Chapter 30

How Animals Move

Objectives

Introduction Describe the feeding and nesting strategy of leaf-cutting ants. Explain how the skeleton of these ants permits such diverse activity.

Movement and Locomotion

30.1 Describe the diverse methods of locomotion and the forces each must resist.

Skeletal Support

30.2 Describe the three main types of skeletons. Note their advantages, their disadvantages, and examples of each.

30.3 Describe the similarities of the skeletons of vertebrates. Distinguish between the axial and appendicular skeletons. Describe three types of joints and provide examples of each.

30.4 Describe the most common skeletal disorders.

30.5 Describe the complex structure of a bone, noting the major tissues that contribute to bones and their functions.

30.6 Explain why bones break and how we can help them heal.

Muscle Contraction and Movement

30.7 Explain how muscles relengthen once contracted.

30.8 Describe the structure and arrangement of the filaments found in a muscle cell.

30.9 Explain the details of how a muscle cell contracts.

30.10 Describe the structure and significance of motor units.

30.10 Explain how a motor neuron makes a muscle fiber contract.

30.10 Describe the role of calcium in a muscle contraction.

30.11 Explain what causes muscles to tire. Distinguish between aerobic and anaerobic exercise. Note the advantages of each.

30.12 Describe an example of an animal using its sensory receptors, central nervous system, skeleton, and muscles to perform an activity.

Key Terms

locomotion
hydrostatic skeleton
exoskeleton
endoskeleton
axial skeleton
appendicular skeleton
ball-and-socket joint
hinge joint
pivot joint
arthritis
osteoporosis
yellow bone marrow
red bone marrow
tendon
skeletal muscle
myofibril
sarcomere
thin filament
thick filament
sliding-filament model
motor unit
neuromuscular junction
aerobic exercise
anaerobic exercise

Word Roots

endo- = within (*endoskeleton:* a hard skeleton buried within the soft tissues of an animal, such as the spicules of sponges, the plates of echinoderms, and the bony skeletons of vertebrates)

hydro- = water (*hydrostatic skeleton:* a skeletal system composed of fluid held under pressure in a closed body compartment; the main skeleton of most cnidarians, flatworms, nematodes, and annelids)

myo- = myscle; **-fibro** = fiber (*myofibril:* a fibril collectively arranged in longitudinal bundles in muscle cells; composed of thin filaments of actin and a regulatory protein and thick filaments of myosin)

para- = near (*parasympathetic division:* one of two divisions of the autonomic nervous system)

sarco- = flesh; **-mere** = a part (*sarcomere:* the fundamental, repeating unit of striated muscle, delimited by the Z lines)

Lecture Outline

Introduction *How Do Ants Move Forests?*

A. Most animal activities involve movement.

1. Leaf-cutter ants exhibit almost continuous movement as they carry out numerous activities (note all the verbs in the following sentences). Individual worker ants slice, pick up, and carry plant parts. They are protected by guard ants that ride on the leaf and gnash their jaws at potential attackers. Back in the nest, workers chew up the leaves, plant the fungus, cultivate the fungi, apply fungicides to inhibit competitors, harvest fungal growth, and carry away refuse. The fungus, not the plant material, is fed to the growing larvae.
2. Insects are able to move and work efficiently because they have light, articulated exoskeletons with tiny, powerful internal muscles (Figure 30.0).
3. Three organ systems play key roles in movement. The nervous system issues commands to the muscular system, which exerts force against a firm skeletal system.

I. Movement and Locomotion

Module 30.1 Diverse means of animal locomotion have evolved.

A. Although muscles and skeletons move in a variety of ways (eating, digestion, circulation), the focus in this chapter is on **locomotion,** or the ability to move from place to place.

B. Some animals remain fixed in one place and let the world come to them. Sponges use flagellated collar cells to move water through their bodies. Some cnidarians (such as *Hydra*) remain attached and move slowly during feeding activities.

C. Locomotion in all its forms requires an animal to overcome two forces: friction and gravity. Water supports against gravity but offers considerable frictional resistance. Air offers little resistance but provides little support.

D. Swimming involves legs as oars (many aquatic insects and mammals), jet propulsion (squids), whole body side to side (fishes), and up and down (whales) (Figure 30.1A).

E. Land animals not only must overcome gravity; they must maintain their balance whether moving forward or while at rest. Terrestrial locomotion includes hopping on springlike back legs, and quadrupedal or bipedal walking and running (and resting) (Figure 30.1B, C).

F. Some land animals crawl (by undulating movements or by peristalsis). During peristalsis, longitudinal muscles shorten and thicken regions, while circular muscles constrict and elongate other regions. In an earthworm, bristles anchor the short, thick regions, and regions anterior to them lengthen (Figure 30.1D).

G. Flying (which is different from gliding) has evolved only in insects, birds, extinct reptiles, and mammals (bats). To fly, animals move wings in patterns that provide lift. Bird wings have cross-sectional shapes of airfoils. Air flowing past an airfoil has lower pressure above relative to below, providing lift (Figure 30.1E).
NOTE: Insects, bats (most of the time), and some birds (hummingbirds) produce lift in a different way. Lift is created by fluttering (which is more like the lift a helicopter produces) or pushing their wings down against the air during a power stroke and slipping them up through the air during a return, nonpower stroke. This type of flight enables these animals to hover, a feat the rest of the birds cannot do without fluttering, and then inefficiently. Some other animal groups (fishes, amphibians, and other mammals) have evolved gliding, which moves the animal through the air or water without producing lift.

H. All types of movement are based on either the contraction of microtubules (see cilia and flagella in Module 4.18) or the contraction of microfilaments (amoeboid movement and muscle contraction).

II. Skeletal Support

Module 30.2 Skeletons function in support, movement, and protection.

A. Skeletons have many functions, including support, protection of soft parts, and movement. There are three main types of skeletons: hydrostatic skeletons, exoskeletons, and endoskeletons.
NOTE: Skeletons can also play a role in mineral storage and blood cell production (Modules 23.17 and 30.5).

B. A **hydrostatic skeleton** consists of a volume of fluid held under pressure in a body compartment. Such skeletons work well for aquatic animals and animals that burrow by peristalsis. Earthworms have a body composed of fluid-filled sections. *Hydra* counters muscle cell contractions against a hydrostatic skeleton of its closed gastrovascular cavity (Figure 30.2A).

C. An **exoskeleton** consists of a rigid, external, armorlike covering. Muscles are attached to the inner surface of the exoskeleton. At joints, the exoskeleton is thin and flexible. Clams and snails have exoskeletons (shells) that are enlarged by secretions from the body margin (mantle). The hollow, tubular exoskeletons of arthropods (Module 18.12) are extremely light for their strength, but they do not grow with the animal. Periodically, during molting, the old skeleton is lost, and, following body growth, a new skeleton is hardened (Figure 30.2B, C). At this time, these animals are particularly vulnerable to predators, and remain so until the new exoskeleton hardens.
NOTE: Although most shell-bearing mollusks move by manipulating a muscular foot, the scallop moves by rapid opening and closing of its shells, producing a jet-propulsive movement that is somewhat random.

D. An **endoskeleton** consists of rigid, internal supports, usually consisting of noncellular material secreted by surrounding cells. Sponges support their cells on spicules. Spicules are made of materials such as calcium salts or silica. Echinoderms have an endoskeleton of calcium plates under their skin (Figure 30.2D). Vertebrates have endoskeletons of bone, cartilage, or a combination of both (Figure 30.2E).

Module 30.3 The human skeleton is a unique variation on an ancient theme.

Review: Human evolution (Modules 19.1–19.6).

A. All vertebrate skeletons have consistent features, both the overall pattern described below and the number, shape, and articulation of the individual bones. The basic patterns are modified according to the needs of each animal.
Review: Primitive and derived characters (Module 15.13).

B. In contrast to the frog skeleton, which supports a quadruped that moves by hopping, the human skeleton supports a biped that walks or runs.

C. The **axial skeleton** consists of a skull protecting the brain, the backbone (vertebral column) protecting the spinal cord and supporting the remaining skeletal elements, and the rib cage surrounding the lungs and heart.

D. The **appendicular skeleton** consists of the bones of the appendages (arms, legs, and fins) and the bones that link the appendages to the axial skeleton (the shoulder [pectoral] and pelvic girdles).
NOTE: The shoulder girdle consists of the clavicle and scapula. Coming off the shoulder girdle are the humerus, radius and ulna, carpals, metacarpals, and phalanges. The pelvic girdle is formed by the coxal bone (os coxa), which consists of three fused bones: the ilium, the ischium, and the pubis. Coming off the pelvic girdle are the femur, patella (kneecap), tibia and fibula, tarsals, metatarsals, and phalanges.
NOTE: A human skeleton can be determined to be that of a female or male by examining the pelvic girdle. There are several differences, but one of the easiest to use is the angle of the pubic arch. If the angle is greater than 90°, then it is the skeleton of a female; if the angle is less than 90°, then it is the skeleton of a male.

E. This is the basic pattern of bones found in most land vertebrates (tetrapods).

F. Comparing the bipedal human skeleton with that of the quadrupedal baboon underscores the evolutionarily distinctive features. The human skull is large and flat-faced. The backbone is S-shaped. The pelvic girdle is shorter, rounder, and oriented vertically. The bones of the hands and feet are different. The hands are adapted for grasping and manipulating, and the feet are adapted to support the entire body bipedally (Figure 30.3B; Figure 19.1C).

G. The versatility of the vertebrate skeleton comes in part from its movable joints. **Ball-and-socket joints** allow movement in all directions. **Hinge joints** are strong and restrict movement to one plane. **Pivot joints** allow bones to rotate, providing ease of manipulation (Figure 30.3C).

Module 30.4 Connection: Skeletal disorders afflict millions.

A. Lower back problems stem from the uneven distribution of weight vertically on the backbone. The S-shape in this area cushions vertical load but cannot bear the lateral force during lifting.

B. One form of **arthritis** (inflammation of the joints) seems to be a normal part of aging, as joints become stiff and cartilage between bones wears down (osteoarthritis).

C. Crippling, rheumatoid arthritis is an autoimmune disease (Module 24.16) in which the immune system attacks and degrades the joints following stress or an infection.

D. **Osteoporosis** is due to hormonal changes (greatly reduced estrogen levels) during aging, particularly in women following menopause. It is characterized by the bones becoming thinner, more porous, and easily broken.
NOTE: For women, bone density begins to decline at about age 30 to 35. Pre- and postmenopausal women should increase Ca^{2+} intake and begin an exercise program to offset this decline.

Module 30.5 Bones are complex living organs.

Review: Tissues, bone, and cartilage (Module 20.5) and the role of the thyroid and parathyroid glands in calcium homeostasis (Module 26.7).

A. Bones are composed of other tissues besides bone and cartilage. These tissues intermix with tissues of the circulatory system (vessels and blood) and nervous system (nerves) (Figure 30.5).

B. Most of the outside surface is covered with fibrous connective tissue. When bones break or crack, this tissue is able to form new bone.

C. At either end of most bones, cartilage replaces connective tissue, forming a surface that cushions the joint (Figure 30.5E).

D. Bone itself is mostly a noncellular matrix of calcium salts (which resist compression) and protein fibers (which resist cracking) surrounding the cells that secrete these materials (Figure 30.5F).

E. The shafts of long bones are made of compact bone, with a dense matrix surrounding a hollow cavity containing stored fat **(yellow bone marrow).** The ends of long bones are made of an outer layer of compact bone and an inner area of spongy bone. Within cavities in the matrix of the spongy bone, specialized tissues produce blood cells **(red bone marrow).**
NOTE: The cavity of long bones reduces the weight of the body and makes movement easier.

Module 30.6 Connection: Broken bones can heal themselves.

A. Bones have the capacity to flex to a slight degree, but when too much force is applied they will break (Figure 30.6A). The average American will break two bones in his or her lifetime.

B. Two factors determine if a bone will break:
   1. The amount of force applied to the bone
   2. The strength of the skeleton, which can be affected by disease and age

C. Bone is a living, dynamic tissue that can heal itself if given the opportunity. However, sometimes the process needs surgical intervention (as seen in Figure 30.6A) in an effort to enhance the healing process.

D. Occasionally bone fails to heal properly or disease limits proper bone health and the injured or diseased bone must be replaced with artificial parts or with bone grafts (Figure 30.6B).

III. Muscle Contraction and Movement

Module 30.7 The skeleton and muscles interact in movement.

A. Muscles are connected to bones by **tendons** (Module 20.5, Figure 20.5D).
NOTE: At joints, bones are held together by ligaments.

B. A muscle can only contract. To extend, it must be pulled by the contraction of an opposing muscle. Thus, movement of most parts of the body requires antagonistic pairs of muscles (Figure 30.7).
NOTE: Nerves that enervate antagonistic muscle pairs have a built-in circuitry that prevents both muscles of a pair from contracting at the same time (this is referred to as reciprocal innervation). A strong electrical shock can bypass this circuitry and cause both nerves to induce their muscles to contract at the same time. This can break bones.

Module 30.8 Each muscle cell has its own contractile apparatus.

A. Striated **skeletal muscle** tissue was introduced in Module 20.6 (Figure 20.6A).

B. Each muscle fiber is a single cell with many nuclei. Within each fiber are numerous, long **myofibrils** (Figure 30.8).

C. A myofibril is composed of contracting units called **sarcomeres,** joined end to end at Z lines.

D. Each sarcomere is composed of **thin filaments** (coiled strands of two actin proteins and one regulatory protein) and **thick filaments** (parallel strands of myosin protein). This structure produces a pattern of light and dark bands in the muscle tissue. The dark bands (Figure 30.8) consist of thick filaments and thin filaments (which do not extend to the center of the dark band). The light bands have only thin filaments and straddle the Z lines that connect adjacent thin filaments.
NOTE: The regulatory protein wrapped around actin is actually two proteins, a complex of troponin and tropomyosin. Tropomyosin physically blocks binding sites for myosin on actin. These sites are unblocked when Ca^{2+} binds to troponin, forcing a conformational change, which in turn moves tropomyosin from its position blocking the binding sites (Module 30.9). This mechanism works essentially the same way in cardiac muscle fibers. In smooth muscle fibers Ca^{2+} binds to calmodulin, which is on the thick filament.

Module 30.9 A muscle contracts when thin filaments slide across thick filaments.

A. In the 1950s, Huxley proposed the **sliding-filament model** of muscle contraction. The model has been supported by considerable later research, and many molecular details have been added to it.
NOTE: The model originally attempted to explain one set of observations seen in living muscle: When the muscle contracts, the dark bands stay the same length, while the light bands decrease in length. When the muscle is fully contracted, an even darker band appears in the middle of the dark bands.

B. Contraction shortens the sarcomere but does not shorten the thick and thin filaments, which slide between each other (Figures 30.8 and 30.9A).

C. Energy-consuming interactions between the myosin molecules of the thick filaments and the actin molecules of the thin filaments cause them to slide along one another. The myosin molecules of the thick filament expose about 350 swollen "heads" per filament. These "walk" along the actin filaments with the expenditure of ATP. Each head can repeatedly move at about five movements per second. The process continues until the muscle fiber stops contracting or is fully contracted (Figure 30.9B).

D. Data suggest that ATP attaches to each head and, upon hydrolysis to ADP and phosphate, adds potential energy to the head ("cocks" it). Ca^{2+} opens a binding site on the adjacent actin molecule. When ADP and phosphate are released from the bound head, its energy is released, pulling the actin in a power stroke.

Module 30.10 Motor neurons stimulate muscle contraction.

Review: Neuron structure and function (Module 28.2).

A. Each muscle fiber is stimulated by just one neuron, but a single neuron can stimulate many fibers, up to several hundred in a large muscle moving the appendicular skeleton. Each such group of muscle fibers is known as a **motor unit** because each is stimulated to contract together (Figure 30.10A).

   NOTE: The fewer the number of muscle fibers per motor unit, the greater the degree of fine control over the muscle.

B. A weak contraction is produced by the stimulation of one motor unit. A strong contraction involves the simultaneous contractions of several motor units.

C. The synapses between neuron and muscle fiber are called **neuromuscular junctions.** The action potential is transmitted to the fiber through the release of the neurotransmitter acetylcholine.

   Review: Synapses and neurotransmitters (Modules 28.6–28.8).

D. At the cellular level, muscle fiber stimulation proceeds as follows. The released acetylcholine changes the permeability of the muscle fiber's plasma membrane. This induces an action potential along the muscle cell membrane and into tubular infoldings of the plasma membrane into the cell. Within the cell, the action potentials cause the endoplasmic reticulum (ER) to release Ca^{2+} into the cytoplasm. Calcium removes the regulatory protein on actin, thus triggering the binding of myosin to actin. When action potentials stop, Ca^{2+} moves back into the ER, allowing the regulatory protein to bind actin, causing the muscle to relax (Figure 30.10B).

Module 30.11 Connection: Athletic training increases strength and endurance.

A. Hallmarks of an elite athlete are mental toughness and the ability to ignore muscle pain and fatigue. The type of training program used by elite athletes helps prepare them for enduring great mental and physical exertion.

B. Recall that the source of energy that muscles use is in the form of ATP generated from glucose in the process of aerobic respiration. Endurance improves with **aerobic exercise** training programs. Aerobic exercise increases blood flow and mitochondria size, and strengthens the heart and circulatory system. Bone mass and strength also increases. But aerobic exercise must be balanced with **anaerobic exercise.**

C. Anaerobic exercise increases muscle power and mass. Anaerobic exercise is designed to push muscle contraction to its maximum, creating an oxygen deficit and therefore forcing anaerobic respiration. This process greatly improves muscle power and size.

D. Elite athletes use balanced exercise programs in an effort to increase muscle endurance, strength, and power (Figure 30.11). Even though most people will never be classified as an elite athlete, a well-balanced workout program that includes both aerobic and anaerobic exercise can improve cardiovascular health and overall body strength.

Module 30.12 The structure-function theme underlies all the parts and activities of an animal.

A. A baseball game, with its requirement for split-second decisions and precise actions, demonstrates some of the remarkable evolutionary adaptations of the human body (Figure 30.12A).

B. Likewise, the cooperative work and movements of individuals in a leaf-cutter ant colony also demonstrate the remarkable adaptations of those animals.

Class Activities

1. Students always enjoy seeing X-rays of broken bones; the worse the break, the more they enjoy it. See if you can find a series that illustrates the various stages of the healing of a broken bone. In such a series you can see the less dense new bone become increasingly dense.
2. Ask your class how the structure of the human skeleton reflects the evolutionary history of the lineage that led to humans. Ask them how they could improve upon the structure of the human skeleton; please ask them what improvements would help prevent some of the problems associated with aging.
3. The demonstrations of skeletal structures, joints, and antagonistic muscles will be much easier, and more dramatic, if you refer to a human skeleton (and, for the material in Figure 30.3B, a baboon skeleton). Some demonstration skeletons show antagonistic muscle insertions. If one is not available, use differently colored cords to demonstrate the locations and functions of antagonistic muscles on the upper arm or leg.
4. To demonstrate the function of hydrostatic skeletons and peristaltic movement, use earthworms on an overhead projector. Place them briefly in a shallow bowl of cool water. The light and temperature of the overhead will cause them to move rapidly away from the projector's heat. Other means of invertebrate movement, such as in shrimp or bivalve mollusks, can also be demonstrated in this way. Worms are available in bait stores or backyard compost piles. The other animals may not be available in all locations.
5. Many students will be interested in the human muscle groups from an athletic and/or body-building perspective. Have a local orthopedic surgeon describe and demonstrate the areas of human musculoskeletal anatomy that are especially vulnerable to injury.

Transparency Acetates

Chapter 30 Introduction: The structure of an ant leg

Figure 30.1D	An earthworm crawling, by peristalsis
Figure 30.1E	A bald eagle flying
Figure 30.2E	Bone (yellow) and cartilage (blue) in the endoskeleton of a vertebrate: a frog
Figure 30.3A	The human skeleton
Figure 30.3B	Bipedal and quadrupedal primate skeletons compared
Figure 30.3C	Three kinds of joints
Figure 30.5	The structure of an arm bone
Figure 30.7	Antagonistic action of muscles in the human arm
Figure 30.8	The contractile apparatus of skeletal muscle
Figure 30.9A	The sliding-filament model of muscle contraction
Figure 30.9B	The mechanism of filament sliding (Layer 1)
Figure 30.9B	The mechanism of filament sliding (Layer 2)
Figure 30.9B	The mechanism of filament sliding (Layer 3)
Figure 30.9B	The mechanism of filament sliding (Layer 4)
Figure 30.10A	The relation between motor neurons and muscle fibers
Figure 30.10B	Part of a muscle fiber (cell) at a neuromuscular junction

Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

Animations and Videos	File Name
Earthworm Movement Video	30-01D-EarthwormMoveVideo-B.mov
Earthworm Movement Video	30-01D-EarthwormMoveVideo-S.mov
Flapping Geese Video	30-01E-FlappingGeeseVideo-B.mov
Flapping Geese Video	30-01E-FlappingGeeseVideo-S.mov
Soaring Hawk Video	30-01E-SoaringHawkVideo-B.mov
Soaring Hawk Video	30-01E-SoaringHawkVideo-S.mov
Swans Taking Flight Video	30-01E-SwanFlightVideo-B.mov
Swans Taking Flight Video	30-01E-SwanFlightVideo-S.mov
Muscle Contraction Animation	30-09-MuscleContractionAnim.mov

Activities and Thinking as a Scientist	Module Number
Web/CD Activity 30A: *The Human Skeleton*	30.3
Web/CD Activity 30B: *Skeletal Muscle Structure*	30.8
Web/CD Activity 30C: *Muscle Contraction*	30.9
Web/CD Thinking as a Scientist: *How Do Electrical Stimuli Affect Muscle Contraction?*	30.10