# Muscles and Muscle Tissue Outline

9.1. There are three types of muscle tissues (pp. 279–280)

A. Skeletal muscle is associated with the bony skeleton and consists of large cells that bear striations and are under voluntary control. (p. 279)

B. Cardiac muscle, found only in the heart, consists of small cells that are striated and under involuntary control. (p. 279)

C. Smooth muscle is found in the walls of hollow organs, and consists of small, elongated, unstriated cells that are under involuntary control. (p. 279)

D. Characteristics of Muscle Tissue (p. 279)

1. Excitability, or responsiveness, is the ability to receive and respond to a stimulus.
2. Contractility is the ability to contract forcibly when stimulated.
3. Extensibility is the ability to be stretched.
4. Elasticity is the ability to resume the cells' original length once stretched.

E. Muscle Functions (pp. 279–280; Table 9.1)

1. Muscles produce movement by acting on the bones of the skeleton, pumping blood, or propelling substances throughout hollow organ systems.
2. Muscles aid in maintaining posture by adjusting the position of the body with respect to gravity.
3. Muscles stabilize joints by exerting tension around the joint.
4. Muscles generate heat as a function of their cellular metabolic processes.
5. Muscles enclose and protect internal organs, form valves that regulate passage of substances in the body, control the size of the pupil of the eye, and attach to hair follicles as arrector pili muscles.

9.2. A skeletal muscle is made up of muscle fibers, nerves, blood vessels, and connective tissues (pp. 280–282; Fig. 9.1)

A. Each skeletal muscle is a discrete organ, in which muscle fibers predominate, but also includes blood vessels, nerves, and connective tissue. (pp. 280–282; Fig. 9.1)

1. Nerve and blood supply allows neural control and ensures adequate nutrient delivery and waste removal.
2. Connective tissue sheaths are found at various structural levels of each muscle: endomysium surrounds each muscle fiber, perimysium surrounds groups of muscle fibers, and epimysium surrounds whole muscles.
3. Skeletal muscles span joints and cause movement to occur from the movable attachment (the muscle's insertion) toward the less movable attachment (the muscle's origin).
4. Muscle attachments may be direct, in which the epimysium fuses with the periosteum or perichondrium; or indirect, in which the connective tissue wrappings of the muscle extend into a rope-like or sheet-like structure that attaches to the bone, cartilage, or fascia.
   a. Indirect attachments, either rope-like tendons, or sheet-like aponeuroses, are the most common because they are durable and are small in size, conserving space across joints.

9.3 Skeletal muscle fibers contain calcium-regulated molecular motors (pp. 282–288; Figs. 9.2–9.6; Table 9.1)

A. Skeletal muscle fibers are large, cylindrical cells with multiple nuclei beneath the sarcolemma, or plasma membrane. (p. 282)

B. Sarcoplasm, the cytoplasm of a muscle cell, is similar to other types of cells, except it has large amounts of glycosomes, for glycogen storage, and myoglobin, an oxygen-binding pigment similar to hemoglobin. (p. 282)

C. Myofibrils account for roughly 80% of cellular volume and contain the contractile elements of the muscle cell. (pp. 282–285; Figs. 9.2–9.4; Table 9.1)

1. Striations are due to a repeating series of dark A bands and light I bands.
2. Myofilaments make up the myofibrils and consist of thick and thin filaments.
3. Striations, alternating dark A bands and light I bands, extend the length of each myofibril.
   a. Each A band has a lighter central region, the H zone, which is bisected vertically by an M line.
   b. Each I band is bisected vertically by a Z disc, and the region extending from one Z disc to the next forms a sarcomere, the smallest contractile unit of a muscle cell.
4. There are two types of myofilaments in muscle cells: thick filaments composed of bundles of myosin, and thin filaments composed of strands of actin.
   a. Each myosin filament consists of myosin molecules that have a rod-like tail attached to two globular heads that form cross bridges with actin during contraction.
   b. Actin filaments consist of polymerized G actin subunits that have active sites that bind myosin heads during contraction.
5. Thin filaments also have a set of regulatory proteins: tropomyosin, that wrap around actin filaments, stabilizing it and blocking myosin binding sites; and troponin, which binds to both actin and tropomyosin, and binds calcium ions.

D. The sarcoplasmic reticulum, a smooth endoplasmic reticulum that regulates the availability of calcium ions, surrounds each myofibril, and forms terminal cisterns at the A band–I band junction. (pp. 285–288; Fig. 9.5; Table 9.1)

1. T tubules are infoldings of the sarcolemma that run between the terminal cisterns, forming triads, that conduct electrical impulses into the cell to cause release of calcium ions from the terminal cisterns.

E. The sliding filament model of muscle contraction states that during contraction, the thin filaments slide past the thick filaments. Overlap between the myofilaments increases and the sarcomere shortens. (p. 288; Fig. 9.6)

9.4 Motor neurons stimulate skeletal muscle fibers to contract (pp. 288–296; Figs. 9.6–9.9; Focus Figures 9.1–9.3)

A. The neuromuscular junction is a connection between an axon terminal of a somatic motor neuron and a muscle fiber that is the route of electrical stimulation of the muscle cell (p. 289; Focus Figure 9.1)

1. The axon terminal and muscle fiber are separated by a narrow gap, the synaptic cleft.
2. Within the axon terminal are synaptic vesicles containing the neurotransmitter acetylcholine, or Ach; while junctional folds of the muscle cell contain millions of Ach receptors.
3. A motor neuron stimulates a skeletal muscle fiber when a nerve impuls causes the release of ACh to the synaptic cleft, which diffuses across the cleft and binds to ACh receptors on the sarcolemma, creating electrical events that lead to the generation of an action potential.
4. After acetylcholine binds to ACh receptors, an enzyme in the synaptic cleft, acetylcholinesterase, breaks down acetylcholine to acetic acid and choline, to prevent continued contraction in the absence of stimulation.

B. Generation of an Action Potential Across the Sarcolemma (pp. 289–294; Figs. 9.8–9.9; Focus Figure 9.1)
1. Generation of an end plate potential occurs when ACh binds to ACh receptors at the neuromuscular junction, causing chemically gated ion channels to open: more $Na^+$ diffuses in than $K^+$ diffuses out, and the membrane depolarizes.
2. The end plate potential triggers an action potential, which propagates along the sarcolemma by causing the opening of voltage gated $Na^+$ channels.
3. Repolarization occurs when voltage gated $Na^+$ channels close, and voltage gated $K^+$ channels open, restoring the resting polarity to the sarcolemma.
   a. During repolarization, the muscle cell is in a refractory period and may not be depolarized until repolarization is complete.

C. Excitation-contraction coupling is the sequence of events by which an action potential on the sarcolemma results in the sliding of the myofilaments. (p. 294; Focus Figure 9.2)
1. A nerve impulse reaches the axon terminal, causing release of ACh to the synaptic cleft.
2. ACh binds to ACh receptors in the sarcolemma, and a net influx of sodium ions causes the generation of an end plate potential.
3. Voltage-gated sodium channels open, allowing the generation and propagation of an action potential on the sarcolemma.
4. Transmission of the action potential along the T tubules, stimulating the release of calcium ions from the sarcoplasmic reticulum to the cytosol.

D. Muscle Fiber Contraction: Cross-Bridge Cycling (pp. 294–296; Focus Figure 9.3)
1. As calcium levels in the cytosol increase, calcium binds to troponin, which causes tropomyosin to slide away from the binding sites for myosin on the actin filaments.
2. Energized myosin heads bind to actin and perform a power stroke, causing actin to slide over myosin.

9.5 Wave summation and motor unit recruitment allow smooth, graded skeletal muscle contractions (pp. 296–301; Figs. 9.10–9.15)

A. A motor unit consists of a motor neuron and all the muscle fibers it innervates. It is smaller in muscles that exhibit fine control. (p. 297; Fig. 9.10)

B. The muscle twitch is the response of a muscle to a single action potential on its motor neuron, and has three phases: the latent period, corresponding to the lag between stimulation and excitation-contraction coupling, the period of contraction, and the period of relaxation. (p. 297; Fig. 9.11)

C. Graded Muscle Responses (pp. 297–299; Figs. 9.12–9.14)

1. Muscle contractions are smooth and vary in strength, leading to different kinds of graded muscle responses.
   a. Wave summation occurs when impulses reach the muscle in rapid succession, preventing the cell from relaxing between stimulation events, ultimately causing contraction to become sustained, a condition called tetanus.
   b. Multiple motor unit summation (recruitment) involves the response of a muscle to increasing stimulus voltage: smaller stimuli result in contraction of the smallest motor units, and as voltage increases, larger, more forceful motor units respond, leading to progressively greater contractile force.

D. Isotonic and Isometric Contractions (pp. 300–301; Fig. 9.15)

1. Isotonic contractions produce uniform tension in a muscle, once a load has been overcome, and result in movement occurring at the joint and a change of length of muscles.
   a. Concentric isotonic contractions result when a muscle generates force when it shortens, while in eccentric isotonic contractions, the muscle generates force as it lengthens.
2. Isometric contractions result in increases in muscle tension, but no lengthening or shortening of the muscle occurs, and often are used to maintain posture or joint stability while movement occurs at other joints.

## 9.6 ATP for muscle contraction is produced aerobically or anaerobically (pp. 301–304; Figs. 9.16–9.17)

A. Providing Energy for Contraction (pp. 301–304; Figs. 9.16–9.17)

1. Muscles contain very little stored ATP, and consumed ATP is replenished rapidly through phosphorylation by creatine phosphate, anaerobic glycolysis, and aerobic respiration.
2. As muscle metabolism transitions to meet higher demand during vigorous exercise, consumed ATP is regenerated by transferring a phosphate to consumed ATP from creatine phosphate, a molecule unique to muscle tissue.
3. As stored ATP and creatine phosphate are consumed, ATP is produced by breaking down blood glucose or stored glycogen in glycolysis, an anaerobic pathway that precedes both aerobic and anaerobic respiration. If adequate oxygen is not available to support aerobic respiration, anaerobic glycolysis converts the pyruvate formed from glycolysis into lactic acid.
   a. This pathway produces only about 5% the ATP from each glucose compared to the aerobic pathway, but ATP production occurs 2½ times faster.
   b. Most of the lactic acid produced is released to the bloodstream and taken to the liver, heart, or kidneys for use, but the lactic acid that remains in the muscle contributes to muscle soreness following exercise.

4. Aerobic respiration provides most of the ATP during light to moderate activity, includes glycolysis, along with reactions that occur within the mitochondria, and produces 32 ATP per glucose, as well as water, and $CO_2$, which will be lost from the body in the lungs.
5. Muscles function aerobically as long as there is adequate oxygen and nutrient delivery to support it, but when exercise demands for ATP exceed the production ability of aerobic reactions, the cell will switch to anaerobic pathways.

B. Muscle fatigue is the physiological inability to contract, and results from ionic imbalances that interfere with normal excitation-contraction coupling. (p. 304)

C. Excess postexercise oxygen consumption (EPOC) is the extra oxygen the body requires following exercise to replenish oxygen on myoglobin, reconvert lactic acid to pyruvic acid, replace stored glycogen, and restore ATP and creatine phosphate reserves. (p. 304)

9.7 The force, velocity, and duration of skeletal muscle contractions are determined by a variety of factors (pp. 304–307; Figs. 9.18–9.21; Table 9.2)

A. Force of Muscle Contraction (pp. 304–305; Figs. 9.18–9.19)
1. As the number of muscle fibers stimulated increases, force of contraction increases.
2. Large muscle fibers generate more force than smaller muscle fibers.
3. As the rate of stimulation increases, contractions sum up, ultimately producing tetanus, allowing the external tension generated by the connective tissue elements to approach internal tension generated by the muscle fibers, increasing contractile force.
4. The length–tension relationship optimizes the overlap between the thick and thin filaments that produces optimal contraction.

B. Velocity and Duration of Contraction (pp. 305–307; Figs. 9.20–9.21; Tables 9.2–9.3)
1. There are three muscle fiber types: slow oxidative fibers, fast glycolytic fibers, and fast oxidative fibers.
   a. Slow oxidative fibers contract slowly, rely mostly on aerobic respiration, and are highly fatigue resistant.
   b. Fast glycolyic fibers contract rapidly, use anaerobic respiration, depend heavily on glycogen, but fatigue quickly.
   c. Fast oxidative fibers are a less common, intermediate type of fiber that provide rapid contraction, but have excellent capillary penetration for oxygen and nutrient delivery, and rely on aerobic respiration.
2. All muscles have varying amounts of all fiber types and, while the proportion of each type is a genetically influenced trait, that proportion can be modified by specific types of exercise.
3. As the load on a muscle increases, velocity and duration of contraction decreases.
4. Recruitment of additional motor units increases velocity and duration of contraction.

9.8 How does skeletal muscle respond to exercise? (pp. 307–308)

A. Aerobic exercise promotes an increase in capillary penetration, the number of mitochondria, and synthesis of myoglobin, leading to higher efficiency

and endurance, while possibly converting fast glycolytic fibers to fast oxidative fibers. (p. 307)

B. Resistance exercise, such as weight lifting or isometric exercise, promotes an increase in the number of mitochondria, myofilaments and myofibrils, and glycogen storage, producing hypertrophied cells that may change from fast oxidative to fast glycolytic fibers. (pp. 307–308)

## 9.9 Smooth muscle is nonstriated involuntary muscle (pp. 308–314; Figs. 9.22–9.25; Table 9.3)

A. Microscopic Structure of Smooth Muscle Fibers (pp. 308–311; Figs. 9.22–9.24; Table 9.3)

1. Smooth muscle cells are small, spindle-shaped cells with one central nucleus, and lack the coarse connective tissue coverings of skeletal muscle.
2. Smooth muscle cells are usually arranged into sheets of opposing fibers, forming a longitudinal layer and a circular layer.
3. Contraction of the opposing layers of muscle leads to a rhythmic form of contraction, called peristalsis, which propels substances through the organs.
4. Smooth muscle lacks neuromuscular junctions, but has varicosities: numerous bulbous swellings that release neurotransmitters to a wide synaptic cleft.
5. Smooth muscle cells have a less developed sarcoplasmic reticulum, sequestering large amounts of calcium in extracellular fluid within caveolae in the cell membrane.
6. Smooth muscle has no striations, no sarcomeres, a lower ratio of thick to thin filaments compared with skeletal muscle, and has tropomyosin but no troponin.
7. Smooth muscle fibers contain longitudinal bundles of noncontractile intermediate filaments anchored to the sarcolemma and surrounding tissues via dense bodies.

B. Contraction of Smooth Muscle (pp. 312–313; Fig. 9.25; Table 9.3)

1. Mechanism of Contraction
   a. Smooth muscle fibers exhibit slow, synchronized contractions due to electrical coupling by gap junctions.
   b. Like skeletal muscle, actin and myosin interact by the sliding filament mechanism; contraction is triggered by a rise in intracellular calcium level, and the process is energized by ATP.
   c. During excitation-contraction coupling, calcium ions enter the cell from the extracellular space, bind to calmodulin, and activate an enzyme, myosin light chain kinase, powering the cross-bridging cycle.
   d. Smooth muscle contracts more slowly and consumes less ATP than skeletal muscle.
2. Regulation of Contraction
   a. Autonomic nerve endings release either acetylcholine or norepinephrine, which may result in excitation of certain groups of smooth muscle cells, and inhibition of others.
   b. Hormones and local factors, such as lack of oxygen, histamine, excess carbon dioxide, or low pH, act as signals for contraction.
3. Special Features of Smooth Muscle Contraction

a. Smooth muscle initially contracts when stretched, but contraction is brief, and then the cells relax to accommodate the stretch.
b. Because the muscle filaments have an irregular overlapping pattern, smooth muscle stretches more and generates more tension when stretched than skeletal muscle.
c. Hyperplasia, an increase in cell number through division, is possible in addition to hypertrophy, an increase in individual cell size.

C. Types of Smooth Muscle (p. 313)
1. Unitary smooth muscle, called visceral muscle, is the most common type of smooth muscle. It contracts rhythmically as a unit, is electrically coupled by gap junctions, and exhibits spontaneous action potentials.
2. Multi-unit smooth muscle is located in large airways to the lungs, large arteries, arrector pili muscles in hair follicles, and the iris of the eye. It consists of cells that are structurally independent of each other, has motor units, and is capable of graded contractions.

## Developmental Aspects of Muscles (pp. 314–317; Fig. 9.26)

A. Nearly all muscle tissue develops from specialized mesodermal cells called myoblasts. (p. 312)
B. Skeletal muscle fibers form through the fusion of several myoblasts, and are actively contracting by week 7 of fetal development. (p. 312; Fig. 9.29)
C. Myoblasts of cardiac and smooth muscle do not fuse but form gap junctions at a very early stage. (p. 312)
D. Muscular development in infants is mostly reflexive at birth, and progresses in a head-to-toe and proximal-to-distal direction. (p. 312)
E. Women have relatively less muscle mass than men due to the effects of the male sex hormone testosterone, which accounts for the difference in strength between the sexes. (p. 312)
F. Muscular dystrophy is characterized by atrophy and degeneration of muscle tissue. Enlargement of muscles is due to fat and connective tissue deposit. (pp. 312, 315)