10 Skeletal Muscle Tissue

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Contracted striated muscle fibers containing myelinated nerve fibers (colored TEM).

Muscle is from a Latin word meaning "little mouse," a name given because flexing muscles look like mice scurrying beneath the skin. Indeed, the rippling skeletal muscles of weight lifters are often the first thing that comes to mind when one hears the word *muscle.* However, muscle is also the main tissue in the heart and in the walls of other hollow organs. Recall from Chapter 4 that muscle tissue is a composite tissue composed of muscle cells and surrounding connective tissues. In all its forms, muscle tissue makes up nearly half the body's mass.

OVERVIEW OF MUSCLE TISSUE

- List four functional properties that distinguish muscle tissue from other tissues.
- Compare and contrast skeletal, cardiac, and smooth muscle tissue.

Functions

Muscle tissue has the following functions:

1. **Movement.** Skeletal muscle attaches to the skeleton and moves the body by moving the bones. The muscle in the walls of visceral organs produces movement by squeezing fluids and other substances through these hollow organs.
2. **Maintenance of posture.** At times, certain skeletal muscles contract continuously to maintain posture, enabling the body to remain in a standing or sitting position.
3. **Joint stabilization.** The role of muscle tone in stabilizing and strengthening joints was discussed in Chapter 9.
4. **Heat generation.** Muscle contractions produce heat that plays a vital role in maintaining normal body temperature at 37°C (98.6°F).

Muscle tissue has some special functional characteristics that distinguish it from other tissues:

1. **Contractility.** One significant characteristic is that muscle contracts forcefully. Muscle cells shorten and generate a strong pulling force as they contract.
2. **Excitability.** Nerve signals or other factors excite muscle cells, causing electrical impulses to travel along the cells' plasma membrane. These impulses then stimulate the cells to contract.
3. **Extensibility.** Muscle tissue can be stretched by the contraction of an opposing muscle.
4. **Elasticity.** After being stretched, muscle tissue can recoil passively and resume its resting length.

Types of Muscle Tissue

There are three types of muscle tissue: *skeletal, cardiac,* and *smooth.* Each type can be characterized by two main features: (1) the presence or absence of light and dark stripes, called *striations,* in the muscle cells and (2) whether control is voluntary or involuntary. Striated muscle tissue has stripes extending transversely across the muscle cells that are visible when the muscle tissue is viewed histologically. Nonstriated muscle does not have these distinctive bands. *Voluntary* and *involuntary* refer to the innervation of the muscle tissue. Voluntary muscle tissue is innervated by voluntary motor nerves and is subject to conscious control; you can control this muscle tissue at will. Involuntary muscle tissue is innervated by the involuntary portion of the nervous system and cannot be controlled consciously.

Skeletal muscle tissue is located in the **skeletal muscles,** discrete organs that attach to and move the skeleton. This tissue makes up a full 40% of body weight. The muscle cells of skeletal muscle tissue are striated (see Figure 4.12a, p. 90), and its contraction is subject to voluntary control. The details of the structure and function of skeletal muscle are covered in this chapter and are summarized in Table 10.1, p. 249.

Cardiac muscle tissue occurs only in the wall of the heart. The muscle cells of cardiac muscle tissue are striated (see Figure 4.12b, p. 91), but its contraction is involuntary, which means that as a rule, we have no direct conscious control over how fast our heart beats.

Most **smooth muscle tissue** in the body is found in the walls of hollow internal organs other than the heart, such as the stomach, urinary bladder, blood vessels, and respiratory passages. The muscle cells of smooth muscle tissue lack striations (see Figure 4.12c, p. 91), and like cardiac muscle tissue, smooth muscle tissue is under involuntary control.

Sometimes, cardiac and smooth muscle tissues are collectively called *visceral muscle,* a term reflecting the fact that both occur in the visceral organs. The properties of the three types of muscle tissue are summarized in Table 10.2, pp. 254–255. The details of cardiac muscle tissue structure and function are described in Chapter 19. The detailed structure and function of smooth muscle tissue are covered in Chapter 23.

Although there are numerous differences among the three types of muscle tissue, there are also important similarities. First, the muscle cells of skeletal and smooth muscle tissue (but not cardiac muscle tissue) are called **fibers** because they are elongated. Second, in all three types of muscle tissue, muscle contraction depends on **myofilaments** (*myo* = muscle). Myofilaments are specific types of microfilaments that are responsible for the shortening of muscle cells. There are two kinds of myofilaments, one containing the protein *actin* and the other containing the protein *myosin.* Recall from p. 34 that these two proteins generate contractile force in every cell in the body. This contractile property is most highly developed in muscle cells. The third similarity among the muscle tissues is one of terminology: The plasma membrane of muscle cells, instead of being called either a plasma membrane or a plasmalemma, is called a **sarcolemma** (sar″-ko-lem′ah) (*sarcos* = flesh or muscle; *lemma* = sheath), the cytoplasm is called **sarcoplasm,** and the endoplasmic reticulum, specialized for the storage of calcium, is called the *sarcoplasmic reticulum.* Despite the different terms, the membranes and cytoplasm of muscle cells are not fundamentally different from those of other cell types.

check your understanding

1. What are the structural similarities shared by all muscle tissue? What are the unique functional characteristics of this tissue?
2. Which types of muscle tissue are striated? Which types are called visceral muscle?

For answers, see Appendix B.

SKELETAL MUSCLE

Each muscle is an organ made of several kinds of tissue: In addition to skeletal muscle tissue, a muscle also contains connective tissue, blood vessels, and nerves. The following sections examine skeletal muscle anatomy from the gross level to the microscopic level.

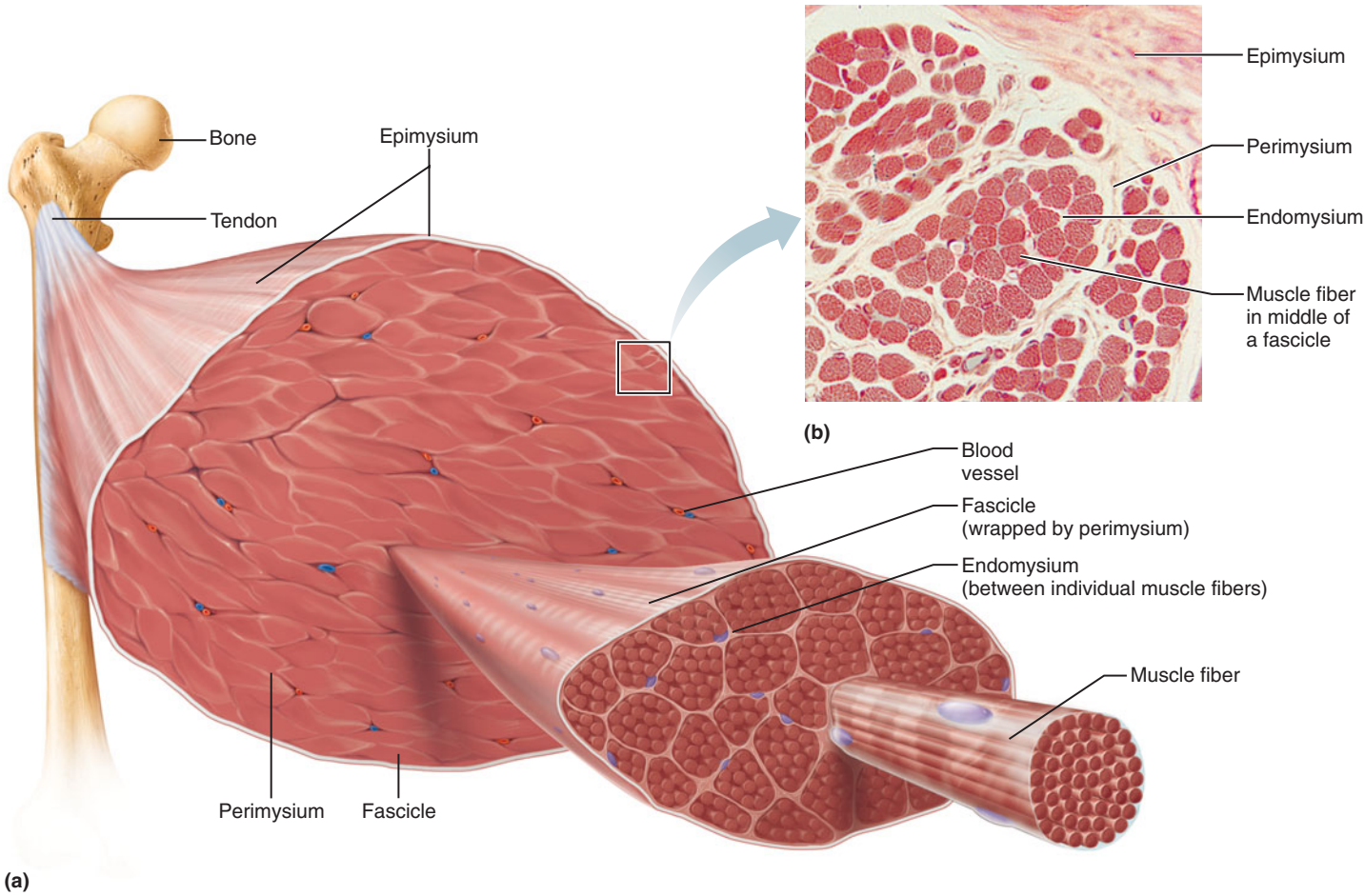


FIGURE 10.1 Connective tissue sheaths in skeletal muscle: epimysium, perimysium, and endomysium. (a) Illustration. **(b)** Photomicrograph of a cross section of part of a skeletal muscle (10×). (See *A Brief Atlas of the Human Body,* Second Edition, Plate 29.)

Basic Features of a Skeletal Muscle

- Name the layers of connective tissue that occur in and around a skeletal muscle, and briefly describe a muscle's blood and nerve supply.
- Define muscle fascicles.
- Describe the various ways in which muscles attach at their origins and insertions.

Connective Tissue and Fascicles

Several sheaths of connective tissue hold the fibers of a skeletal muscle together. These sheaths, from external to internal, are as follows **(Figure 10.1)**:

1. **Epimysium.** An "overcoat" of dense, irregular connective tissue surrounds the whole skeletal muscle. This coat is the **epimysium** (ep″ĭ-mis′e-um), a name that means "outside the muscle." Sometimes the epimysium blends with the deep fascia that lies between neighboring muscles.
2. **Perimysium.** Within each skeletal muscle, the muscle fibers are separated into groups. Each group, which resembles a bundle of sticks tied together, is called a **fascicle** (fas′ĭ-kl; "bundle"). Surrounding each fascicle is a layer of fibrous connective tissue called **perimysium** (per″ĭ-mis′e-um; "around the muscle [fascicle]").
3. **Endomysium.** Within a fascicle, each muscle fiber is surrounded by a fine sheath of loose connective tissue consisting mostly of reticular fibers. This layer is the **endomysium** (en″do-mis′e-um; "within the muscle").

These fibrous connective tissues bind muscle fibers together and hold them in parallel alignment so they can work together to produce force. The continuity between these sheaths is apparent in Figure 10.1b, and all three sheaths are continuous with the **tendon,** the connective tissue structure that joins skeletal muscles to bones (Figure 10.1a). When muscle fibers contract, they pull on the surrounding endomysium. Because of the continuity between sheaths, this pull is then exerted on the perimysium, epimysium, and tendon, a sequence that transmits the force of contraction to the bone being moved. The sheaths also provide a muscle with much of its natural elasticity and carry the blood vessels and nerves that serve the muscle fibers.

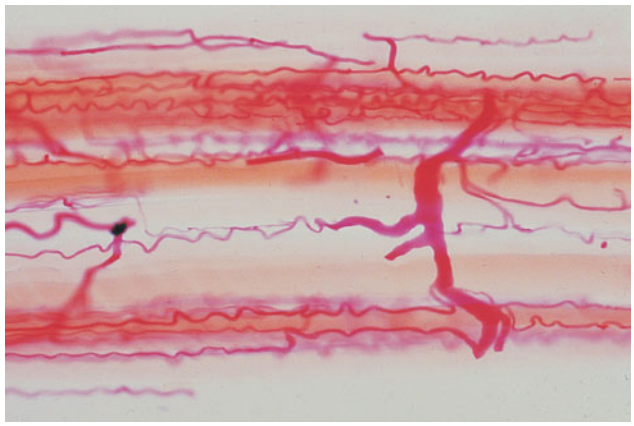


FIGURE 10.2 Photomicrograph of the capillary network surrounding skeletal muscle fibers. The arterial supply was injected with dark red gelatin to demonstrate the capillary bed. The muscle fibers, which run horizontally across the photograph, are stained orange. Note the wavy appearance of the thinnest capillaries (22×).

Nerves and Blood Vessels

In general, each skeletal muscle is supplied by one nerve, one artery, and one or more veins—all of which enter or exit the muscle near the middle of its length. The nerves and vessels branch repeatedly in the intramuscular connective tissue, with the smallest branches serving individual muscle fibers.

The rich blood supply to muscles reflects the high demand that contracting muscle fibers have for nutrients and oxygen. Capillaries in the endomysium form a network (Figure 10.2). These long capillaries are wavy when the muscle fibers contract and stretched straight when the muscle extends.

The innervation of skeletal muscle is described later in this chapter (p. 248).

Muscle Attachments

A muscle attachment is the location on a bone where a muscle connects to the bone. Each skeletal muscle extends from one bone to another, crossing at least one movable joint. When the muscle contracts, it causes one of the bones to move while the other bone usually remains fixed. The attachment of the muscle on the less movable bone is called the **origin** of the muscle, whereas the attachment on the more movable bone is called the muscle's **insertion** (Figure 10.3). Thus, when the muscle contracts, its insertion is pulled toward its origin. In the muscles of the limbs, the origin is by convention the more proximal attachment of the muscle, and the insertion is the more distal attachment. However, it is important to realize that the functions of the origin and the insertion may switch, depending on body position and the movement produced when the muscle contracts. For example, the conventional attachments for the brachialis muscle in the arm are origin on the shaft of the humerus and insertion on the proximal ulna, as Figure 10.3 shows. These are accurate terms when referring to the usual position of the limb and the function of this muscle, which is flexing the forearm, as when you lift an object. Consider, though, the position of the upper limb and its movement when you are hanging from a bar doing chin-ups. In this situation, it is the humerus that moves, not the ulna. Thus the conventional origin of the brachialis is the attachment that moves, and the insertion is stable.

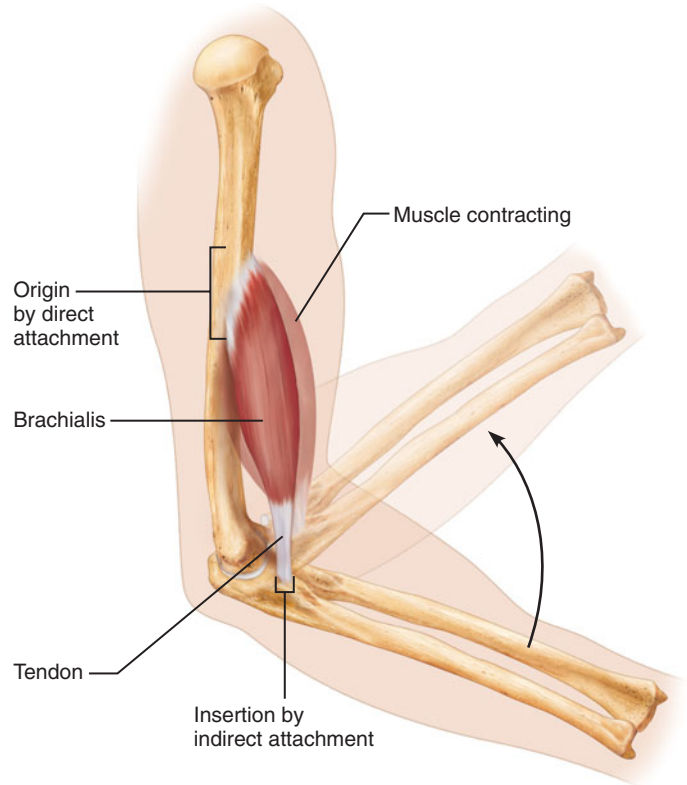


FIGURE 10.3 Muscle attachments (origin and insertion). When a skeletal muscle contracts, its insertion is pulled toward its origin.

Many muscles span two or more joints. Such muscles are called *biarticular* ("two-joint") *muscles* or *multijoint muscles.* For example, look at Figure 10.3 and imagine a muscle that originates on the humerus, runs along the forearm without attaching to the radius or ulna, and inserts on the carpals. Contraction of such a muscle would cause movements at two joints: the elbow and the wrist.

Muscles attach to their origins and insertions via strong fibrous connective tissues that extend into the fibrous periosteum of the bone. In *direct,* or *fleshy, attachments,* the attaching strands of connective tissue are so short that the muscle fascicles themselves appear to attach directly to the bone. In *indirect attachments,* the connective tissue extends well beyond the end of the muscle fibers to form either a cordlike tendon or a flat sheet called an **aponeurosis** (ap″o-nu-ro′sis). Indirect attachments are more common than direct attachments, and most muscles have tendons. Raised bone markings are often present where tendons meet bones. These markings include tubercles, trochanters, and crests (see Table 6.1 on p. 131). Although most tendons and aponeuroses attach to bones, a few attach to skin, to cartilage, to sheets of fascia, or to a seam of fibrous tissue called a **raphe** (ra′fe; "seam").

(a) Photomicrograph of **portions of two isolated muscle fibers** (400×). Notice the obvious striations (alternating dark and light bands).

(b) Diagram of **part of a muscle fiber** showing the myofibrils. One **myofibril** is extended from the cut end of the fiber.

(c) Small part of one **myofibril enlarged to show the myofilaments** responsible for the banding pattern. Each **sarcomere** extends from one Z disc to the next.

(d) Enlargement of one sarcomere (sectioned lengthwise). Notice the myosin heads on the thick filaments.

(e) Cross-sectional view of a sarcomere cut through in different locations.

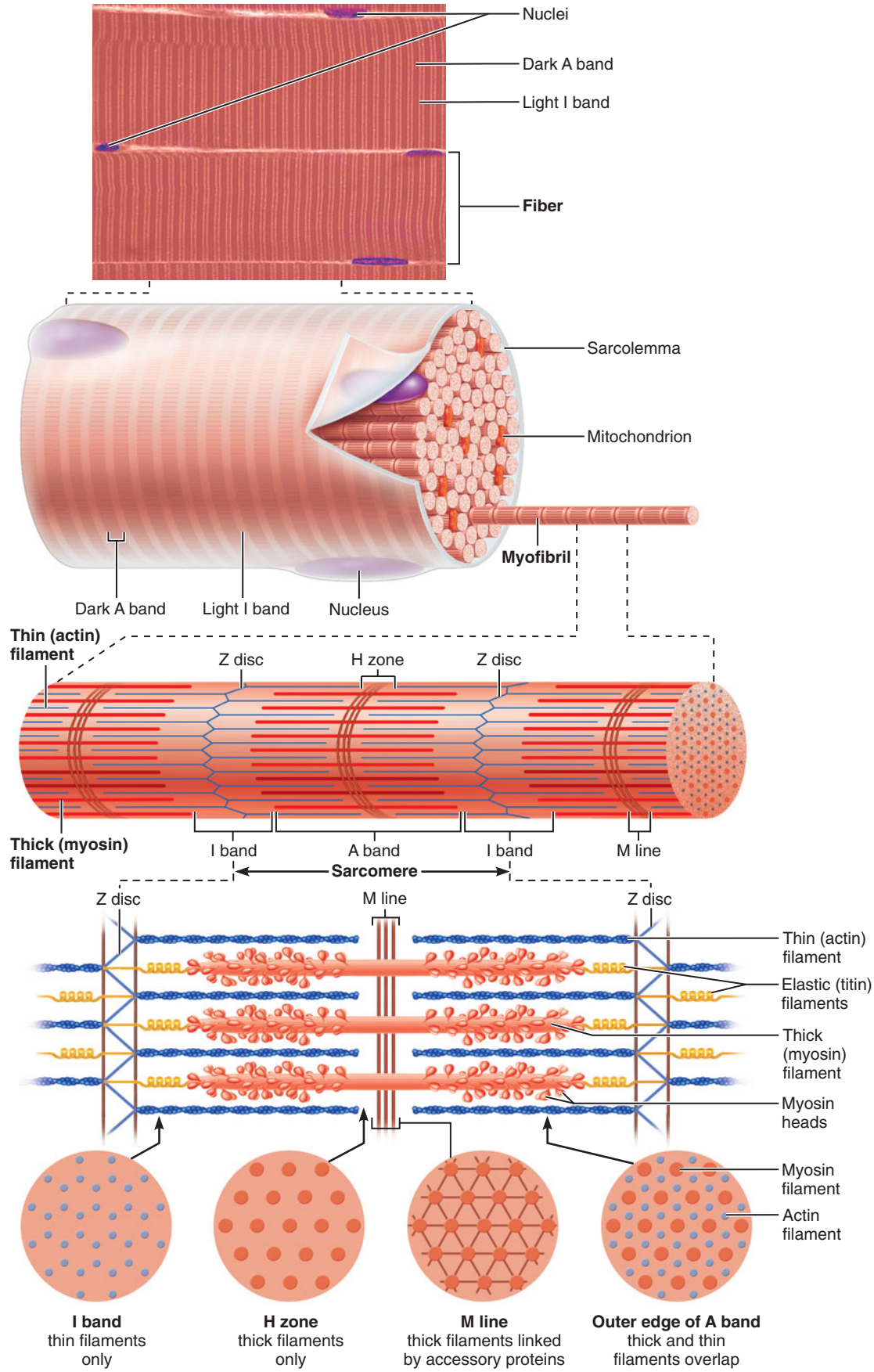


FIGURE 10.4 Microscopic anatomy of the skeletal muscle fiber (cell). (See *A Brief Atlas of the Human Body,* Second Edition, Plate 28.)

check your understanding

3. Name the connective tissue that surrounds a fascicle.
4. What are the functional definitions of the origin and insertion of a muscle? In the limbs, what are the conventional definitions of a muscle's origin and insertion?

For answers, see Appendix B.

Microscopic and Functional Anatomy of Skeletal Muscle Tissue

- Describe the microscopic structure of a skeletal muscle fiber and the arrangement of its contractile thick and thin filaments into sarcomeres and myofibrils.
- Describe the structure and functions of sarcoplasmic reticulum and T tubules in muscle fibers.
- Explain the sliding filament mechanism of muscle contraction, including the role of titin.
- Describe the innervation of skeletal muscle fibers at neuromuscular junctions. Define a motor unit.
- Compare and contrast the three kinds of skeletal muscle fibers.

The Skeletal Muscle Fiber

Skeletal muscle fibers are long, cylindrical cells (**Figure 10.4a** and **b**). They are huge cells, relatively speaking. Their diameter is 10–100 μm (up to ten times that of an average body cell), and their length is phenomenal: from several centimeters in short muscles to dozens of centimeters in long muscles. It would be inaccurate to call skeletal muscle fibers the biggest cells in the body, however, because each one was formed by the fusion of hundreds of embryonic cells. Because the fibers develop this way, they contain many nuclei. These nuclei lie at the periphery of each fiber, just deep to the sarcolemma (Figure 10.4b).

Myofibrils and Sarcomeres

Under the light microscope, the light and dark striations in skeletal muscle fibers are clearly visible. These striations result from the internal structure of long, rod-shaped organelles called **myofibrils.** Myofibrils are unbranched cylinders that are present in large numbers, making up more than 80% of the sarcoplasm. They are specialized contractile organelles unique to muscle tissue. Note that these are *fibrils,* as distinguished from the larger *fibers* (= muscle cells) and the smaller *myofilaments* (described earlier and discussed in detail shortly) in the following way: Myofilaments are contractile proteins located within the myofibril. The myofibril is an organelle within the muscle fiber. The relationship between these three structures is shown in Table 10.1, p. 249.

The myofibrils in a fiber are separated from one another by other components of the sarcoplasm **(Figure 10.5)**. Among those components are mitochondria and glycosomes, both of which supply energy for muscle contraction. Unfortunately, distinguishing individual myofibrils in histological sections is difficult (Figure 10.4a) because the striations of adjacent myofibrils line up almost perfectly.

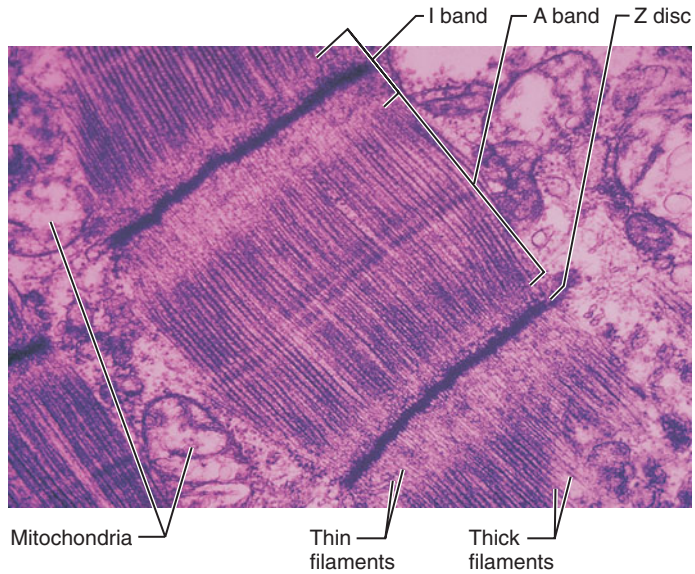


FIGURE 10.5 Sarcoplasm of a skeletal muscle fiber. Electron micrograph shows parts of two myofibrils. Other components of sarcoplasm, such as mitochondria and glycosomes shown here, separate adjacent myofibrils (16,000×).

A myofibril is a long row of repeating segments called **sarcomeres** (sar′ko-mērz; "muscle segments") (Figure 10.4c and d). The sarcomere is the basic unit of contraction in skeletal muscle. The boundaries at the two ends of each sarcomere are called **Z discs** (or sometimes **Z lines**). Attached to each Z disc and extending toward the center of the sarcomere are many fine myofilaments called **thin (actin) filaments,** which consist primarily of the protein actin, although they contain other proteins as well. In the center of the sarcomere and overlapping the inner ends of the thin filaments is a cylindrical bundle of **thick (myosin) filaments.** Thick filaments consist largely of myosin molecules. They also contain ATPase enzymes that split ATP (energy-storing molecules) to release the energy required for muscle contraction. Both ends of a thick filament are studded with knobs called *myosin heads* (Figure 10.4d).

The sarcomere structure explains the pattern of striations in skeletal muscle fibers. The dark bands are created by the full length of the thick filaments in the sarcomeres, along with the inner ends of the thin filaments, which overlap the thick filaments. This region of each sarcomere is called the **A band** (Figure 10.4c). The central part of an A band, where no thin filaments reach, is the **H zone.** The **M line** in the center of the H zone contains tiny rods that hold the thick filaments together (Figure 10.4d). The two regions on either side of the A band, regions that contain only thin filaments, are called the **I bands.** It is the I bands of the sarcomeres that create the light portions of the light-dark pattern of striations seen along the length of any skeletal muscle fiber. Notice in Figure 10.4c that each I band is part of two adjacent sarcomeres and has a Z disc running through its center. Recall that the striations of

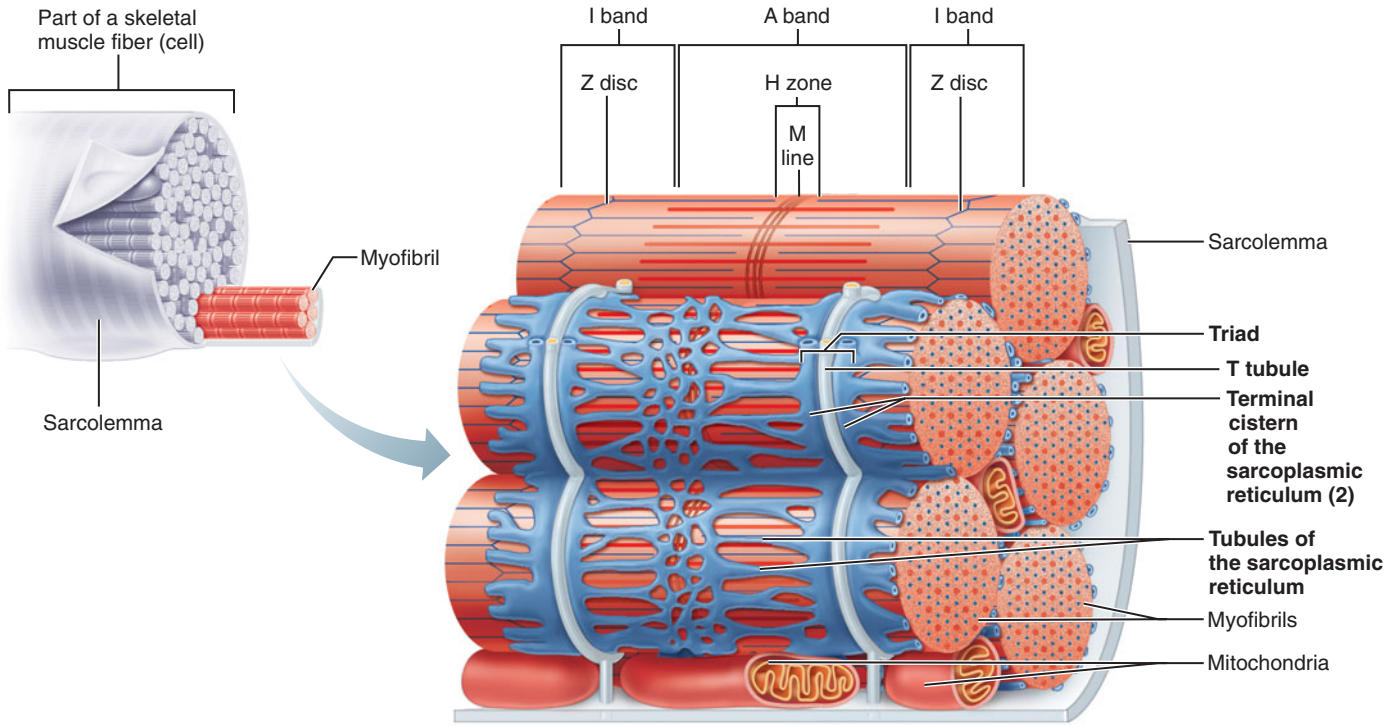


FIGURE 10.6 Sarcoplasmic reticulum and T tubules in the skeletal muscle fiber.

adjacent myofibrils align perfectly, allowing us to see the various bands in a muscle fiber (Figure 10.4a and b). To help you remember which band is which, remember there is an "*A*" in *dark;* thus, the dark bands are the A bands; there is an "*I*" in *light;* thus, the light bands are I bands. These notations actually refer to how these regions refract polarized light: the A bands are *anisotropic,* and the I bands are *isotropic.*

Figure 10.4e shows each of these sarcomere regions in cross section, illustrating the types of myofilaments and their arrangement in each region of the sarcomere.

Sarcoplasmic Reticulum and T Tubules

Each skeletal muscle fiber contains two sets of tubules that participate in the regulation of muscle contraction: sarcoplasmic reticulum and T tubules **(Figure 10.6)**. **Sarcoplasmic reticulum (SR)** is an elaborate smooth endoplasmic reticulum whose interconnecting tubules surround each myofibril like the sleeve of a loosely crocheted sweater surrounds your arm. Most SR tubules run longitudinally along the myofibril. Other SR tubules, called **terminal cisterns** ("end sacs"), form larger, perpendicular cross-channels over the junction between each A band in a myofibril and its adjacent I bands (A-I junctions). The sarcoplasmic reticulum and the terminal cisterns store large quantities of calcium ions (Ca^{2+}). These ions are released when the muscle is stimulated to contract.

T tubules (transverse tubules) are deep invaginations of the sarcolemma that run between each pair of terminal cisterns (Figure 10.6). The complex of the T tubule flanked by two terminal cisterns at the A-I junction is called a **triad** (tri′ad; "group of three").

Contraction in skeletal muscle is ultimately controlled by nerve-generated impulses that travel along the sarcolemma of the muscle fiber. Because the T tubules are continuations of the sarcolemma, they conduct each impulse to the deepest regions of the muscle fiber, thus ensuring that the deep-lying myofibrils contract at the same time as the superficial ones. Impulses traveling down the T tubules stimulate the release of calcium from the terminal cistern. Calcium diffuses through the cytosol to the thin filaments and triggers muscle contraction. After contraction, calcium is pumped back into the sarcoplasmic reticulum for storage.

check your understanding

5. Place the following structures in order from smallest to largest, and define each: myofibril, muscle fiber, myofilament, sarcomere.
6. Which myofilaments are found only in the A band?
7. What are the functions of the terminal cistern and the T tubules?

For answers, see Appendix B.

Mechanism of Contraction

There are two types of muscle contraction involved in producing movement, concentric contraction and eccentric contraction. **Concentric contraction** is the more familiar type, in which the muscle shortens and does work—picking up a book or kicking a ball. **Eccentric contraction** occurs when a muscle generates force as it *lengthens.* The mechanism for this type of contraction is less understood, but eccentric contractions are essential for controlled movement and resistance to gravity. Both types of contraction occur during push-ups. During the up

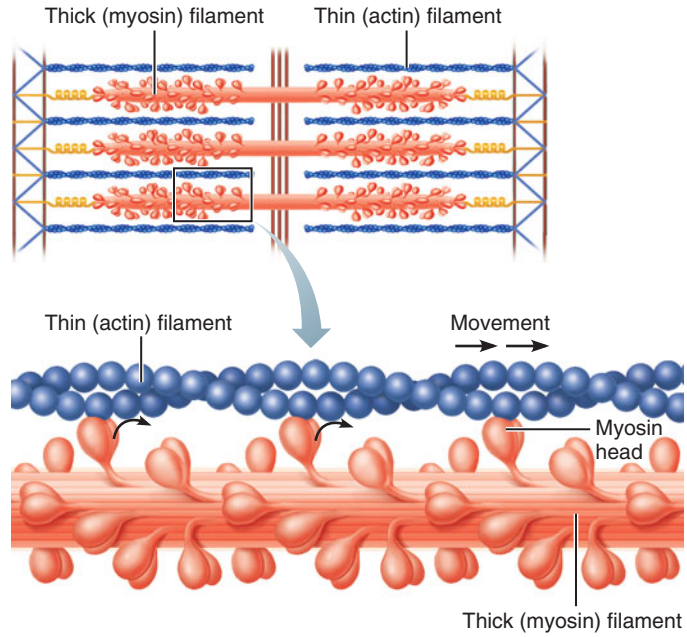
portion of the exercise, concentric contractions in the pectoralis muscles of the chest raise the torso off the floor. During the down portion of the movement, these same muscles contract eccentrically and by doing so resist gravity and control the downward motion of the torso. Eccentric contraction occurs in many movements that resist gravity: going down stairs, running downhill, landing from a jump. Whenever muscles are acting as a brake, they are contracting eccentrically.

DELAYED-ONSET MUSCLE SORENESS Post-exercise soreness is not uncommon for both trained and recreational athletes. Soreness that begins 8–24 hours after an activity is called **delayed-onset muscle soreness** or **post-exercise muscle soreness.** Starting an exercise regimen, occasional participation in a physically demanding activity, or increasing the duration or intensity of a regular workout can all result in sore muscles. This soreness is caused by microscopic tears in the muscle fibers and is most common after eccentric exercise. The inflammatory response to these small tears results in swelling in the connective tissues surrounding the muscle fibers. The swelling then compresses sensory nerve endings in the muscle, causing the characteristic soreness. The good news is that delayed-onset muscle soreness does not last long (3–7 days) and that low-level aerobic activity increases blood supply to the muscle and speeds recovery. Another piece of good news is that these microscopic tears stimulate increased production of myofibrils and myofilaments, resulting in increased muscle strength.

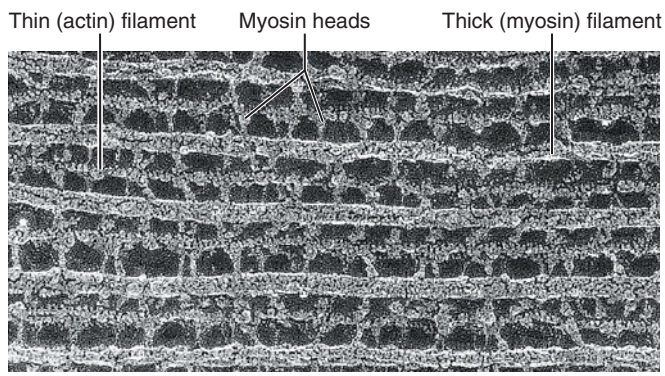
Concentric contraction of skeletal muscle is explained by the **sliding filament mechanism** (Figure 10.7). Contraction results as the myosin heads of the thick filaments attach to the thin filaments at both ends of the sarcomere and pull the thin filaments toward the center of the sarcomere by swiveling inward. After a myosin head pivots at its "hinge," it lets go, returns to its original position, binds to the thin filament farther along its length, and pivots again. This ratchet-like cycle is repeated many times during a single contraction. It should be emphasized that the thick and thin filaments themselves do not shorten: The thin filament merely slides over the thick filament.

The sliding filament mechanism is initiated by the release of calcium ions from the sarcoplasmic reticulum and the binding of those ions to the thin filaments. This process is powered by ATP.

Figure 10.8 shows how contraction affects the striation pattern of skeletal muscle. In a fully relaxed sarcomere (Figure 10.8 ①), the thin filaments partially overlap the thick filaments. Note the length of the A band, the I band, and the position of the Z discs in the relaxed sarcomere. When the muscle is stimulated to contract, as shown in Figure 10.8 ②, the action of the thick filaments forcefully pulls the two Z discs closer together, causing each sarcomere to shorten. As the Z discs move closer together, the I bands shorten, and the H zones disappear completely. Notice that the decrease in



(a) Myosin heads attach to actin in the thin filaments, then pivot to pull the thin filaments inward.



(b) Transmission electron micrograph of part of a sarcomere, showing myosin heads attached to the thin filaments

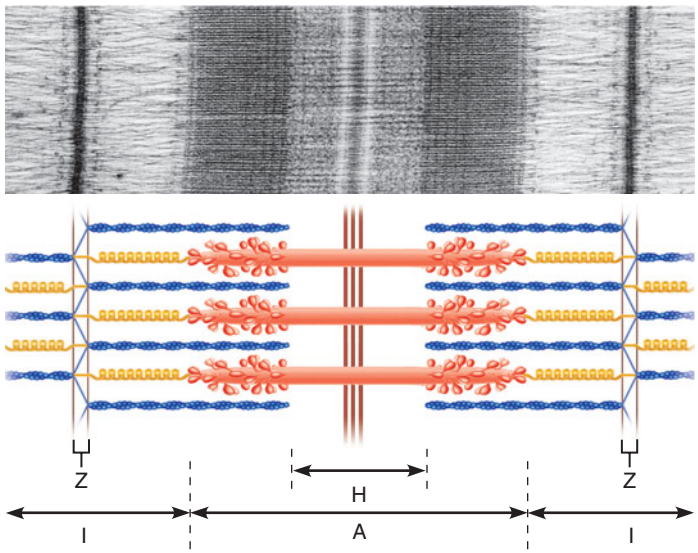
FIGURE 10.7 Sliding filament mechanism for concentric contraction in a skeletal muscle.

length of the I band and the loss of the H zone are due to the increased amount of overlap of the thin and thick filaments. The length of the thin filament has not changed. The A bands stay the same length because the length of the thick filaments also does not change.

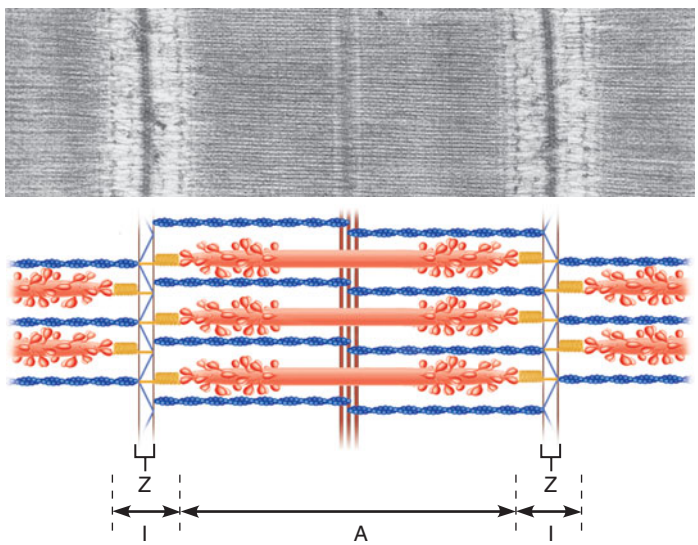
When a muscle is stretched rather than contracted, the amount of overlap between the thin and thick filaments decreases: The I bands and H zones lengthen as the Z discs move apart. Again, there is no change in the width of the A bands.

Muscle Extension

You know that muscle tissue is extensible and that muscle fibers are stretched (extended) back to their original length after they contract. What is responsible for this stretching? Basically, a skeletal muscle—and its contained fibers—are



① Fully relaxed sarcomere of a muscle fiber



② Fully contracted sarcomere of a muscle fiber

FIGURE 10.8 Changes in striations as skeletal muscle contracts. The numbers indicate the sequence of events from ① relaxed to ② fully contracted. Electron micrographs (top view in each case) show enlargements of 33,400×.

stretched by a movement that is the *opposite* of the movement the muscle normally produces. For example, a muscle that normally *abducts* the arm at the shoulder is stretched by *adducting* the arm at this joint.

Muscle Fiber Length and the Force of Contraction

The optimal resting length for skeletal muscle fibers is the length that will generate the greatest pulling force when the muscle is contracted. This optimal length occurs when a fiber is slightly stretched, so that its thin and thick filaments overlap to only a moderate extent (Figure 10.8 ①). Under these conditions, the myosin heads can move and pull along the whole length of the thin filaments. Under other conditions, contraction is suboptimal: If a muscle fiber is stretched so much that the thick and thin filaments do not overlap at all, the myosin heads have nothing to attach to, and no pulling force can be generated. Alternatively, if the sarcomeres are so compressed that the thick filaments are touching the Z discs, little further shortening can occur (Figure 10.8 ②).

What is true for a muscle fiber is true for an entire muscle. Whole skeletal muscles have a range of optimal operational length that runs from about 80% of their normal resting length to about 120% of that length. The sites of muscle attachments tend to keep muscles within that optimal range; that is, the joints normally do not let any bone move so widely that its attached muscles could shorten or stretch beyond their optimal range.

The Role of Titin and Other Myofibril Proteins

Titin (ti′tin) is a springlike molecule in sarcomeres that resists overstretching. The titin molecules in a sarcomere extend from the Z disc to the thick filament and run within the thick filament to attach to the M line (see Figure 10.4d). When first identified, titin generated much excitement because it is the largest protein ever discovered. It has two basic functions: (1) It holds the thick filaments in place in the sarcomere, thereby maintaining the organization of the A band; and (2) it unfolds when the muscle is stretched, then refolds when the stretching force is released, thereby contributing to muscle elasticity. Titin does not resist stretching in the ordinary range of extension, but it becomes stiffer the more it uncoils; therefore, it strongly resists excessive stretching that tries to pull the sarcomere apart.

In each myofibril, several proteins surround the Z discs. These proteins bind adjacent sarcomeres together.

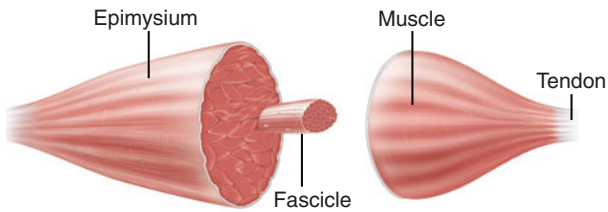
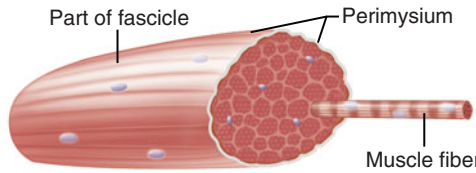
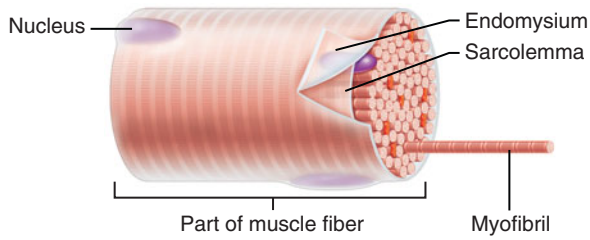
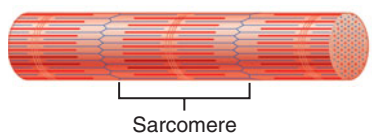
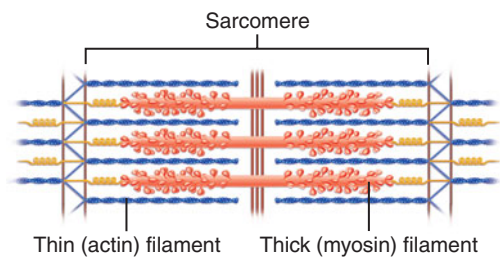
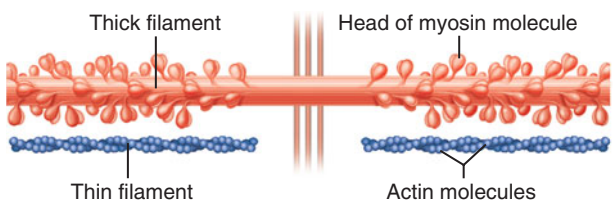
Table 10.1 provides a quick review of the macroscopic and microscopic structure of skeletal muscle.

Innervation of Skeletal Muscle

The release of calcium ions from the sarcoplasmic reticulum and the subsequent contraction of skeletal muscle is initiated by nervous stimulation. The nerve cells that innervate muscle fibers are called **motor neurons.** As discussed in Chapter 4 (p. 92), a neuron has cell processes that extend from the cell body: *dendrites* are receptive regions of the neuron; an *axon* is a long, singular cell process that initiates and transmits nerve impulses.

Each muscle fiber in a skeletal muscle is served by a nerve ending, which signals the fiber to contract. The point at which the nerve ending and fiber meet is called a **neuromuscular junction** or a *motor end plate* **(Figure 10.9)**. The nerve part of the junction is a cluster of enlargements at the end of the axonal process that stores chemical messenger molecules, neurotransmitters. These enlargements are called **axon terminals.** The axon terminals are separated from the sarcolemma of the muscle fiber by a space called the **synaptic cleft** (Figure 10.9b). The axon terminals contain vesicles that release neurotransmitter when a nerve impulse reaches the terminals (Figure 10.9 ①). The neurotransmitter

TABLE 10.1 Structure and Organizational Levels of Skeletal Muscle

Structure and Organizational Level		Description	Connective Tissue Wrappings
Muscle (organ)		A muscle consists of hundreds to thousands of muscle cells, plus connective tissue wrappings, blood vessels, and nerve fibers.	Covered externally by the epimysium
Fascicle (a portion of the muscle)		A fascicle is a discrete bundle of muscle cells, segregated from the rest of the muscle by a connective tissue sheath.	Surrounded by a perimysium
Muscle fiber (cell)		A muscle fiber is an elongated multinucleate cell; it has a banded (striated) appearance.	Surrounded by the endomysium
Myofibril (complex organelle containing myofilaments)		Myofibrils are rodlike contractile elements that occupy most of the muscle cell volume. Composed of sarcomeres arranged end to end, they appear banded, and the bands of adjacent myofibrils are aligned.	
Sarcomere (a segment of a myofibril)		A sarcomere is the contractile unit, composed of myofilaments made up of contractile proteins.	
Myofilament or filament		Contractile myofilaments are of two types—thick and thin. The thick filaments contain bundled myosin molecules; the thin filaments contain actin molecules (plus other proteins). The sliding of the thin filaments past the thick filaments produces muscle shortening. Elastic filaments composed of titin molecules (not shown) maintain the organization of the A band and provide for elastic recoil when muscle contraction ends.	

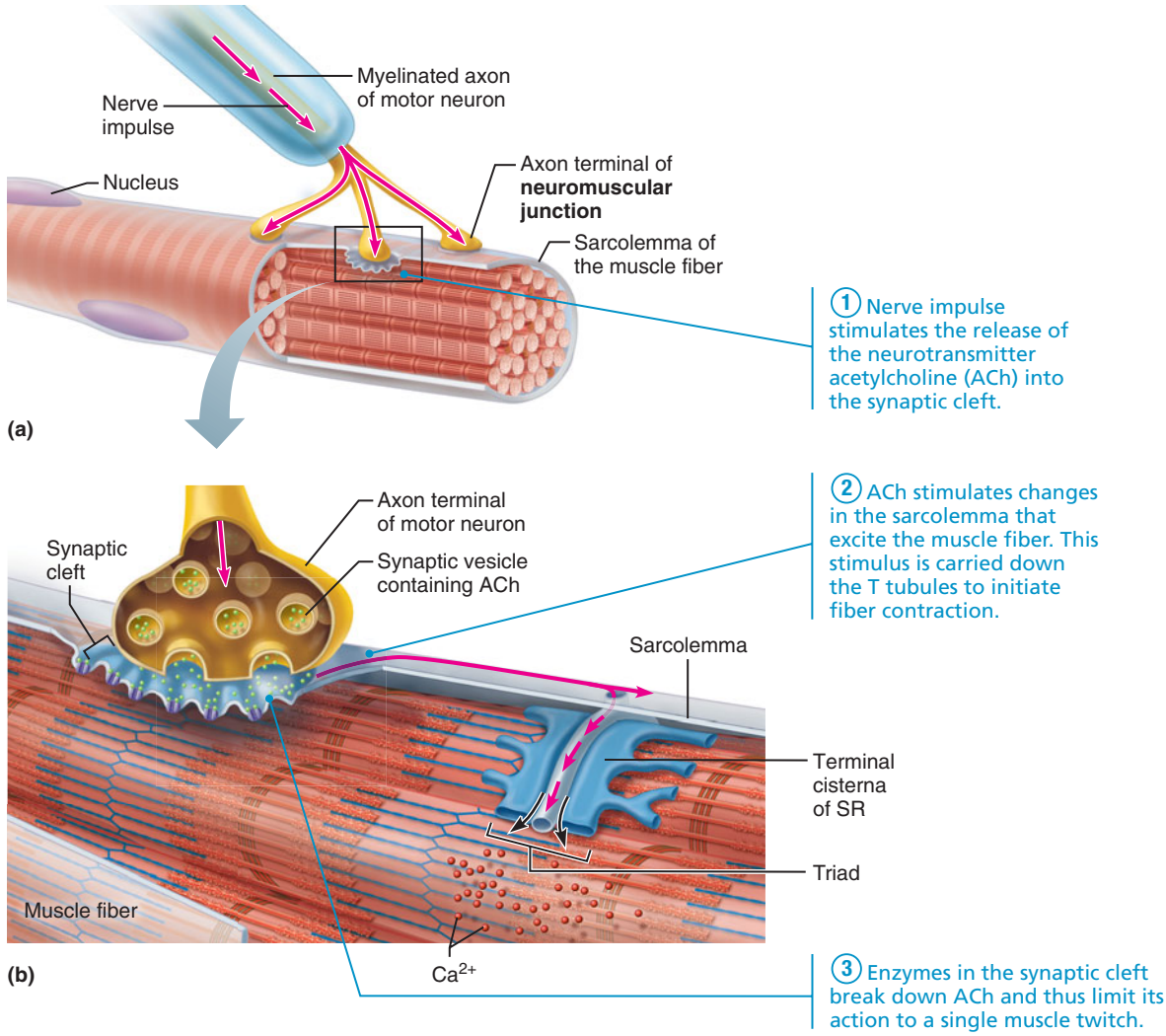


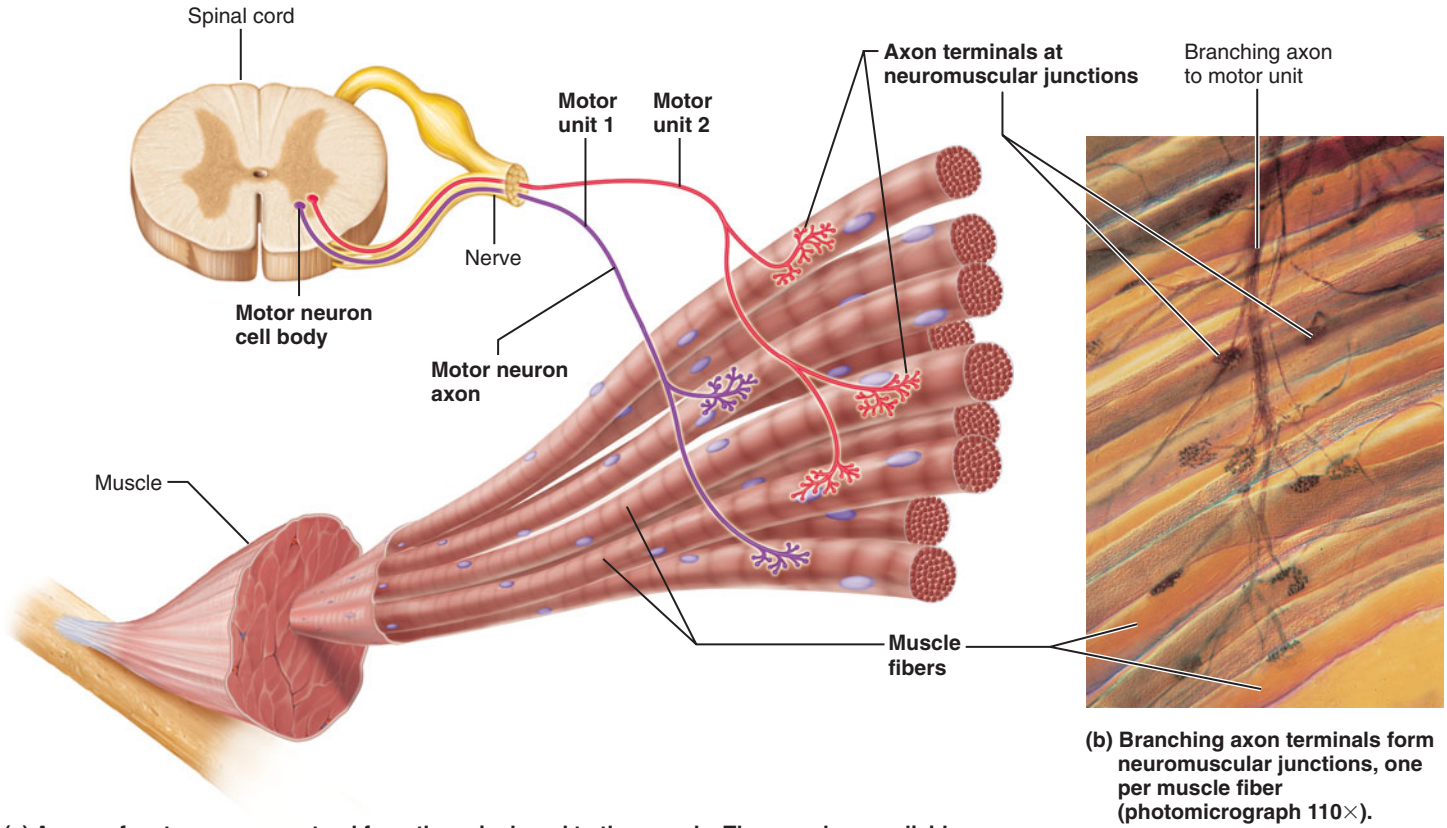
FIGURE 10.9 The neuromuscular junction. (a) An axon of a motor neuron forming three neuromuscular junctions with a skeletal muscle fiber. **(b)** Enlargement of a single neuromuscular junction contacting a muscle cell.

at the neuromuscular junction—acetylcholine—diffuses across the synaptic cleft and binds to receptor molecules on the sarcolemma, where it induces an impulse that initiates fiber contraction (Figure 10.9 ②).

The neuromuscular junction has several unique features. Each axon terminal lies in a trough-like depression of the sarcolemma, which in turn has its own invaginations (Figure 10.9b). The invaginations of the sarcolemma are covered with a basal lamina (not illustrated). This basal lamina contains the enzyme acetylcholinesterase (as″ĕ-til-ko″lin-es′ter-ās), which breaks down acetylcholine immediately after the neurotransmitter signals a single contraction (Figure 10.9 ③). This ensures that each nerve impulse to the muscle fiber produces just one twitch of the fiber, preventing any undesirable additional twitches that would result if acetylcholine were to linger in the synaptic cleft.

The axon of a motor neuron branches to innervate a number of fibers in a skeletal muscle. A motor neuron and all the muscle fibers it innervates are called a **motor unit.** Figure 10.10 illustrates two simplified motor units. When a motor neuron fires, all the skeletal muscle fibers in the motor unit contract together. Although the average number of muscle fibers in a motor unit is 150, the number may run as high as several hundred or as low as four. Muscles that require very fine control (such as the muscles moving the fingers and eyes) have few muscle fibers per motor unit, whereas bulky, weight-bearing muscles, whose movements are less precise (such as the hip muscles), have many muscle fibers per motor unit. The muscle fibers of a single motor unit are not clustered together but rather are spread throughout the muscle. As a result, stimulation of a single motor unit causes a weak contraction of the entire muscle.

In addition to variation in the size of motor units in different muscles, each individual muscle contains many motor units. The addition of motor units to accomplish a movement is called **recruitment.** If a small force is required, a small number of motor units are stimulated. As more force is needed,



(a) Axons of motor neurons extend from the spinal cord to the muscle. There each axon divides into a number of axon terminals that form neuromuscular junctions with muscle fibers scattered throughout the muscle.

(b) Branching axon terminals form neuromuscular junctions, one per muscle fiber (photomicrograph 110×).

FIGURE 10.10 Motor units. Each motor unit consists of one motor neuron and all the muscle fibers it innervates. (See *A Brief Atlas of the Human Body,* Second Edition, Plate 30.)

additional motor units are recruited. Thus the same muscle is capable of lifting a pencil off the desk or lifting this textbook.

check your understanding

8. Why is overlap of the thin and thick filaments essential for muscle contraction?
9. Which region of the myofibril changes in length during contraction: the A band, the I band, or the Z disc?
10. Differentiate a neuromuscular junction from a motor unit.

For answers, see Appendix B.

Types of Skeletal Muscle Fibers

The various types of skeletal muscle fibers are categorized according to two characteristics: (1) how they manufacture energy (ATP) and (2) how quickly they contract. Some muscle fibers predominantly produce ATP aerobically (using oxygen) and are thus called **oxidative fibers.** Others make ATP anaerobically (without oxygen) via glycolysis and are referred to as **glycolytic fibers.** The speed of contraction, fast versus slow, depends on how quickly a fiber breaks down ATP to gain the energy needed for contraction. Based on these characteristics, muscle fibers are divided into three general classes: *slow oxidative fibers (SO), fast glycolytic fibers (FG),* and *fast oxidative fibers (FO)* **(Figure 10.11)**. Most of the muscles in the body contain all three fiber types, but the proportions differ from one muscle to another.

Slow Oxidative Fibers (SO) These relatively thin fibers are red because of their abundant content of *myoglobin* (mi″o-glo′bin), an oxygen-binding pigment in their sarcoplasm. As their name implies, slow oxidative fibers obtain their energy from aerobic metabolic reactions; thus they have a relatively large number of mitochondria (the sites of aerobic metabolism) and a rich supply of capillaries. Slow oxidative fibers contract slowly, are extremely resistant to fatigue as long as enough oxygen is present, and deliver prolonged contractions. There are many of these fibers in the postural muscles of the lower back, muscles that must contract continuously to keep the spine straight and maintain posture. Because they are thin, slow oxidative fibers do not generate much power.

RHABDOMYOLYSIS Although oxygen-binding myoglobin increases endurance, it can cause problems if it leaks from muscle. Damage to skeletal muscles caused by crushing or by extreme, destructive exercise may lead to a condition called **rhabdomyolysis** (rab″do-mi-ol′i-sis; "disintegration of rod-shaped [skeletal] muscle"). The condition was originally recognized in survivors of bombings and earthquakes who had been pinned under fallen buildings. In rhabdomyolysis, myoglobin pours into the bloodstream and clogs the blood-filtering kidneys, causing kidney failure, which eventually leads to heart failure.

Fast Glycolytic Fibers (FG) Fast glycolytic fibers are pale because they contain little myoglobin. They are about twice the diameter of slow oxidative fibers, contain more myofilaments, and thus generate much more power. Because these fibers depend on anaerobic pathways to make ATP, they contain few mitochondria or capillaries but have many glycosomes containing glycogen as a fuel source. Fast glycolytic fibers contract rapidly and tire quickly. They are common in the muscles of the upper limbs, which often lift heavy objects for brief periods.

Fast Oxidative Fibers (FO) Fast oxidative muscle fibers are intermediate in many of their characteristics in comparison with the other two fiber types. Like fast glycolytic fibers, they contract quickly; like slow oxidative fibers, they are oxygen dependent and have a high myoglobin content, a large number of mitochondria, and a rich supply of capillaries. Because fast oxidative fibers depend largely on aerobic metabolism, they are fatigue resistant but less so than slow oxidative fibers. The speed of contraction of fast oxidative fibers is between that of the other two fiber types. The diameter of the fiber is also intermediate; thus, these fibers are more powerful than slow oxidative fibers but not as powerful as fast glycolytic fibers. They are abundant in the muscles of the lower limbs, which must move the body for long periods during locomotion.

Because individual muscles contain a mixture of the three fiber types, each muscle can perform different tasks at different times. A muscle in the calf of the leg, for example, uses its glycolytic fibers to propel the body in a short sprint, its fast oxidative fibers in long-distance running, and its slow oxidative fibers in maintaining a standing posture.

Although everyone's muscles contain mixtures of the three fiber types, some people have relatively more of one type. These differences are genetically controlled and no doubt influence the athletic capabilities of endurance versus strength. It is possible to transform muscle fiber types through training, however. Specifically, intense resistance training can convert fast glycolytic fibers to fast oxidative fibers. Any fibers converted in this way do revert to their original type when the training stops. In fact, an interesting overshoot phenomenon has been observed. After training ends, the percentage of fast glycolytic fibers increases significantly from the pretraining level. This phenomenon is the physiological basis for tapering off training prior to a major competitive event, a common practice among athletes.

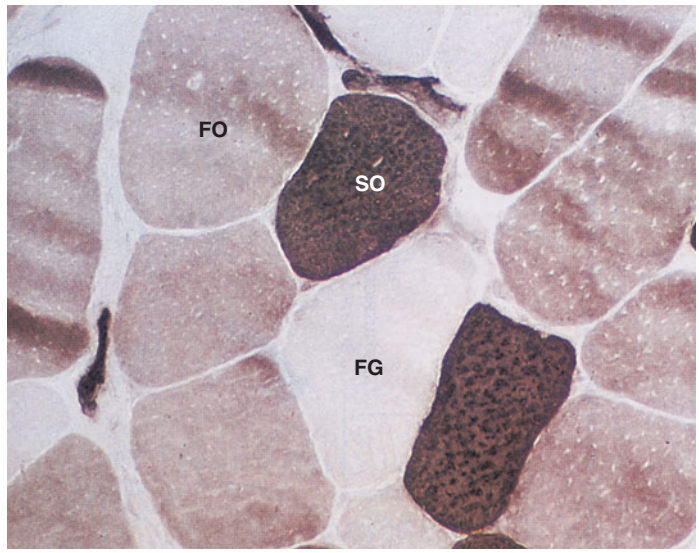


FIGURE 10.11 Cross section of the three types of fibers in skeletal muscle. From generally smallest to largest, they are slow oxidative fibers (SO), fast oxidative fibers (FO), and fast glycolytic fibers (FG). The staining technique used in this preparation differentiates the fibers by the abundance of their mitochondria, mitochondrial enzymes, and other features (480×).

Weight training also increases the diameter and strength of fast muscle fibers. Weight lifting increases the production of the contractile proteins actin and myosin, of the myofilaments containing these proteins, and of the myofibril organelles these myofilaments form. As the number and size of the myofibrils increase, the fibers enlarge. Skeletal muscle is multinucleated, and the enlarged fibers need additional nuclei to direct and support the formation of new proteins. Small immature muscle cells, called satellite cells, are scattered in the muscle tissue outside the muscle fibers. These cells fuse with the fibers, contributing the additional nuclei needed as the fibers enlarge. Thus, muscle fibers do not increase in number by dividing mitotically. Rather, they increase in diameter by building more contractile proteins and myofilaments. It is by this process that weight lifters develop large muscles.

check your understanding

11. Which fiber type dominates in the lower limb muscles of Usain Bolt, the 2008 Olympic gold medalist in the 100-meter dash?

For the answer, see Appendix B.

DISORDERS OF SKELETAL MUSCLE TISSUE

➤ Explain some symptoms of muscular dystrophy, myofascial pain syndrome, and fibromyalgia.

The body's skeletal muscle tissue experiences remarkably few disorders. Given good nutrition and sufficient exercise, it is amazingly resistant to infection throughout life. Noninfectious disorders of skeletal muscle, however, include *muscular dystrophy, myofascial pain syndrome,* and *fibromyalgia.*

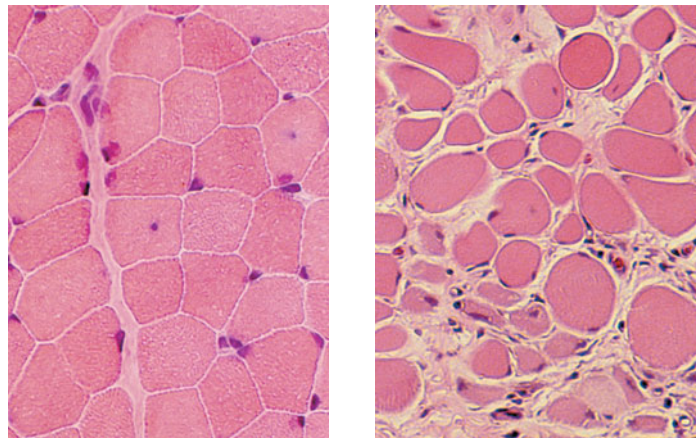
Muscular Dystrophy

Muscular dystrophy is a group of inherited muscle-destroying diseases that generally appear in childhood. The affected muscles enlarge with fat and connective tissue while the muscle fibers degenerate **(Figure 10.12)**. The most common and most serious form is **Duchenne muscular dystrophy,** which is inherited as a *sex-linked recessive disease.* This means that females carry and transmit the abnormal gene, but it is expressed almost exclusively in males. It affects 1 of every 3500 boys. This tragic disease is usually diagnosed when the boy is between 2 and 10 years old. Active, apparently normal children become clumsy and start to fall frequently as their muscles weaken. The disease progresses from the pelvic muscles to the shoulder muscles to the head and chest muscles. Victims rarely live past age 20 and usually die of respiratory infections or respiratory failure.

Recent research has identified the cause of Duchenne muscular dystrophy: The diseased muscle fibers lack a submembrane protein called *dystrophin,* which links the cytoskeleton of the muscle fiber to the extracellular matrix. Without this strengthening protein, the sarcolemma weakens, and the consequent leakage of extracellular calcium ions into the muscle fibers can fatally disrupt muscle function.

Scientists have explored possible treatments by injecting mice with embryonic muscle cells called myoblasts (discussed shortly), which then fuse with the unhealthy muscle fibers and induce them to produce dystrophin. Genes that promote the manufacture of dystrophin have also been injected. Similar treatments have not yet been successful in humans. Success may be near, however, because measurements suggest researchers are now getting about half as many healthy myoblasts into human dystrophic muscles as will be needed to improve their strength. Another treatment is to coax dystrophic muscle to produce more *utrophin,* a protein that is related to dystrophin and can substitute for it functionally.

Another kind of muscular dystrophy, called **myotonic dystrophy,** can appear at any age between birth and age 60. The symptoms of this inherited, slow-progressing disease include skeletal-muscle spasms followed by muscle weakness and abnormal heart rhythm. This disorder is also caused by an underlying genetic defect, and the pattern of inheritance is now well understood.



(a) Normal muscle tissue **(b) Muscle tissue from a patient with DMD**

FIGURE 10.12 Duchenne muscular dystrophy. (a) Normal muscle tissue, hematoxylin and eosin (H&E) stained (140×). **(b)** Muscle tissue from a patient with Duchenne muscular dystrophy (DMD), H&E stained (100×).

Myofascial Pain Syndrome

In **myofascial pain syndrome,** pain is caused by tightened bands of muscle fibers that twitch when the skin over them is touched. The sensitive areas of skin are called trigger points. Myofascial pain syndrome is mostly associated with overused or strained postural muscles, and the pain is often felt some distance from the trigger point, in predictable places called *reference zones.* This syndrome is very common, affecting up to half of all people, mostly those from 30 to 60 years old. The pain is treated with nonsteroidal anti-inflammatory drugs and by stretching the affected muscle. Massage also helps, and exercising the affected muscle can lead to long-term recovery.

Fibromyalgia

Fibromyalgia (fi″bro-mi-al′ge-ah) is a mysterious chronic-pain syndrome of unknown cause (*algia* = pain). Its symptoms include severe musculoskeletal pain, fatigue, sleep abnormalities, and headache. It affects about 2% of all people, mostly women. The most common sites of pain are the lower back or neck, but for a condition to be identified as fibromyalgia, pain must be present in at least 11 of 18 standardized points that are spread widely over the body. Not all of these points are over muscles, and muscle problems do not seem to be the primary cause. However, fibromyalgia is included in this chapter because it can be mistaken for myofascial pain syndrome (see above). Fibromyalgia is treated with antidepressants, exercise, and pain relievers.

check your understanding

12. What changes are apparent in the muscle tissue of a boy with Duchenne muscular dystrophy?

For the answer, see Appendix B.

TABLE 10.2 Comparison of Skeletal, Cardiac, and Smooth Muscle

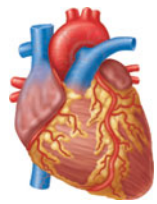
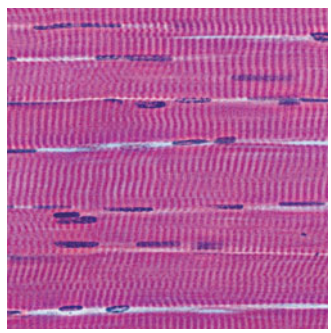
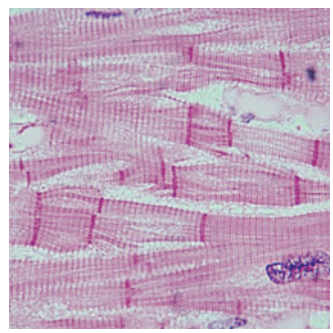
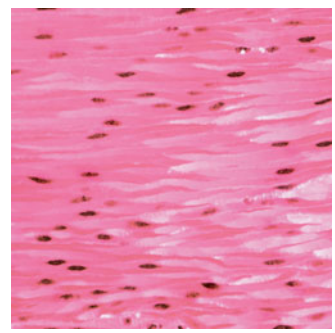
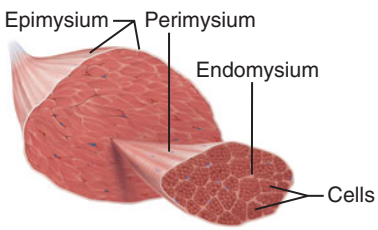
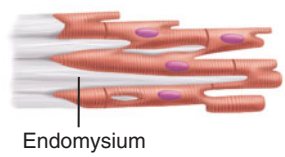
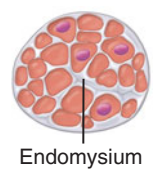
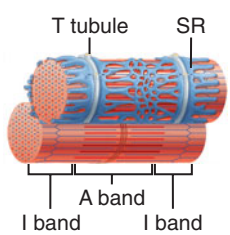
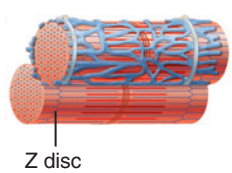
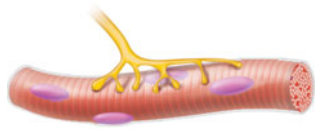
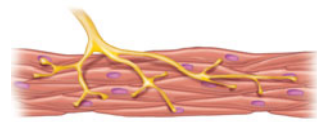
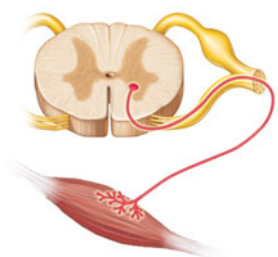
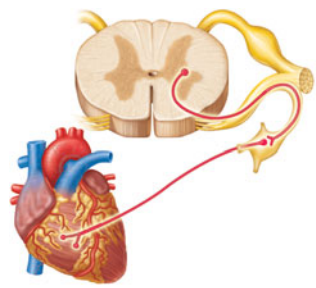
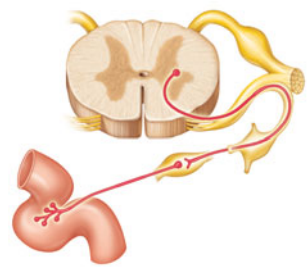
Characteristic	Skeletal	Cardiac	Smooth
Body location	 Attached to bones or (some facial muscles) to skin	 Walls of the heart	 Mostly in walls of hollow organs, such as the stomach, respiratory tubes, bladder, blood vessels, and uterus
Cell shape and appearance	  Single, very long cylindrical, multinucleate cells with obvious striations	  Branching chains of cells; uni- or binucleate; striations	  Single, fusiform, uninucleate; no striations
Connective tissue components	 Epimysium, perimysium, and endomysium	 Endomysium attached to fibrous skeleton of heart	 Endomysium
Presence of myofibrils composed of sarcomeres	Yes	Yes, but myofibrils are of irregular thickness	No, but actin and myosin filaments are present throughout
Presence of T tubules and site of invagination	 Yes; two in each sarcomere at A-I junctions	 Yes; one in each sarcomere at Z discs; larger diameter than those of skeletal muscle	No T tubules; has caveolae along the sarcolemma

TABLE 10.2 *continued*

Characteristic	Skeletal	Cardiac	Smooth
Elaborate sarcoplasmic reticulum	Yes	Less than skeletal muscle; scant terminal cisternae	Equivalent to cardiac muscle; some SR contacts the sarcolemma
Source of (Ca^{2+}). for calcium pulse	Sarcoplasmic reticulum (SR)	SR and from extracellular fluid	SR and from extacellular fluid
Presence of gap junctions	No	Yes; at intercalated discs	Yes; in single-unit muscle
Cells exhibit individual neuromuscular junctions	 Yes	No	 Not in single-unit muscle; yes in multiunit muscle
Regulation of contraction	Voluntary via axon terminals of the somatic nervous system 	Involuntary; intrinsic system regulation; also autonomic nervous system controls; stretch 	Involuntary; autonomic nerves, hormones, local chemicals; stretch 
Energetics	Aerobic and anaerobic	Aerobic	Mainly aerobic

SKELETAL MUSCLE TISSUE THROUGHOUT LIFE

- Describe the embryonic development and capacity for regeneration of skeletal muscle tissue.
- Explain the changes that occur with age in skeletal muscle.

With rare exceptions, all muscle tissues develop from embryonic mesoderm cells called *myoblasts.* Myoblasts fuse to form skeletal muscle fibers **(Figure 10.13)**. This fusion of embryonic cells is the reason skeletal muscle fibers are multinucleated. The muscle fibers begin to make thick and thin myofilaments and gain the ability to contract. Ordinarily, the skeletal muscles are contracting by week 7, when the embryo is only about 2 cm long. Nerves grow into the muscle masses from the spinal cord, bringing the skeletal muscles under the control of the nervous system.

Skeletal muscle fibers never undergo mitosis after they are formed. During childhood and adolescence, these cells lengthen and thicken, however, to keep up with the growing body. Furthermore, during the late fetal period and thereafter skeletal muscle fibers are surrounded by scattered *satellite cells,* which are immature cells that resemble undifferentiated myoblasts (Figure 10.13). During youth, satellite cells fuse into the existing muscle fibers to help them grow. Following injury to a muscle, satellite cells proliferate in the damaged muscle tissue and start producing proteins to repair the injury. Some satellite cells fuse with surrounding muscle fibers; others remain as satellites. However, the regeneration capacity of skeletal muscle tissue is not complete, and severely damaged tissue is replaced primarily by scar tissue.

There are differences between men and women in the strength of skeletal muscle. On average, the body strength of adult men is greater than that of adult women. There seems to

a closer look

Anabolic Steroid Abuse

Society loves a winner, and top athletes reap large social and monetary rewards. Thus it is not surprising that some will try anything that might increase their performance—including the use of anabolic steroids. Anabolic steroids, variants of the male sex hormone testosterone engineered by pharmaceutical companies, were introduced in the 1950s to treat victims of anemia and certain muscle-wasting diseases and to prevent muscle atrophy in patients immobilized after surgery. Testosterone triggers the increase in muscle and bone mass and other physical changes that occur during puberty and convert boys into men. Convinced that megadoses of steroids could enhance masculinization in grown men, many athletes and bodybuilders were using them by the early 1960s. Today, steroid use is no longer confined to athletes. It is estimated that nearly one in every ten young men has tried steroids, and their use is growing rapidly among young women.

It is difficult to determine the extent of anabolic steroid use because most international competitions ban the use of drugs, and therefore users (and prescribing physicians or drug dealers) are reluctant to talk about it. Nonetheless, there is little question that many professional bodybuilders and athletes are heavy users. These athletes claim that anabolic steroids enhance muscle mass and strength, reduce muscle damage resulting from intense workouts, and reduce recovery time following workouts.

Do the drugs do all that is claimed? Research studies report increased isometric strength and body weight in steroid users. Although these results delight weight lifters, there is a hot dispute over whether the increased strength translates into improved athletic performance. Performance requires fine muscle coordination and endurance, and the effects of steroids on performance are still in question.

Do the alleged advantages of steroids outweigh their risks? Absolutely not. Physicians say steroids cause bloating of the face; acne and hair loss; shriveled testes and infertility; damage to the liver that promotes liver cancer; and changes in blood cholesterol levels that may predispose users to coronary heart disease. In addition, women can develop masculine characteristics, such as smaller breasts, enlarged clitoris, excess body hair, and thinning scalp hair. The psychiatric hazards of anabolic steroid use may be equally threatening: Recent studies indicate that one-third of users suffer serious mental problems. Depression, delusions, and manic behavior—in which users undergo Jekyll-and-Hyde personality swings and become extremely violent (termed *'roid rage*)—are all common.

A more recent arrival on the supplement scene, originally sold over the counter as a "nutritional performance enhancer," is androstenedione. This "pro-hormone," taken orally and converted to testosterone and estrogen in the body, was sold and used legally from 1996 until 2004. Baseball great Mark McGwire used androstenedione and greatly popularized its use. One drawback is that large quantities need to be ingested to result in small increases in testosterone levels, and more recent studies actually show no increase. At these large doses, estrogen levels are significantly elevated, resulting in feminizing effects. In addition, levels of high-density lipoproteins ("good" cholesterol) are reduced, increasing the risk of heart disease. In 2004, the FDA classified the drug as a controlled substance and banned its use in sports.

As one drug becomes illegal, others are developed. Some people admit to a willingness to try almost anything to win, short of killing themselves. Are they unwittingly doing just that?

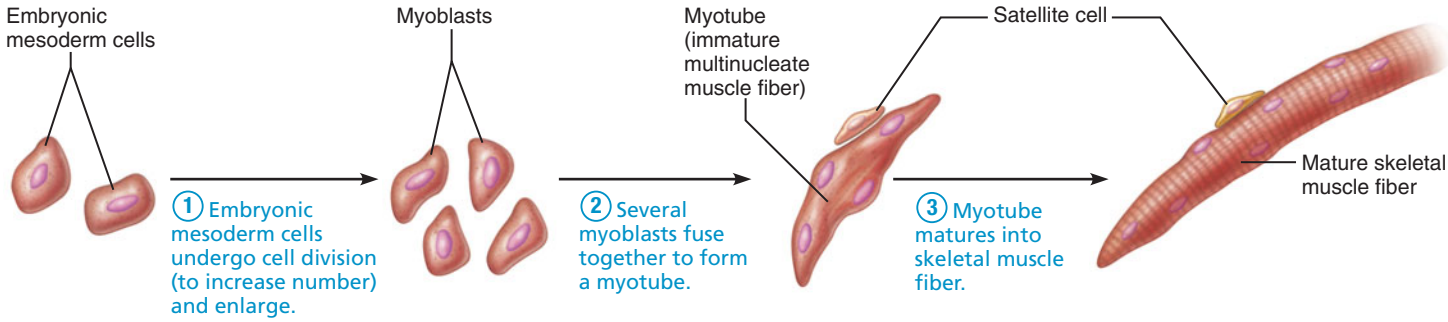


FIGURE 10.13 Formation of a multinucleate skeletal muscle fiber by fusion of myoblasts.

be a biological basis for this difference. Individuals vary, but on average, women's skeletal muscles make up 36% of body mass, compared to 42% in men. The greater muscular development of men is due mostly to the effects of androgen hormones (primarily testosterone) on skeletal muscle, not to the effects of exercise. Because men are usually larger than women, the average difference in strength is even greater than the percentage difference in muscle mass would suggest. (Body strength per unit muscle mass, however, is the same in both sexes.) With strenuous muscle exercise, enlargement of muscles is greater in men than in women, again because of the influence of male sex hormones. Some athletes take large doses of synthetic male sex hormones ("steroids") to increase their muscle mass. This illegal and dangerous practice is discussed in **A Closer Look** on p. 256.

As humans age, the amount of connective tissue in skeletal muscles increases, the number of muscle fibers decreases, and the muscles become stringier or, to say the same thing another way, more sinewy. Because skeletal muscles form so much of a person's body mass, body weight declines in many elderly people. The loss of muscle leads to a decrease in muscular strength, usually by 50% by age 80. This condition is called **sarcopenia** (sar″ko-pe′ne-ah), literally, "flesh wasting." It can have grave implications for health because it leads to many serious falls in the elderly. The proximate cause of sarcopenia may be a reduction in the rate at which the aging satellite cells can rebuild muscle. Fortunately, sarcopenia can be reversed by exercise, even in people of very advanced age. Weight training in the elderly does not retard the loss of muscle fibers but does increase the size of the remaining fibers, thus maintaining muscle strength.

check your understanding

13. Why are skeletal muscle fibers multinucleated?
14. How can older adults prevent or reverse the effects of sarcopenia?

For answers, see Appendix B.

RELATED CLINICAL TERMS

LOWER BACK PAIN Backache. May be due to a herniated or cracked disc, but is usually due to injured ligaments and muscle strain (see below). The injured back muscles contract in spasms, causing rigidity in the lumbar region and painful movement. Backaches plague 80% of all Americans at some time in their lives, but most cases resolve themselves.

MYALGIA (mi-al′je-ah; "muscle pain") Muscle pain resulting from any muscle disorder.

MYOPATHY (mi-op′ah-the; *path* = disease) Any disease of muscle.

SPASM A sudden, involuntary twitch of skeletal (or smooth) muscle, ranging in severity from merely irritating to very painful. May be due to chemical imbalances or injury. Spasms of the eyelid or facial muscles, called *tics*, may result from psychological factors. Massaging the affected area may help to end the spasm. A *cramp* is a prolonged spasm that causes a muscle to become taut and painful.

STRAIN Tearing of a muscle, often due to a sudden movement that excessively stretches the muscle. Also known as *muscle pull*. May involve the muscle-tendon junction. Bleeding within the muscle and inflammation lead to pain.

CHAPTER SUMMARY

You can use the following media study tool for additional help when you review specific key topics of Chapter 10.

PAL = ***Human Anatomy Lab***™

Overview of Muscle Tissue (pp. 240–241)

1. Muscle tissue produces movement, maintains posture, stabilizes joints, and generates body heat. It has the special properties of contractility, excitability, extensibility, and elasticity.
2. The three types of muscle tissue are skeletal, smooth, and cardiac muscle. Skeletal muscle attaches to the skeleton, has striated cells, and can be controlled voluntarily. Cardiac muscle occurs in the heart wall, has striated cells, and is controlled involuntarily. Smooth muscle occurs chiefly in the walls of hollow organs, has nonstriated cells, and is controlled involuntarily.
3. A cell in skeletal or smooth muscle (but not cardiac muscle) is called a fiber. A large percentage of the sarcoplasm of muscle cells is myofilaments that generate contractile force.

Skeletal Muscle (pp. 241–252)

Basic Features of a Skeletal Muscle (pp. 242–243)

4. Each skeletal muscle is an organ. The connective tissue elements of a skeletal muscle are the epimysium around the whole muscle, the perimysium around a fascicle, and the endomysium around fibers. A fascicle is a bundle of muscle fibers. All these connective tissue sheaths form the tendon.
5. Every skeletal muscle fiber is stimulated to contract by a nerve cell. Skeletal muscle has a rich blood supply. Fine nerve fibers and capillaries occupy the endomysium.
6. Each muscle extends from an immovable (or less movable) attachment, called the origin, to a more movable attachment, called an insertion.
7. Muscles attach to bones through tendons, aponeuroses, or direct (fleshy) attachments. Some muscles cross two or more joints.

Microscopic and Functional Anatomy of Skeletal Muscle Tissue (pp. 245–252)

8. A skeletal muscle fiber is a long, striated cell formed from the fusion of many embryonic cells. It contains many peripherally located nuclei.
9. Myofibrils are cylinder-shaped organelles that show distinct dark and light banding patterns, or striations. They are the main component of the sarcoplasm of skeletal muscle cells. A myofibril is a row of sarcomeres arranged end to end. A sarcomere extends from one Z disc to the next. Thin (actin) filaments extend centrally from each Z disc. Thick (myosin) filaments occupy the center of each sarcomere and overlap the inner ends of the thin filaments.
10. From large to small, the levels of organization in a muscle are whole muscle, fascicle, fiber, myofibril, sarcomere, and myofilament (see Table 10.1, p. 249).
11. The sarcoplasmic reticulum is a specialized smooth endoplasmic reticulum in the muscle fiber. T tubules are deep invaginations of the sarcolemma. When a nerve cell stimulates a muscle fiber, it sets up an impulse in the sarcolemma that signals the sarcoplasmic reticulum to release Ca^{2+}, which then initiates the sliding of the myofilaments (muscle contraction).
12. Muscle contraction occurs by both concentric contraction, which shortens the muscle, and eccentric contraction, in which the muscle generates force while lengthening.
13. According to the sliding filament mechanism, concentric muscle contraction results when the thin filaments are pulled toward the center of the sarcomere by a pivoting action of myosin heads on the thick filaments.
14. The myofilaments determine the striation pattern in skeletal muscle fibers. There are A bands, where thick filaments are located; I bands, which contain only thin filaments; and Z discs, where thin filaments from adjacent sarcomeres join; plus M lines and H zones, where only thick filaments occur. During contraction, the Z discs move closer together, and the I bands and H zones shorten.
15. A muscle is extended, or stretched, by a skeletal movement caused by the contraction of an opposing muscle. The huge titin molecules in the sarcomere resist overextension, and, along with the connective tissue elements, give muscle its elasticity.
16. The muscles attach to the skeleton in a way that keeps them at a near-optimal length for generating maximum contractile forces.
17. Motor neurons innervate skeletal muscle fibers at neuromuscular junctions (motor end plates). The axon terminal releases acetylcholine, which signals the muscle cell to contract. The basal lamina of the muscle cell releases the enzyme acetylcholinesterase into the synaptic cleft, which breaks down acetylcholine immediately after the neurotransmitter signals a single contraction. Each muscle fiber must be served by a neuromuscular junction.
18. A motor unit consists of one motor neuron and all the skeletal muscle fibers it innervates. Motor units contain different numbers of muscle fibers distributed widely within a muscle. All muscle fibers in the motor unit contract simultaneously.
19. There are three types of skeletal muscle fibers: (1) slow oxidative fibers (fatigue resistant and best for maintaining posture), (2) fast glycolytic fibers (for short bursts of power), and (3) fast oxidative fibers (for long-term production of fairly strong contraction). Most muscles in the body contain a mixture of these fiber types.

PAL **Histology/Muscular System**

Disorders of Skeletal Muscle Tissue (p. 253)

20. The disorders discussed in this section include muscular dystrophy, myofascial pain syndrome, and fibromyalgia.

Skeletal Muscle Tissue Throughout Life (pp. 255–257)

21. Muscle tissue develops from embryonic mesoderm cells called myoblasts. Skeletal muscle fibers form by the fusion of many myoblasts.
22. Mature skeletal muscle tissue has some ability to regenerate because of its satellite cells.
23. On the average, men have more muscle mass than women. This disparity is due to the effects of male sex hormones.
24. Skeletal muscles are richly vascularized and resistant to infection, but in old age they shrink, become fibrous, and lose strength. This condition, called sarcopenia, is reversible through exercise.

REVIEW QUESTIONS

Multiple Choice/Matching Questions

For answers, see Appendix B.

1. The connective tissue that lies just outside the sarcolemma of an individual muscle cell is called the (a) epimysium, (b) perimysium, (c) endomysium, (d) endosteum.
2. A fascicle is (a) a muscle, (b) a bundle of muscle cells enclosed by a connective tissue sheath, (c) a bundle of myofibrils, (d) a group of myofilaments.
3. Thick and thin myofilaments have different properties. For each phrase below, indicate whether the filament described is thick or thin (write *thick* or *thin* in the blanks).

   ____ **(1)** contains actin

   ____ **(2)** contains myosin heads

   ____ **(3)** contains myosin

   ____ **(4)** does not lie in the H zone

   ____ **(5)** does not lie in the I band

   ____ **(6)** attaches to a Z disc
4. Write *yes* or *no* in each blank below to indicate whether each of the following narrows when a skeletal muscle fiber contracts.

   ____ **(1)** H band

   ____ **(2)** A band

   ____ **(3)** I band

   ____ **(4)** M line
5. Match the level of skeletal muscle organization given in the key with its description:

   Key:

   (a) muscle (b) fascicle (c) fiber
   (d) myofibril (e) myofilament

   ____ **(1)** rod-shaped organelle; made of sarcomeres

   ____ **(2)** an organ

   ____ **(3)** a bundle of cells

   ____ **(4)** a group of large molecules

   ____ **(5)** a cell
6. The function of T tubules in muscle contraction is to (a) make and store glycogen, (b) release Ca^{2+} into the cell interior and then pick it up again, (c) transmit an impulse deep into the muscle cell, (d) make proteins.
7. Which fiber type would be the most useful in the leg muscles of a long-distance runner? (a) fast glycolytic, (b) slow glycolytic, (c) fast oxidative.
8. The ions that first enter a muscle cell when an impulse passes over its sarcolemma and then trigger muscle contraction are (a) calcium, (b) chloride, (c) sodium, (d) potassium.
9. Fill in each blank with the correct answer from the key. More than one answer may be correct.

   Key:

   (a) skeletal muscle (b) cardiac muscle (c) smooth muscle

   ____ **(1)** striated and involuntary

   ____ **(2)** striated and voluntary

   ____ **(3)** not striated and involuntary

   ____ **(4)** is present in wall of bladder

   ____ **(5)** is located only in the heart

   ____ **(6)** its fibers are giant, multinucleate cells

   ____ **(7)** the individual muscle cells are called muscle fibers

   ____ **(8)** has no A or I bands

   ____ **(9)** it is located in the walls of hollow body organs

   ____ **(10)** its extranuclear materials are called sarcoplasm instead of cytoplasm, and the plasma membrane is called the sarcolemma

Short Answer Essay Questions

10. Name and explain the four special functional characteristics of muscle tissue.
11. (a) Distinguish a tendon from an aponeurosis and a fleshy attachment. (b) Define origin and insertion, and explain how they differ.
12. Explain the sliding filament theory of contraction by drawing and labeling a relaxed and a contracted sarcomere.
13. Define motor unit.
14. List the structural differences between the three distinct types of skeletal muscle fibers.
15. Cindy Wong was a good anatomy student, but she realized she was mixing up the following "sound-alike" structures in skeletal muscle: myofilaments, myofibrils, fibers, and fascicles. Therefore, she compiled a brief table to define and differentiate these four structures. Construct a table like hers.
16. What is the function of the sarcoplasmic reticulum in a skeletal muscle cell?
17. Define sarcolemma and sarcoplasm.
18. Where is titin located, and what are its functions?
19. What is the general distribution of skeletal muscle fiber types in various body regions (trunk, upper limb, lower limb) and how is fiber type related to function of that body region?

CRITICAL REASONING & CLINICAL APPLICATION QUESTIONS

1. A certain anatomy student decided that his physique left much to be desired. He joined a health club and began to "pump iron" three times a week. After 3 months of training, during which he was able to lift increasingly heavy weights, his arm and chest muscles became much larger. Explain what happened to the fibers in these muscles.
2. Diego, who had not kept in shape, went out to play a game of touch football. As he was running, the calf region of his leg began to hurt. The next day he went to a doctor, who told him he had a strain. Diego kept insisting that no joints hurt. Clearly, he was confusing a *strain* with a *sprain.* Explain the difference.
3. Chickens are capable of only brief bursts of flight, and their flying muscles consist of fast glycolytic fibers. The breast muscles of ducks, by contrast, consist of slow and fast oxidative fibers. What can you deduce about the flying abilities of ducks?
4. Takashi, an osteopathic physician, saw that Mrs. and Mr. Rogers were suffering because their son was fighting a long battle with Duchenne muscular dystrophy. To comfort them, Takashi said that one day physicians hope to be able to cure this disease by injecting healthy myoblasts into the weakened muscles. What are myoblasts?
5. Why are muscle infections relatively rare (compared to respiratory or skin infections, for example)?
6. As a sprinter, Lateesha knew that the best way to treat pulled muscles was through "RICE" (see Chapter 9, p. 231). What does that mean?
7. After her first day of skiing for the season, Janine woke up with stiff, achy muscles. What caused the sore muscles, and should Janine head out to the slopes for a second day of skiing?
8. Given what you have learned about increasing muscle strength through weight training, why do athletes taper off their training regimen prior to a major competitive event?
9. Skeletal muscle cells cannot divide. How does skeletal muscle repair itself when injured?