterior occupies the front of the shin adjacent to the tibia and extends toward the medial foot. Lateral to it, the extensor digitorum longus sends tendons toward the toes, while the extensor hallucis longus passes toward the great toe. Along the lateral side of the leg, the fibularis longus forms a large superficial muscle, with the fibularis brevis located deeper and more distally. Near the ankle, the fibularis tertius contributes a tendon on the anterior-lateral aspect of the foot. The superior and inferior extensor retinacula form connective tissue bands across the front of the ankle that secure the tendons as they pass into the foot. This view highlights the muscles of the anterior and lateral compartments of the leg.

In the middle panel, the posterior surface of the lower leg is shown. The gastrocnemius forms the prominent superficial calf muscle and is divided into medial and lateral heads that arise above the knee. Deep to the gastrocnemius is the broad soleus muscle, which occupies much of the posterior calf. The slender plantaris lies between these muscles and contributes a long tendon descending toward the heel. Inferiorly, the gastrocnemius and soleus converge to form the calcaneal (Achilles) tendon, which inserts onto the calcaneus. This view emphasizes the large superficial calf muscles and their common attachment to the heel.

In the right panel, part of the soleus has been cut and reflected to expose deeper structures of the posterior leg. The popliteus is visible near the back of the knee, extending obliquely across the joint. The tibialis posterior occupies the deep central portion of the posterior compartment, while the flexor digitorum longus lies medially and sends tendons toward the lateral four toes. The flexor hallucis longus lies more laterally and sends a tendon to the great toe. Along the lateral side of the leg, the fibularis longus and fibularis brevis remain visible. This view demonstrates the organization of the deep posterior compartment and its relationship to the more superficial calf muscles.

Together, the three panels show the arrangement of the major anterior, lateral, and posterior muscle groups of the lower leg, highlighting the differences between superficial and deep muscle layers and their connections to the foot and ankle.

Figure 11.6.3: Dorsal and Plantar Muscles of the Foot

This figure presents four views of foot muscles to compare the dorsal surface of the right foot with the layered muscles of the left sole in plantar view. The upper panel shows the superficial muscles and tendons on the dorsum of the foot, while the three lower panels progressively show the superficial, intermediate, and deep layers of the plantar musculature.

In panel (a), the right foot is shown from a lateral view, highlighting muscles and tendons visible on the dorsal and lateral aspects of the foot. The tibialis anterior descends along the anterior leg and extends toward the medial foot. The extensor digitorum longus and extensor hallucis longus continue onto the dorsum of the foot, where their tendons extend to the toes and great toe. The extensor digitorum brevis lies on the dorsal surface of the foot and contributes tendons to several toes. Along the lateral side of the foot, the fibularis longus, fibularis brevis, and fibularis tertius pass toward the foot and ankle. Posteriorly, the tendocalcaneus (Achilles tendon) descends to the heel. This view emphasizes the tendons and muscles that contribute to extension of the toes and stabilization of the foot.

In panel (b), the left sole is shown in plantar view with the most superficial layer exposed. A broad plantar aponeurosis occupies the central portion of the sole and extends from the heel toward the toes. Along the medial side of the foot, the abductor hallucis runs toward the great toe. Along the lateral border, the abductor digiti minimi extends toward the little toe. Between these muscles, the flexor digitorum brevis occupies the central sole and sends tendons toward the lateral four toes. This layer forms the superficial muscular framework of the plantar foot.

In panel (c), the intermediate layer of the left sole is shown after removal of the superficial muscles. The quadratus plantae lies near the heel and extends forward toward the tendons of the toes. The lumbricals arise from the flexor tendons and extend toward the toes as slender muscles positioned along the forefoot. This layer lies deep to the flexor digitorum brevis and contributes to coordinated toe movements.

In panel (d), the deep layer of the left sole is shown. The flexor hallucis brevis occupies the medial side of the forefoot beneath the great toe, while the flexor digiti minimi brevis lies along the lateral side beneath the little toe. These deeper muscles are

positioned close to the metatarsal region and are associated with movements of the great and little toes.

Together, the four panels demonstrate the organization of the intrinsic muscles of the foot, progressing from the dorsal surface and superficial plantar structures to the deeper muscular layers of the sole.

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