“Join our Gym!” scream the ads. “Live longer, live healthier. Change your body by working out with us!” Who are they kidding? Can 40 minutes of exercise a few times a week make me look better, feel better, have more energy, even live longer? Can these benefits emerge from pushing my muscular system to do more than walk from the couch to the fridge? Sounds fishy. Apparently, many people are skeptical of these ads, because fitness centers are always on the lookout for new members.

But once you understand the workings of the muscular system, you might give these pitches a bit more credence. Skeletal muscles, the ones you use to work out at the gym, run from danger, or even sit upright, are built like a set of nested cables that amplify the tiny force of molecular “machines” to produce your every motion, from the fine motor actions of signing your name to the huge force needed to shove a car uphill. When you begin a long-term exercise program of weight lifting or cycling, your muscles respond by changing in ways that improve their ability to lift weights or cycle tomorrow. In a “toned” muscle, individual fibers fire at random, and that causes them to hold their shape—and to use extra fuel. Kilogram for kilogram, a toned individual can eat more calories without gaining weight. But keeping in shape has important psychological benefits as well. Exercise liberates compounds that make you feel better. And there is mounting evidence that exercise is good for the immune system and can even help you live longer.
CHAPTER 6

The Muscular System Has Many Functions

**LEARNING OBJECTIVES**

List the functions of the muscular system.

Understand how skeletal muscles promote blood flow.

**Concept Check**

What is the primary function of the muscular system?

**Explain** two other functions of the muscular system.

---

 Movement through the environment is a defining characteristic of animal life. Humans move by applying tension to the bones and joints of the skeletal system, thereby propelling us through the world to find food, shelter, and clothing and to satisfy various social and emotional needs. This movement is generated by the muscular system, in close interaction with the nervous and skeletal systems.

Muscular tissue is contractile tissue. Studies of the muscular system usually focus on skeletal muscle and its connective-tissue covering. The human body has two other types of muscle tissue—smooth muscle and cardiac muscle (Chapter 11)—which are not found in the skeletal muscles.

Beyond manipulating our environment and moving through it, skeletal muscles have other functions. They help stabilize movement at joints. When we lift a heavy object, muscles in your forearms stabilize the wrists to prevent flexion—or extension—of the hand. You may have seen a weight-lifter lose a lift when the bar tilted sideways. The muscles’ stabilizing ability was overtaxed, allowing the joints to unwillingly flex.

The contraction of muscles in the appendages aids in the flow of lymph and blood through the body. When they contract, skeletal muscles squeeze blood vessels and convert them into pumps. Pregnant women are reminded to walk to help push the additional blood volume in their legs toward the heart. Muscles also protect internal organs, as exemplified by the “six-pack” muscles in front of the digestive organs.

Skeletal muscle has yet another function. Think how your body responds to cold. Shivering is the random contraction of muscles designed not to produce movement but to maintain thermal homeostasis by generating heat. Muscles are heat-producing organs. In fact, they are the largest producers of internal heat in the human body, making heat whenever they are used and even (to a limited degree) while at rest.

---

**Skeletal Muscles Are Contractile Organs**

**LEARNING OBJECTIVES**

Explain the difference between origin and insertion.

Define the relationship between muscle agonists and antagonists.

Describe the anatomy of a skeletal muscle.

Diagram the arrangement of proteins in the sarcomere.

---

Most people do not consider muscles to be organs, but they fit the definition: A muscle is made of tissues that are combined to perform a specific job in the organism. All human skeletal muscles have a similar function and structure. They contract, or get shorter, to produce movement. Muscles can relax to their original (“resting”) length or even elongate beyond that. In general, each skeletal muscle has an origin, an end that remains stationary when the organ shortens, and an insertion, an end that moves during contraction. Knowing the origin and insertion of any skeletal muscle offers clues about its function. If you mentally pull the insertion toward the origin, you can visualize the effect of contraction.

To coordinate and control body movements, most human skeletal muscles function as a member of an antagonistic or synergistic pair. One or more muscles provide movement (the prime mover or agonist) while a second muscle or group opposes that movement (the antagonist). Moving your hand to your shoulder requires the simultaneous contraction of the prime movers, the...
brachialis and biceps brachii muscles, and relaxation of the antagonist, the triceps brachii. These muscle pairs can often be identified by simply looking carefully at the superficial muscles. Occasionally the prime mover will be on the anterior surface and the antagonist will be on the posterior surface (Figures 6.2 and 6.3).

Skeletal Muscles Are Contractile Organs
SKELETAL MUSCLE IS BUILT LIKE TELEPHONE CABLE

Skeletal muscles are beautiful, simple organs, with an awe-inspiring degree of organization. When we look closely, we see an amazing effective internal configuration that shows the importance of repetition and how small forces, properly organized and coordinated, can produce strength and beauty. If you cut through the center of a skeletal muscle, you will see an internal structure that resembles a telephone cable (Figure 6.4). Skeletal muscle is composed of numerous elongated structures, running from origin to insertion, one nested inside another.

What is the function of all these connective tissue layers within the skeletal muscle? Individual skeletal muscle cells are long—sometimes 30 centimeters (or even longer in the sartorius muscle of the thigh). Muscle cells are also quite slender and exceedingly fragile. These fragile long cells must shorten, creating tension. Without connective tissue support, the soft tissue of the muscle cell would not be able to withstand the tension needed to provide movement, and the cell would rip itself apart rather than shorten the organ. In a telephone cable, individual wires are coated with insulation, then grouped in small packets within a larger cable. Similarly, skeletal muscle is grouped into individually protected cells, into fascicles, and then into the entire organ.

PROTEINS DRIVE MUSCLES

This “nested fibers” arrangement extends to the microscopic organization of skeletal muscle tissue. Look at a single muscle cell, or myofiber, and you will see an even smaller level of elongated, nested fibers.

The muscle cell itself is covered in a cell membrane very much like that discussed in Chapter 5. In this case it is called a sarcolemma, and it has specialized areas, T tubules, that conduct the contraction message. Inside the sarcolemma is a parallel series of myofibrils (Figure 6.5, page 164).
Inside these myofibrils, we find one final level of nested, elongated structures, the microfilaments composed of the proteins actin and myosin. These two microscopic proteins interact in a way that causes the entire muscle tissue to shorten, and therefore produce movement.

If you interweave your fingers and slide them together, you can approximate the interaction of actin and myosin. These proteins are held in regular arrangements in the contractile units, or sarcomeres, which are stacked end to end in the myofibrils. Although each sarcomere is quite small, when they all contract at once, the force generated is large enough to tap your toe or leap tall buildings in a single bound. Every one of our body movements originates in the interaction of these tiny proteins within the highly organized skeletal muscle: blinking, shoveling snow, playing the piano, or bench-pressing 200 kilograms.

**THE SARCOMERE IS BUILT FOR CONTRACTION**

If you examine a sarcomere, you'll get clues to the nature of muscular contraction. When relaxed, bands are visible in individual sarcomeres. These sarcomeres, and consequently their bands, line up in the muscle cell, visible as continuous dark and light areas on the cell. This alignment of sarcomeres and banded appearance produce bands or striations in the muscle cell as a whole. We refer to skeletal muscle as a striated tissue. The ends of the sarcomere make thin dark lines, called the Z discs, that run transverse to the length of the muscle cell (think, “Z is the end of the alphabet and Z is the end of the sarcomere”). Attached to the Z discs, and extending to the middle of the sarcomere on each side, are thin actin filaments. Thick myosin filaments are suspended in the center of the sarcomere between the actin filaments.

Passing light through a sarcomere reveals patterns of light and shadow due to the relative thickness of these structures (see Figure 6.5).
Muscle Contraction Occurs as Filaments Slide Past One Another

The contraction of skeletal muscle stems from the movement of actin and myosin, as described in the sliding filament model, proposed in 1969. The use of the word “model” indicates that although we know quite a bit about the mechanics of sarcomere contraction, the picture emerging from research laboratories is continually refining that understanding.

The contraction of a skeletal muscle starts when an impulse from a motor neuron (nerve cell carrying information to a muscle) reaches an area called the neuromuscular junction. At this junction, the motor neuron ends very close to a group of muscle cells, separated only by a small fluid-filled space called the synaptic cleft. The arrival of an impulse at the neuromuscular junction stimulates calcium-magnesium ATPase to pull calcium back into the sarcoplasmic reticulum, and specifically calcium sequestrin, to the SR. The sarcoplasmic reticulum stores calcium ions and releases them when acetylcholine binds to the surface of the cell membrane, delivering the chemical signal for the skeletal muscle to contract. This impulse to contract is then passed through the entire muscle cell by a small fluid-filled space called the synaptic cleft and binds to receptors on the surface of the muscle cell membrane, delivering the chemical signal for the skeletal muscle to contract. This impulse to contract is then passed through the entire muscle cell by a small fluid-filled space called the synaptic cleft and binds to receptors on the surface of the muscle cell membrane, delivering the chemical signal for the skeletal muscle to contract. This impulse to contract is then passed through the entire muscle cell via the specialized membrane structures called T tubules.

Inside the muscle cell is a particular organelle called the sarcoplasmic reticulum (SR), which stores much like the endoplasmic reticulum discussed in Chapter 3. The sarcoplasmic reticulum stores calcium ions and releases them when acetylcholine binds to the surface of the cell. Calcium is held within the SR by a protein called calcium sequestrin. The storage and release of calcium from the SR is accomplished by an enzyme on the surface of the sarcoplasmic reticulum, calcium-magnesium ATPase, which removes calcium from the cytoplasm and moves it into the SR. Calcium-magnesium ATPase works by converting ATP to ADP, powering a calcium "pump." It may surprise you to learn that free calcium inside the cell is toxic. Calcium-magnesium ATPase removes excess calcium from the muscle cell cytosol and adds it to the inner chamber of the SR, thereby ensuring the survival of the cell.

What happens next is a series of chemical reactions that follow one another like a line of falling dominos (Figure 6.9). The sliding filament model explains our best understanding to date of how muscle cells shorten.

Note that neither actin nor myosin undergoes any kind of chemical transformation, nor do they interconvert as the muscle cell contracts. Actin merely slides over the myosin filament, pulling the Z lines with it, hence the name “sliding filament model.” This cycle of myosin grabbing exposed actin sites and releasing inwards continues until (1) the removal of acetylcholine from the sarcolemma stimulates calcium-magnesium ATPase to pull calcium back into the sarcoplasmic reticulum, or (2) the supply of ATP is exhausted. Without a fresh supply of ATP, the myosin heads cannot release the actin molecule.

This is exactly what happens during rigor mortis. The death of the muscle cells causes the sarcoplastic reticulum, and specifically calcium sequestrin, to lose its ability to hold calcium. This triggers a release of the stored calcium, which causes the stored ATP in the myosin heads to begin a contraction cycle. Lacking oxygen supply and blood flow, the ATP used during cross-bridge formation cannot be replaced. Myosin heads cannot release the actin without fresh ATP supply, so the sarcomere is stuck in the crossbridge condition until the actin and myosin proteins begin to decompose. The extent of decomposition of these proteins is one clue that coroners use to determine time of death.
There are four steps in the transmission of an impulse at the NMJ:

Step 1: Ach is released from the end of the neuron.
Step 2: Ach binds to receptors on the muscle cell membrane, stimulating the release of calcium inside the muscle cell.
Step 3: A contraction cycle is begun in the muscle cell.
Step 4: The Ach in the synapse is removed by enzymes, ending its effects on the muscle cell.

Calcium binds to troponin, one of the two accessory proteins on the actin thin filament. The troponin molecule in this diagram is shown in blue, and the bound calcium ions are the smaller purple structures attached. This binding shifts the position of the troponin, which in turn shifts the position of the second accessory protein on the thin filament, tropomyosin, exposing the binding site on the actin filament. Meanwhile, the myosin heads in the thick filament are sitting at the ready, with the energy to contract stored right in the split golf club head. Remember that ATP is the molecule of energy in the body. The myosin heads obtain a molecule of ATP and immediately split it into ADP and a phosphate group (P), releasing energy from the bond, which becomes ready for muscle contraction.

With actin binding sites exposed, the myosin head is able to reach toward the actin binding site and react, using the energy from the split ATP of the myosin head. Linking the myosin head to the actin binding site creates a cross-bridge between the thick and thin filaments of the sarcomere.

As the myosin head releases energy, it bends toward the center of the sarcomere in the power stroke of the cycle. This slight bend pulls the actin filament across the myosin filament toward the H zone.

With the addition of fresh ATP, the myosin head will drop the actin, return to the ready position, and immediately grab a new actin-binding site. This process will continue until the calcium is re-sequestered and the troponin and tropomyosin are returned to their pre-contraction state.
CHAPTER 6

The Muscular System

Muscle Contraction Occurs as Filaments Slide Past One Another

If we zoom out from the microscopic scale, hundreds of simultaneous, asynchronous ratchet-like movements pull the thin filaments of each individual sarcomere into the H zone. Because the thin filaments are attached to the Z lines, this pulls the Z lines along with the actin, shortening the sarcomere. With millions of sarcomeres lined up in each muscle cell, and many muscle cells innervated by one motor neuron, these tiny chemical reactions shorten the entire muscle. See Figure 6.11 for a summary of these events.

The strength of an individual contraction event is also dictated by the sliding filament model. There is a strong correlation between the degree of overlap of the thick and thin filaments in the sarcomere and the amount of tension produced during contraction. Sarcomeres generate maximum tension with optimal overlap. When the Z lines of the sarcomeres are pushed too closely together (the muscle is understretched), or when the thick and thin filaments barely overlap (overstretched), the muscle fiber cannot generate much tension (Figure 6.11).

Summary of events in contraction and relaxation of skeletal muscle

1. Nerve impulse arrives at axon terminal of motor neuron and triggers release of acetylcholine (ACh).
2. ACh diffuses across synaptic cleft, binds to its receptor in the motor end plate, and triggers a muscle action potential (AP).
3. Acetylcholmesterase in synaptic cleft destroys ACh so another muscle action potential does not arise unless more ACh is released from motor neuron.
5. Troponin–tropomyosin complex slides back into position where it blocks the myosin binding sites on actin.
6. Contraction: power strokes use ATP; myosin heads bind to actin, swivel, and release; thin filaments are pulled toward center of sarcomere.
7. Ca2+ ions bind to troponin on thin filament, exposing the binding sites for myosin.
8. Muscle AP travelling along transverse tubule opens Ca2+ release channels in the sarcoplasmic reticulum (SR) membrane, which allows calcium ions to flood into the sarcoplasm.
9. Ca2+ active transport pumps release channels in SR close and Ca2+ active transport pumps use ATP to restore low level of Ca2+ in sarcoplasm.
10. Elevation of Ca2+ in sarcoplasm allows myosin heads to bind to actin, cause the muscle to shorten, and then release thin filaments.

This graph illustrates the strength of contraction at various-length sarcomeres. As you can see, the sarcomeres that are squished together too much cannot contract. As the thick and thin filaments slide apart, they reach an optimal length where contraction is quite forceful. As the sarcomere gets even longer, the power behind the contraction lessens. Eventually the sarcomere will be too long for there to be any overlap between thick and thin filaments. With no overlap, there can be no contraction.
CHAPTER 6

The Muscular System

Whole-Muscle Contractions Emerge From Tiny Impulses

**LEARNING OBJECTIVES**

- Define the all-or-nothing basis of muscle contraction.
- Explain summation, treppe, and tetanus.
- Identify the parts of a single muscle twitch.

Knowing the biochemistry of contraction and muscle anatomy, we now have a good foundation for discussing whole-muscle contraction. How does an entire large muscle like that of your thigh contract and generate movement?

Muscle cells are grouped in **motor units**, composed of one motor neuron and the set of muscle cells it controls (Figure 6.12). The entire motor unit contracts when it receives a signal from the motor nerve, which causes the release of the calcium ions that triggers the sliding action just discussed. Muscle cells contract on an all-or-nothing basis. Nothing happens when the nerve stimulus is too weak to cause the release of calcium from the sarcoplasmic reticulum. In muscle cells, when the threshold stimulus is reached, calcium is released and the entire muscle cell contracts. (Figure 6.13) Graded contraction is not possible at the cellular level. The all-or-nothing nature is similar to a mouse trap baited with cheese. A mouse can nibble the cheese and remove small amounts without consequence. But as soon as the mouse removes enough cheese, the trap snaps shut, trapping the hungry rodent.

**Muscle tension**

As adults, our postural muscles remain in tetanus throughout the day. Newborns, however, are not yet able to do this. As his neuromuscular junctions develop, this infant will be able to keep his head up for short periods of time. The “head bobbing” stage will last only a few days, after which tetanus is achieved in the neck muscles, and the baby will be able to observe and interact with his surroundings for long periods of time.

**Myogram**

Figure 6.13

A myogram records a single contraction of one motor unit, called a single twitch. During the latent period, calcium ions are moving, actin active sites are being exposed and myosin heads are taking up slack in the myofilaments, but contraction is not visible from outside the cell. Once the slack is taken up, the cell suddenly and visibly shortens, causing the sharp rise in the myogram at the contraction period. As the calcium is re-sequestered and the actin filaments with associated Z disks are released from the myosin cross bridges, the sarcomeres slide back to their original location. On the myogram, the shallow return to baseline is called the relaxation period.

**Graded contraction**

A smooth transition from a small, weak contraction to a forceful contraction.

**Treppe**

The increased strength of contraction after successive identical stimuli.

**K**
on our first attempt to lift it. Conversely, lifting a piece of movie-set Styrofoam requires far less force than the brain rallies. On the set of the 1996 disaster flick *Twister* (Figure 6.15), the semi-trailer that is blown into the air was made of large chunks of Styrofoam. The stagehands threw these Styrofoam trucks into the air after unintentionally using too many motor units to lift them.

Even during tetanic contraction, a small number of muscle cells are relaxing. The pattern of contraction and relaxation is asynchronous. If all the cells functioned in unison, the muscle would bounce between completely contracted to totally relaxed and back to completely contracted! That’s a recipe for jittery, stuttering motion.

The body can make ATP for muscular contraction through either the aerobic or anaerobic pathways. The highly efficient aerobic pathway literally burns glucose, forming water, carbon dioxide, and ATP. ATP is generated aerobically in the mitochondria. This pathway produces the largest amount of ATP and is the dominant method of energy production.

During heavy muscle activity, oxygen supply cannot keep up with the energy demands. ATP production then shifts to the anaerobic pathways. Anaerobic pathways are less efficient, producing far fewer ATP molecules per glucose molecule. Anaerobic pathways produce lactic acid, which is detrimental to sarcomere functioning. Lactic acid is eventually removed from the tissue by conversion to pyruvic acid, which gets shunted into the TCA (Krebs) cycle and the electron transport chain (Figure 6.16).
The conversion of lactic acid to pyruvic acid (Figure 6.17) requires oxygen, which is one reason we breathe heavily after exertion. We are repaying the oxygen debt incurred as a result of increased muscular activity. The added oxygen is carried through the bloodstream to the lactic acid-laden tissue. The oxygen reacts with the lactic acid, converting it to pyruvic acid and then to Coenzyme A, which the mitochondria can use.

Creatine phosphate is important in the anaerobic phase of muscle energy production because it stores energy much like ATP, in a phosphate bond. Creatine is a highly reactive compound that picks up the phosphates released when the myosin heads drop the actin active site. Recall that the ATP stored in the myosin head is broken into ADP and a free phosphate ion prior to myosin grabbing the actin active site. This free phosphate ion is released when the myosin head bends toward the center, sliding the actin filaments. This freed phosphate ion reacts with creatine to form creatine phosphate. Creatine phosphate then provides a reserve of phosphate for the formation of ATP from ADP. As long as there is a fresh supply of creatine, this cycle will prolong the contracting ability of the tissue (Figure 6.18). Even the most fit person, will eventually experience muscle fatigue. The Health, Wellness and Disease box, “Muscle Fatigue: Muscle Woes” (page 178), explains what happens in these instances.

MUSCLE TWITCHES CAN BE FAST OR SLOW

What causes some muscles to enlarge with exercise, whereas others seem to get stronger without any outward or visible changes? There are three types of muscle cells—fast twitch (or fast glycolytic), intermediate (or fast oxidative-glycolytic) and slow twitch (or slow oxidative) (Figure 6.19). Slow twitch muscle cells appear red, have a large blood supply, have many mitochondria within their sarclemma, and store an oxygen-carrying protein called myoglobin. These cells are sometimes called nonfatiguing or aerobic cells. Everything about these muscle cells is designed to provide oxygen to the mitochondria, to sustain the supply of ATP within the sarcosomes. Distance running and other aerobic sports stimulate these cells. In these muscle cells, efficiency and strength come not from increasing mass but from using oxygen more efficiently. Fast twitch, or anaerobic, muscle cells are almost total opposites. Fast twitch cells provide a short burst of incredible energy and contraction power, but they fatigue quickly. Fast twitch cells are thicker, contain fewer mitochondria, usually contain larger glycogen reserves, and have a less developed blood supply. These are the cells that are responsible for hypertrophy. Because short bursts of power come from these fibers, exercises that continuously require bursts of power will enlarge them. Weight training puts demands on fast twitch fibers, resulting in the hypertrophy we associate with bodybuilding.

Although training can alter the functioning of both red (slow twitch) and white (fast twitch) fibers, it does not change their proportions. Training can cause fast twitch fibers to function more like slow twitch fibers, providing more endurance with increased exercise. Despite this, your percentage of fast and slow twitch fibers is genetically predetermined. The ratio can, however, differ for each muscle group. You may have a preponderance of fast twitch fibers in your shoulder and back muscles, whereas your quadriceps muscle group may contain more slow twitch fibers. Olympic-caliber athletes are often those blessed with higher percentages of red or white fibers than the average person. Sprinters, obviously, benefit from a high proportion of fast twitch muscles, and long-distance skiers need more of the aerobic muscle cells.

Figure 6.17 The conversion of lactic acid to pyruvic acid and then on to ATP

Creatine phosphate reaction

Figure 6.18

Creatine phosphate reaction

Figure 6.18

Glycogen

A large polysaccharide easily broken down to release individual glucose molecules.
Muscle Fatigue, Muscle Woes

Endurance training can gradually transform fast twitch fibers to fast oxidative-glycolytic fibers (FOG, or intermediate fibers). These fibers are slightly larger in diameter, have more mitochondria, a greater blood supply, and more endurance than typical white fibers. The vast majority of human muscles are composed of these intermediate fibers. Regardless of which type of muscle fiber you wish to enlarge, there are many benefits to an exercise regimen. The I Wonder . . . feature outlines a few of these benefits.

Toned Muscles Work Better, Look Better

When muscles are used often, we say they have “good muscle tone.” What we are really saying is that even at rest, some muscle cells are always contracted. In a toned muscle, individual cells sporadically contract and relax, causing no movement but keeping the muscle taut. We can see muscle definition through the skin, due to this partial contraction. Increased tone is an important benefit of regular exercise, and not just for the “buff” look. Toned muscles are more effective at burning energy, meaning they use more ATP per gram than less-toned muscle tissue. People who are in shape can eat more without gaining weight because that continual, low-level contraction burns ATP.

Here is our first indication about the truth of those fitness club claims that exercise will help control weight. Making ATP takes energy in the form of calories.
The Dangers of Steroid Hormones

For those who want a shortcut to big, powerful muscles, testosterone and related steroid hormones have long been the drug of choice. Testosterone and estrogen are the steroid hormones that cause sex-linked traits to emerge during puberty. In males, testosterone causes the voice to deepen and (at interest here) growth of the skeletal muscles; in females, estrogen causes growth of the breasts and plays a key role in regulating fertility. Steroid hormones that cause muscle growth are called anabolic steroids. Both males and females produce testosterone, which enlarges body mass by increasing the production of proteins and red blood cells.

Steroid hormones are based on cholesterol, and their lipid structure gives them the ability to diffuse right through the plasma membrane. Once inside muscle cells, anabolic steroids stimulate the formation of proteins such as actin, myosin, and dystrophin, which build up existing muscle cells. Skeletal muscles seldom divide, so after puberty most muscle growth comes from enlargement within individual cells, called hypertrophy. Resistance training can also cause hypertrophy, and adding anabolic steroids greatly speeds the process.

Maintaining a toned muscle mass requires more ATP and therefore more calories than maintaining a less athletic body. Bottom line, a well-exercised body burns more calories in a day than an inactive body.

Exercise or chemical compounds can also change the size of a muscle. See the Ethics and Issues box, “The Dangers of Steroid Hormones,” for a discussion of steroid abuse. This is the only organ system in your body that can be altered so much by lifestyle choices. Scientists think the total number of muscle fibers is essentially set at birth, so how do we alter the appearance of this system? Through muscle enlargement or hypertrophy (hypertrophy is when muscle grows bigger). Scientists believe hypertrophy is caused by the addition of new myofibrils within the endomysium of individual muscle cells, which thicken individual myofibrils. This means hypertrophic muscles should have thicker muscle cells, packed with more sarcomeres than other muscle cells. Exercise that requires muscle to contract to at least 75 percent of maximum tension will cause hypertrophy. Body builders use this knowledge to create sculpted figures of their muscular system. Interestingly, aerobic exercises like cycling and dancing will not cause hypertrophy, but they still provide the cardiovascular and metabolic effects of increased muscle tone.

THE MUSCULAR SYSTEM HOLDS ONE OF OUR KEYS TO SURVIVAL

To see the muscular system in a different light, consider how the human lifestyle has changed in the past 20,000 years or so. We no longer live like the other animals, where our muscular system must function at peak performance to provide nutrition and keep us safe (Figure 6.20). Yet our muscles were designed to provide movement, to manipulate the environment, and to help maintain homeostasis by generating internal heat. The muscular system protects the organs in our viscera and maintains our upright posture. Today, although we need to satisfy these functions to stay alive, our lifestyle and technologies fulfill many of those needs. We heat our homes, wear clothing, and even add protective gear such as athletic pads to defend our internal organs from damaging blows. Our muscular system can grow flaccid without substantially endangering our survival, at least in the short term.

In the twentieth century did humans gain the luxury of choosing to work their muscular systems for better fitness. It is interesting to contemplate how different your muscular system, and therefore your entire body, would be if you depended on it for survival. Society and modern living have certainly had their impact on this system.
CHAPTER SUMMARY

1. The Muscular System Has Many Functions
   The muscular system is composed of skeletal muscle tissue. Its most obvious function is to generate movement; how-
   ever, it also performs other vital functions. The muscular system generates heat, stabi-
   lizes joints, helps move lymphatic fluid through the body, and supports and pro-
   tects soft internal organs.

2. Muscle Anatomy: Repetition Makes Strength
   Muscles are highly organized organs, protected by layers of connective tissue. The epimysium covers the entire organ,
   with fascicles of muscle cells covered in perimysium and individual myofibers sur-
   rounded by endomysium. Skeletal muscles extend from the immovable origin to the
   movable insertion, and often work in antagonistic pairs. Within the muscle itself, the
   proteins actin and myosin are arranged in specific patterns called sarcomeres. Thick
   myosin filaments are surrounded by thinner actin filaments, attached directly to the Z
   lines. The sarcomere is the contractile unit of skeletal muscle, extending from one Z
   disk to another.

3. Form in Function: How Muscles Contract
   The contraction of muscle is controlled by nervous impulses passed on to the muscle cell at the neuromuscular
   junction. The nerve cell dumps acetylcholine into the synapse between the nerve cell and the muscle cell, beginning
   muscular contraction. A series of chemical actions causes the filaments of myosin and actin to slide past each other,
   shortening the sarcomere and the muscle. Initially, calcium is released into the muscle cell, binding to the tropomyosin and troponin of the actin fil-
  ament. The actin active sites are exposed so

4. Whole-Muscle Contraction: Emerge From Tiny Impulses
   Whole-muscle contractions produce powerful movement from the combined si-
   multaneous contraction of millions of sar-
   comeres. Muscle cells contract in an all-or-
   nothing fashion, with identifiable phases. Each motor unit contracts in unison when the
   motor neuron fires with enough force to reach threshold. Initially, the muscle cells show no outward signs of shortening; this
   is the latent period. Ions are moving, and
   the muscle returns to its original length.

5. Putting the Muscles to Work
   Muscle cells can produce different
types of movement. All movement requires ATP, either stored in the cell or produced
   via metabolic pathways. Cellular respiration cannot keep pace with strenuous use of
   muscles, so creatine phosphate is em-
   ployed to store inorganic phosphate used in the conversion of ATP to ADP. Individual
   muscle cells respond differently to twitch
   impulses. Muscle fibers can be fast and eas-
   ily exhausted, slow and nonfatiguing, or
   somewhere between these two. Fast twitch fibers have a large supply of ready energy,
   with limited ability to remove waste or cre-
   ate ATP. Slow twitch fibers have less imme-
   diate energy but more ability to create ATP and remove wastes. Most of the skeletal
   muscle in the human body is composed of intermediate fibers.

KEY TERMS
- aerobic pathways
- anaerobic pathways
- endomysium
- epimysium
- globular
- myofibrils
- oxygen debt
- skeletal muscle
- smooth muscle
- TCA (Krebs) cycle
- troponin
- trophie
- threshold stimulus
- t tubules
- threshold stimulus
- TCA (Krebs) cycle
- trophie

CRITICAL THINKING QUESTIONS
1. In Greek mythology Achilles was an amazing warrior, unde-
   feated in many battles. His undoing was an arrow to the tendon
   of the gastrocnemius muscle (see Figure 6.3). Where was
   his wound? In common language, why did
   the arrow end Achilles’ fighting career? Anatomically speaking,
   how destroyed his fighting ability?
2. Briefly describe the structural diversity of muscle cells, starting with the
   sarcomere and ending with the structure of the sarcomere.
   Why do you suppose muscle cells are set up this way? Where is
   their strength? Are any weaknesses created by this arrange-
   ment? Why? Envision the cut end of a rope or cable. What hap-
   pens to the arrangement of the fibers? What happens to a rope
   if you apply tension from the side rather than the end?
3. When a muscle is stimulated to contract by an external electro-
   ical source instead of the motor neurons, there is a period be-
   fore external movement appears. We know ATP is being used immediately after the current is applied. What is happening
during this latent period? How would you expect the latent pa-
   riod to compare between a toned, “in shape” individual and
   someone without muscle tone?
4. List the sources of energy that are readily available for muscle
   contraction. What happens in endurance events? Where do the
   muscles of the leg get their steady energy supply during a gru-
   elling athletic event like a marathon? Does it make sense for en-
   durance athletes to take in nutrients during events?
5. We know training affects muscle fibers by making them more
   efficient. Specifically how does this occur? Assume you have
   begun endurance training for the Tour de France. What will this
   training do for your red muscle fibers? for your white and inter-
   mediate muscle fibers? Will effective training alter the propor-
   tion of these fibers?
1. The functions of the muscular system include all of the following EXCEPT:
   a. Manipulating and moving through our environment
   b. Stabilizing joints during motion
   c. Generating heat
   d. Aiding in blood flow through the body
   e. All the above are functions of the muscular system

2. Looking at your own biceps brachii (the muscle in your forearm that allows you to flex your arm), locate its insertion.
   a. The humerus
   b. The elbow
   c. The radius
   d. The carpals

3. The muscle that is primarily responsible for any action of the body is referred to as the
   a. Antagonist
   b. Agonist
   c. Synergist
   d. Fixator

4. Identify the outermost layer of connective tissue surrounding a muscle (identified as A in the figure).
   a. Epimysium
   b. Endomysium
   c. Perimysium
   d. Myofiber

5. The structure indicated as A in this figure serves to
   a. Sequester calcium
   b. House actin and myosin
   c. Protect the muscle cell
   d. Carry the impulse to contract quickly through the entire cell
   e. All of the above are functions of the muscular system

6. The contractile unit of skeletal muscle is the
   a. Sarcomere
   b. Sarcolemma
   c. Epimysium
   d. Actin

7. The Z lines are represented in this image by structure
   a. A
   b. B
   c. C
   d. D

8. The globular protein instrumental in muscle contraction is found in the__________of the sarcomere.
   a. A band
   b. I band
   c. Z line
   d. Middle
   e. Both a and b are correct.

9. The events at the neuromuscular junction begin with
   a. ACh binding to receptors on the muscle cell
   b. Neurotransmitter being dumped into the neuromuscular synapse
   c. Calcium being released from the SR
   d. Sliding filaments

10. The protein to which calcium binds in step one of this image is
    a. Actin
    b. Myosin
    c. Troponin
    d. Tropomyosin

11. True or False: Once calcium binds to the proper protein, moving it off the active site, myosin heads bend toward the center of the sarcomere.

12. This graph indicates that
    a. Muscle tension is independent of sarcomere length
    b. Muscle tension increases steadily with increasing sarcomere length
    c. Powerful contractions can only be generated in a very narrow range of sarcomere lengths
    d. Sarcomeres with Z lines nearly touching generate more power than those with Z lines spread far apart.

13. The portion of the myogram indicated as B corresponds to what action?
    a. Relaxation
    b. Latent period
    c. contraction
    d. treppe

14. The most efficient production of energy for muscular contraction is
    a. Aerobic pathways
    b. Anaerobic pathways
    c. Lactic acid metabolism
    d. Creatine phosphate

15. The muscle fiber that is quick to contract and quick to fatigue is the
    a. Fast glycolytic fiber
    b. Slow oxidative fiber
    c. Non-fatiguing fiber
    d. aerobic fiber

16. Identify the type of movement produced by the muscle indicated B on the figure.
    a. Supination
    b. Extension
    c. Adduction
    d. Flexion
    e. Abduction

17. Identify the muscle indicated as A on the above diagram.
    a. Rectus abdominus
    b. Triceps brachii
    c. Quadriceps group
    d. Pectoralis major

18. The antagonist for the muscle indicated B on the same figure is the
    a. Hamstrings
    b. Gluteus maximus
    c. Deltoid
    d. Triceps brachii

19. Identify the type of movement produced by the muscle indicated as B on the figure.
    a. Extension
    b. Plantar flexion
    c. Rotation
    d. Dorsiflexion

20. The muscle identified as A on the same diagram moves the
    a. Spinal column
    b. Base of the skull
    c. Shoulder
    d. Forearm

**SELF TEST**

**CHAPTER 6 The Muscular System**

1. The functions of the muscular system include all of the following EXCEPT:
   a. Manipulating and moving through our environment
   b. Stabilizing joints during motion
   c. Generating heat
   d. Aiding in blood flow through the body
   e. All the above are functions of the muscular system

2. Looking at your own biceps brachii (the muscle in your forearm that allows you to flex your arm), locate its insertion.
   a. The humerus
   b. The elbow
   c. The radius
   d. The carpals

3. The muscle that is primarily responsible for any action of the body is referred to as the
   a. Antagonist
   b. Agonist
   c. Synergist
   d. Fixator

4. Identify the outermost layer of connective tissue surrounding a muscle (identified as A in the figure).
   a. Epimysium
   b. Endomysium
   c. Perimysium
   d. Myofiber