The Muscular System

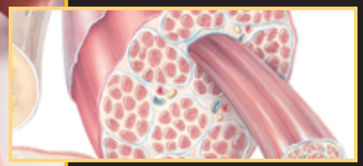
6

"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.

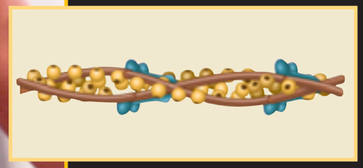
But once you understand the workings of the muscular system, you might give these pitches a bit more credence. Skeletal muscles, the ones you use to work out at the gym, run from danger, or even sit upright, are built like a set of nested cables that amplify the tiny force of molecular "machines" to 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 OUTLINE

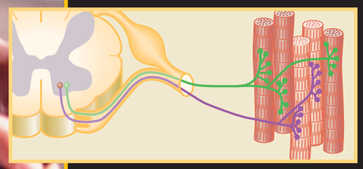
- The Muscular System Has Many Functions p. 000



- Skeletal Muscles are Contractile Organs p. 000



- Muscle Contractions Occurs as Filaments Slide Past One Another p. 000



- Whole-Muscle Contractions Emerge from Tiny Impulses p. 000

- Muscles Require Energy to Work Smoothly and Powerfully p. 000

The Muscular System Has Many Functions

Learning Objectives

List the functions of the muscular system.

Understand how skeletal muscles promote blood flow.

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.

Skeletal muscle Contractile tissue composed of protein filaments arranged to move the skeletal system.

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 lying 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.

The muscular system is at work here, allowing this child to move in precisely defined patterns as she creates her snow sculpture. No doubt she is also shivering slightly in the freezing air.

Concept Check

What is the primary function of the muscular system?

Explain two other functions of the muscular system.

Skeletal Muscles Are Contractile Organs

Learning Objectives

Explain the difference between origin and insertion.

Define the relationship between muscle agonists and antagonists.

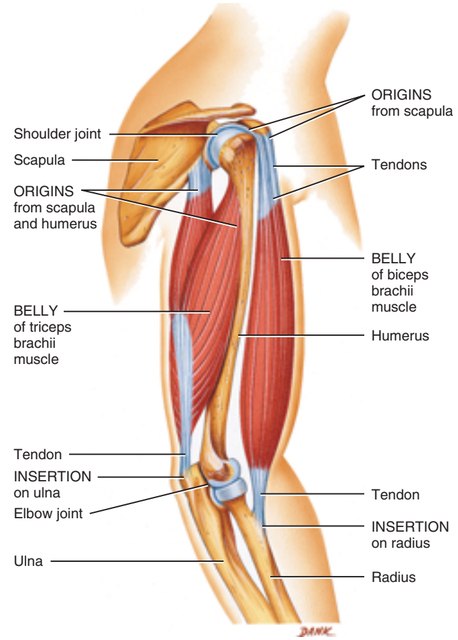
Describe the anatomy of a skeletal muscle.

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 (FIGURE 6.1). 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

Antagonistic (synergistic) pair Muscles with opposing actions working together to provide smooth and controlled movements.



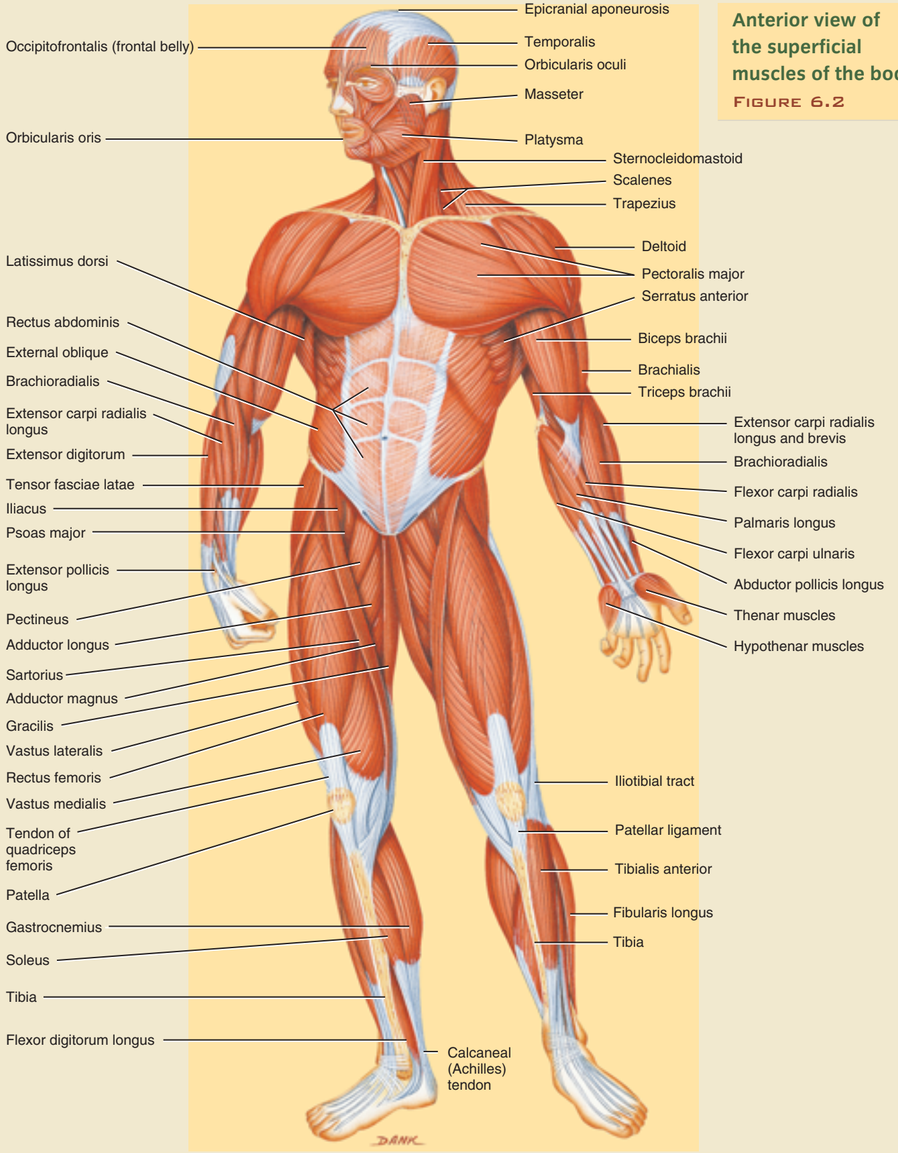
Origin and insertion of a skeletal muscle

Muscle origin and insertion FIGURE 6.1

To raise your hand toward your shoulder, the humerus must remain stable while the radius and ulna move upward. This movement is accomplished by contraction of the *brachialis* and *biceps brachii*. The origin for the brachialis is at the middle of the humerus, and the insertion is the proximal end of the ulna. When the brachialis muscle contracts, the humerus remains stationary and the ulna moves toward it. The origin for the biceps brachii is on the scapula, and its insertion is on the radius. When this muscle contracts, the scapula above the humerus remains in place and the radius moves upward to meet it.

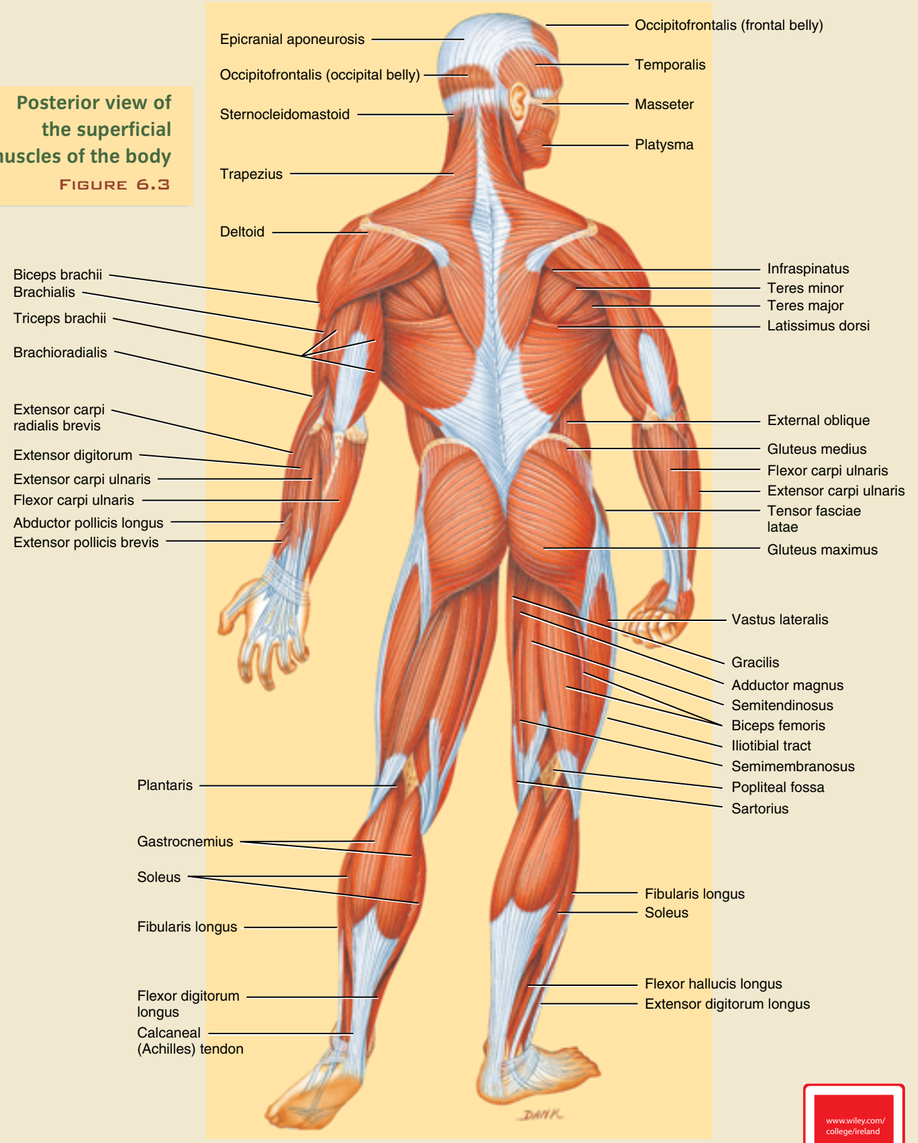
brachialis and biceps brachii muscles, and relaxation of the antagonist, the triceps brachii. These muscle pairs can often be identified by simply looking carefully at the superficial muscles. Occasionally the prime mover will be on the anterior surface and the antagonist will be on the posterior surface (FIGURES 6.2 AND 6.3).

Anterior view of the superficial muscles of the body
FIGURE 6.2



Anterior view

Posterior view of the superficial muscles of the body
FIGURE 6.3



Posterior view

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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 amazingly 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.

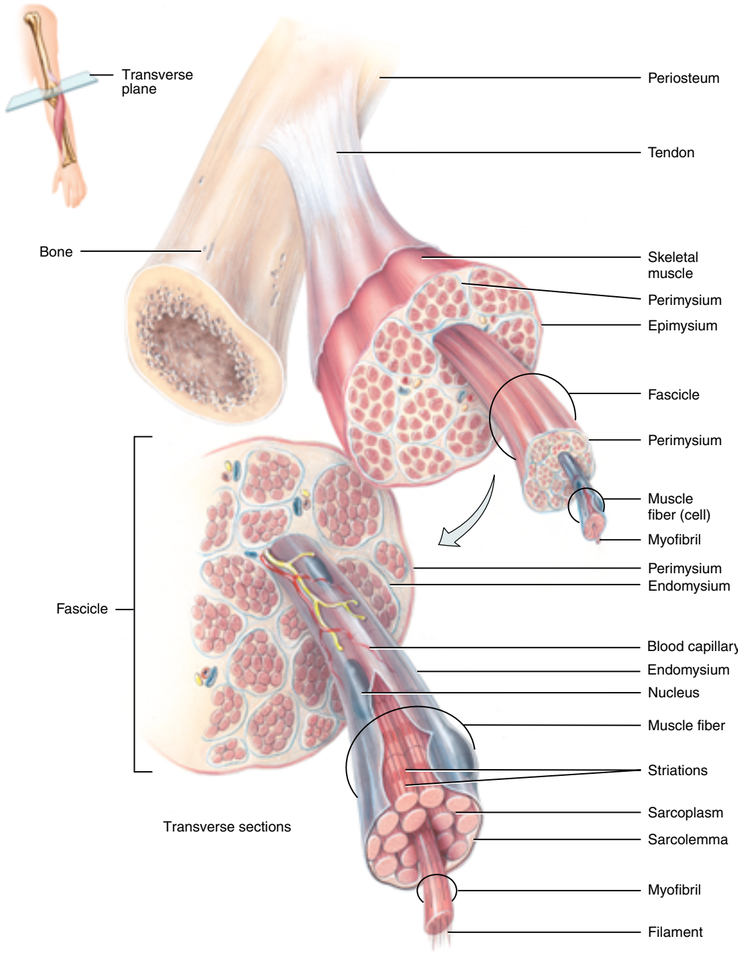
Epimysium
The outermost covering on a muscle, separating one muscle from the next.

Perimysium
An inner connective tissue covering and supporting a group of muscle cells.

Endomysium
The innermost connective tissue lining, covering individual muscle cells, on top of the muscle cell membrane.

The outermost lining of skeletal muscle is the *deep fascia* or **epimysium**. Within this lining, blood vessels, nerves, and bundles of muscle cells are surrounded by a second lining, the **perimysium**. Each group of covered muscle cells is called a *fascicle*. (If you drag a fork across the top of a raw T-bone steak, those little tabs you see are the fascicles.) Within the perimysium is yet another lining, the **endomysium**, which surrounds individual muscle cells. (*Epi* = on top of; *peri* = around, like the perimeter of a circle; *endo* = within; and *my* is the root for "muscle.")

Anatomy of a muscle FIGURE 6.4



PROTEINS DRIVE MUSCLES

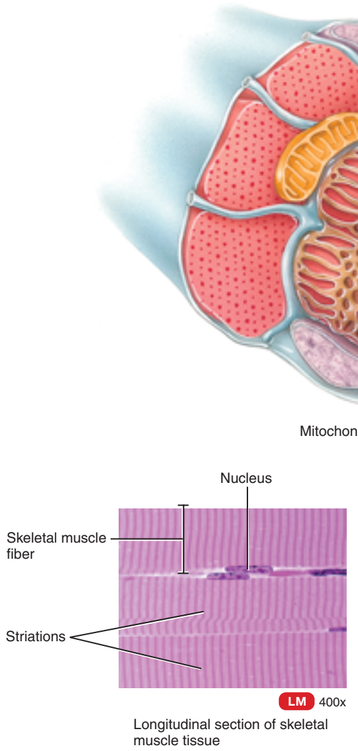
This "nested fibers" arrangement extends to the microscopic organization of skeletal muscle tissue. Look at a single muscle cell, or **myofiber**, and you will see an even smaller level of elongated, nested fibers.

The muscle cell itself is covered in a cell membrane very much like that discussed in Chapter 3. 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).

T tubules Areas where the sarcolemma forms a tube that crosses through the muscle cell, carrying contractile impulses to the opposite side of the cell.

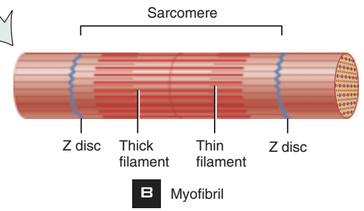
Myofibrils
Linearly arranged groups of the contractile proteins actin and myosin.

Organization of skeletal muscle from the gross to the molecular level FIGURE 6.5

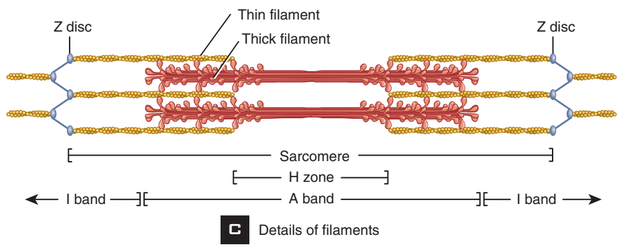


Longitudinal section of skeletal muscle tissue

A Details of a muscle fiber



B Myofibril



C Details of filaments

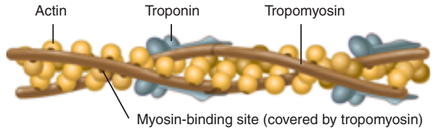
Inside these myofibrils, we find one final level of nested, elongated structures, the microfilaments composed of the proteins **actin** and **myosin**. These two microscopic proteins interact in a way that causes the entire muscle tissue to shorten, and therefore produce movement.

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.

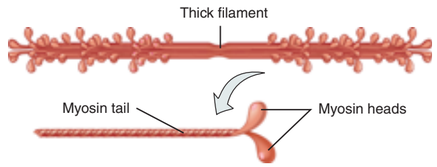
THE SARCOMERE IS BUILT FOR CONTRACTION

If you examine a sarcomere, you'll get clues to the nature of muscular contraction. When relaxed, bands are visible in individual sarcomeres. These sarcomenres, 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).



Portion of a thin filament



One thick filament (above) and a myosin molecule (below)

The Arrangement of Actin, Troponin, and Tropomyosin in a Thin Filament FIGURE 6.6

Actin is a **globular** protein, looking much like a string of pearls in the thin filaments of the sarcomere. Each thin filament is composed of two strands of actin, twisted about one another. Within the grooves of this double strand lie two additional small globular proteins that respond to calcium ion concentration. These accessory proteins, *troponin* and *tropomyosin*, cover the active site on each actin molecule, where they regulate contraction.

Globular
spherical or round.

Myosin filament FIGURE 6.7

The thick filament is composed of a grouping of myosin proteins oriented with their golf-club heads toward the Z lines in both directions and their shafts bundled together in the H zone. This arrangement leaves the thick filaments with a central area at the H zone where there are no heads. Heads extend off the filament in both directions, toward both Z lines. Many myosin heads extend from the thick filaments, arranged 360° around the filament. These heads are positioned so they do not overlap one another, but provide a continuous swirl of extended heads throughout the A bands.

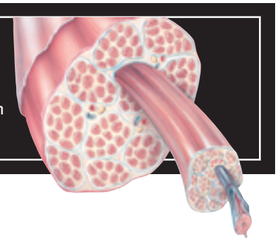
The biochemistry of muscle contraction emerges from the structure of actin and myosin (FIGURE 6.6 and FIGURE 6.7). Actin is a thin, globluar protein with an area that will interact with myosin. In comparison, myosin is a larger, heavier protein, shaped like a golf club with a double head. The myosin head includes an area that will interact with to the actin molecule under the correct circumstances.

CONCEPT CHECK

How does an agonist assist in muscle contractions?

When a skeletal muscle contracts, does the origin or the insertion move?

Describe the anatomy of a muscle, starting with the outermost layer.



Muscle Contraction Occurs as Filaments Slide Past One Another

LEARNING OBJECTIVES

Outline the appearance of the neuromuscular junction.

Describe the steps in the sliding filament model.

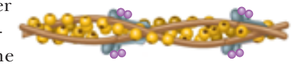
The contraction of skeletal muscle stems from the movement of actin and myosin, as described in the **sliding filament model**, proposed in 1969. The use of the word "model" indicates that although we know quite a bit about the mechanics of sarcomere contraction, the picture emerging from research laboratories 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 **synapse,** or synaptic cleft.

Nerves send a contraction impulse across the synapse with chemical messengers, called neurotransmitters. The most common of these messengers is **acetylcholine**, abbreviated **ACh**. When acetylcholine is released from the axon terminal, it diffuses across 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 looks 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. (FIGURE 6.8)

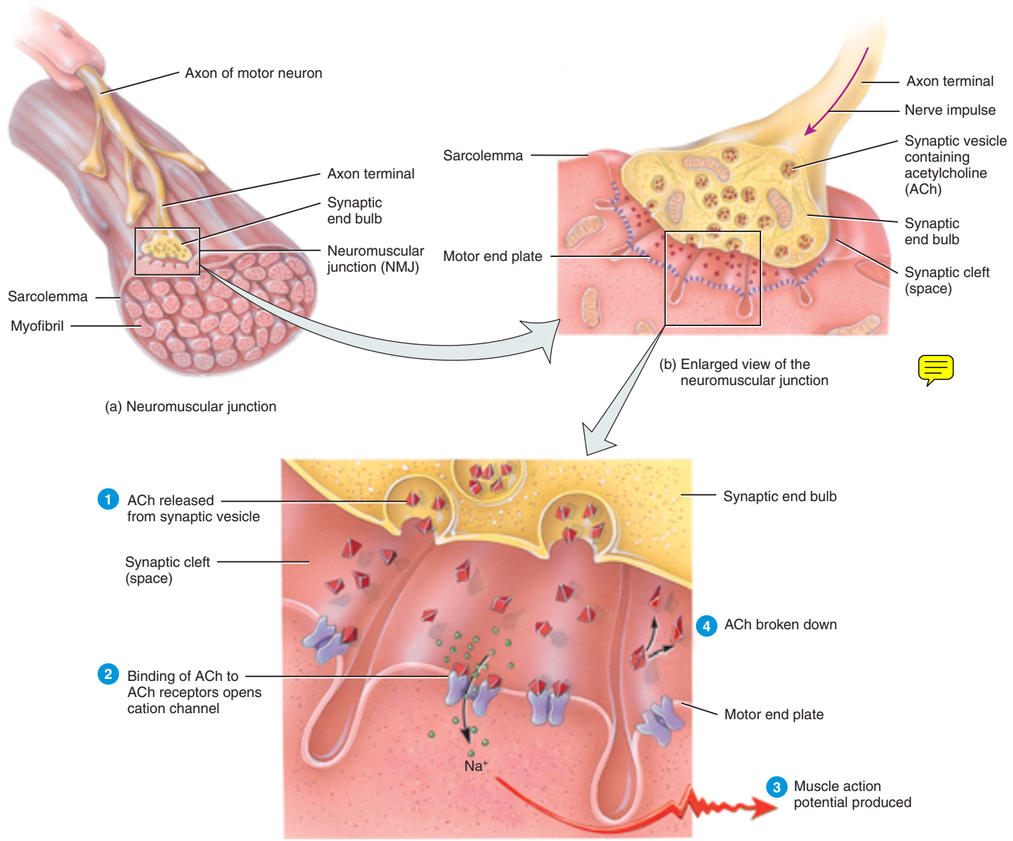
What happens next is a series of chemical reactions that follow one another like a line of falling dominoes (FIGURE 6.9). The sliding filament model explains our best understanding to date of how muscle cells shorten.



Note that neither actin nor myosin undergoes any kind of chemical transformation, nor do they intertwine 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 ratcheting inward 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 sarcoplasmic 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 cross-bridge 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.

Neuromuscular Junction FIGURE 6.8



(c) Binding of acetylcholine to ACh receptors in the motor end plate

There are four steps in the transmission of an impulse at the NMJ:

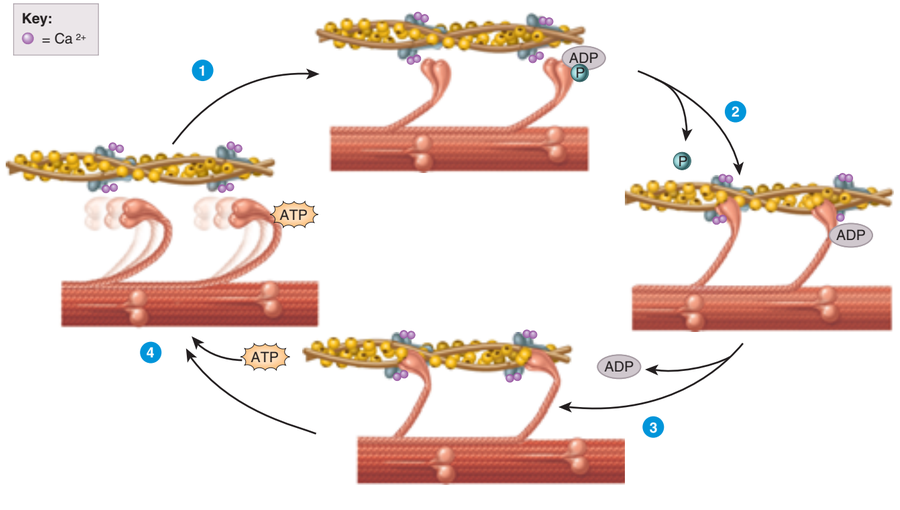
Step 1 ACh is released from the end of the neuron.

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.

Contraction Cycle FIGURE 6.9



Step 1 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.

Step 2 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.

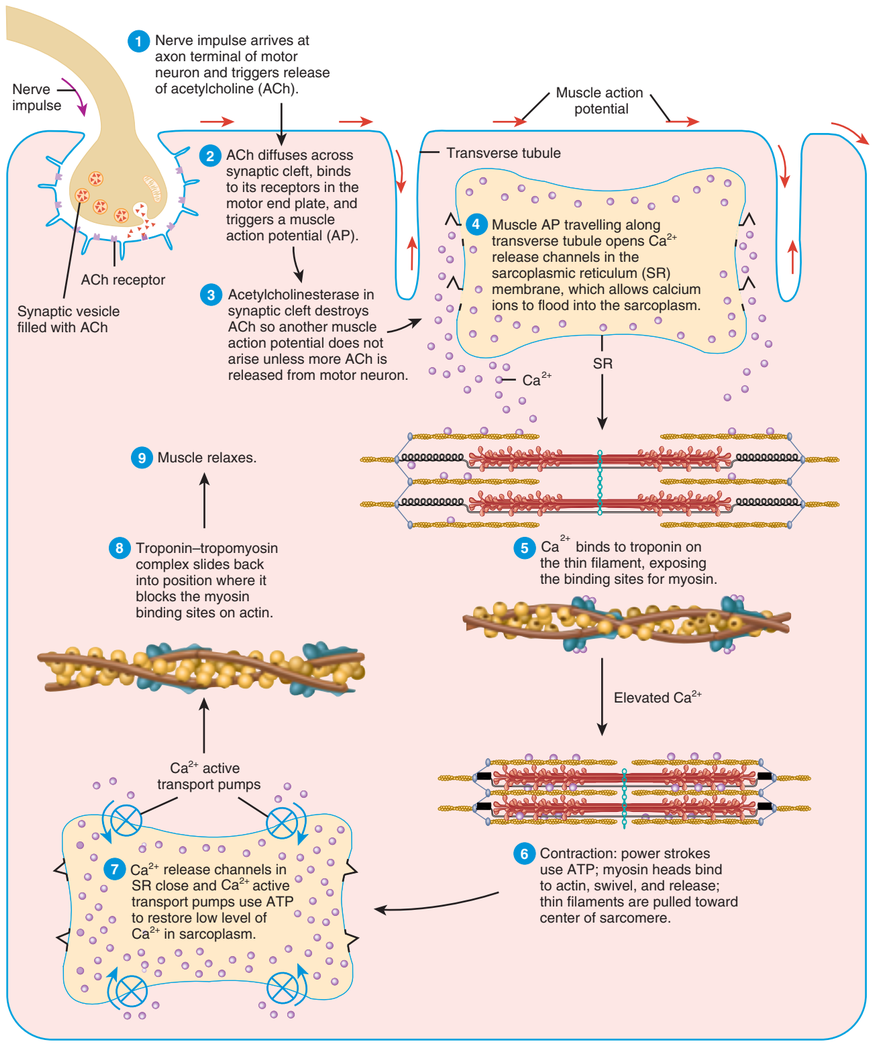
Step 3 As the myosin head releases energy, it bends toward the center of the sarcomere in the **power stroke** of the cycle. This slight bend pulls the actin filament across the myosin filament toward the H zone.

Step 4 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-sequesterd and the troponin and tropomyosin are returned to their pre-contraction state.

Process Diagram

Summary of events in contraction and relaxation of skeletal muscle

FIGURE 6.10



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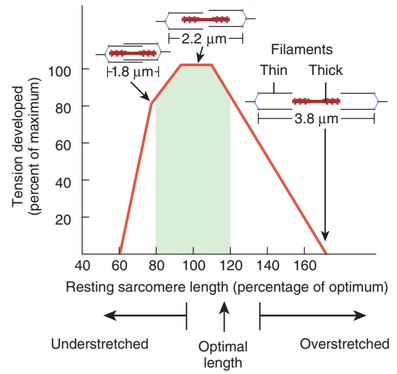
If we zoom out from the microscopic scale, hundreds of simultaneous, asynchronous ratchet-like movements pull the thin filaments of each individual sarcomere into the H zone. Because the thin filaments are attached to the Z lines, this pulls the Z lines along with the actin, shortening the sarcomere. 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 6.10 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).



Length-tension relationship in a skeletal muscle fiber FIGURE 6.11

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.

CONCEPT CHECK

Diagram a typical sarcomere.

How is the action of the neuromuscular junction related to the sliding filament theory?

Explain how ATP is used in muscle contraction.

Whole-Muscle Contractions Emerge From Tiny Impulses

Learning Objectives

Define the all-or-none basis of muscle contraction.

Identify the parts of a single muscle twitch.

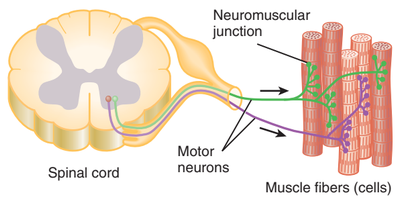
Explain summation, treppe. and tetanus.

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 that 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.

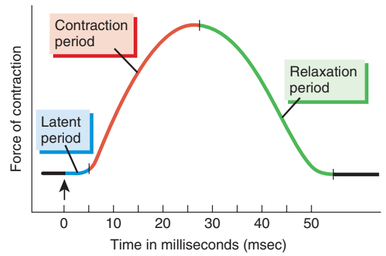
Threshold stimulus
The minimal amount of stimulation needed to cause a reaction.

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



Motor unit Figure 6.12

Each motor unit is individually controlled. Contraction strength depends on how many motor units are stimulated, not on how powerfully the individual cells contract. Few motor units are stimulated during a weak contraction, but feats of strength require many motor units.



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 myofibers, 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*.

Treppe
The increased strength of contraction after successive identical stimuli.

Single twitches are not effective in producing body movement, because they last only a fraction of a second. To produce a meaningful amount of contraction, the motor unit requires multiple stimuli, reaching the muscle cell in such quick succession that it has no time to relax. Each contraction builds on the heels of the last, until the muscle cell is continuously contracted. This buildup of contractions is called **summation,** and the phenomenon of increased strength for similar stimuli is known as **treppe**. Warming up prior to an athletic event takes advantage of treppe. As the athlete continues to perform the motions required in competition, the muscles undergo treppe. Each successive contraction gets a little stronger. By the time the event starts, the muscles are ready to perform at peak strength. Once continuous contraction is achieved, the muscle is said to be in **tetanus**. (This continuous, and normal, contraction of the muscle is not the same as the bacterial infection also called tetanus.) The neck muscles of an adult are in tetanus most of the day. It is unusual to see adults' heads bobbing like a newborn's (Figure 6.14)—unless they are trapped in a boring lecture!

Summation explains how single twitches can provide sustained movement, but how is the strength of contraction monitored and regulated? You know you are capable of graded contractions—you can pick up a pencil with ease, using the same muscles that you would use to pick up a big stack of weighty textbooks. The answer is that contractions are graded by recruiting more motor units, under the brain's control. Before lifting, your brain makes an assumption, based on your experience, about the weight of the object, and begins the contraction by stimulating the appropriate number of motor units. If the original number of recruited motor units is incorrect, the brain will adjust by either recruiting more motor units or releasing some extra ones. We have all been fooled at some time. A small bar of silver is far heavier than it looks and can make us feel foolish

Muscle tension Figure 6.14

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.

Twister FIGURE 6.15

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.

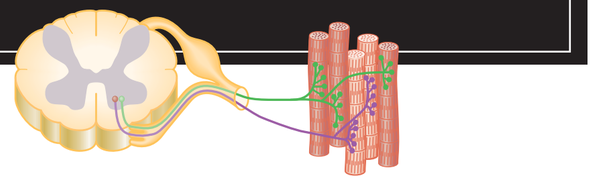
Even during tetanic contraction, a small number of muscle cells are relaxing. The pattern of contraction and relaxation is asynchronous. If all the cells functioned in unison, the muscle would bounce between completely contracted to totally relaxed and back to completely contracted! That's a recipe for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

CONCEPT CHECK

Define motor unit.

What is happening in the muscle during the latent period of a muscle twitch?

How does treppe relate to athletic performance?



Muscles Require Energy to Work Smoothly and Powerfully

LEARNING OBJECTIVES

Describe the health benefits of toned muscles.

Compare aerobic and anaerobic energy pathways.

Explain the roles of ATP and creatine phosphate in muscle contraction.

Describe the different types of muscle fiber.

Now that we have examined the anatomy and physiology of skeletal muscles, it's time to look at how they work together to produce smooth, powerful movement. Let's start by looking at ATP, the general-purpose source of readily available energy inside cells.

Aerobic pathway Metabolic pathway that requires oxygen to burn glucose completely.

Anaerobic pathways Metabolic pathways that occur in the cytoplasm and burn glucose to lactic acid, releasing some energy.

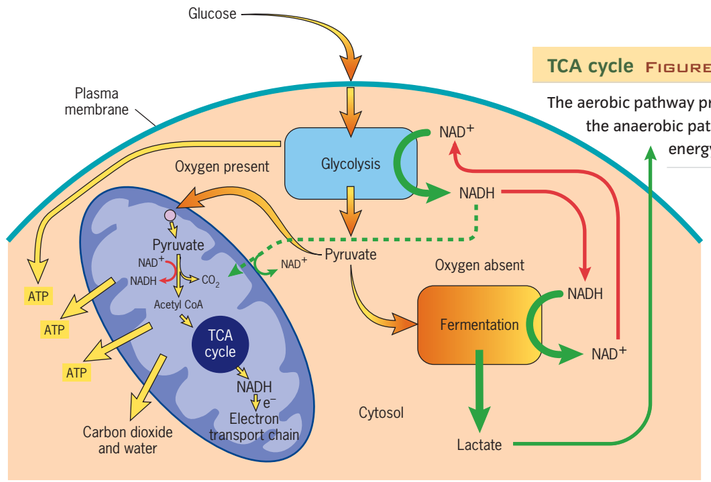
CONTRACTION ENERGY CAN BE PRODUCED AEROBICALLY OR ANAEROBICALLY

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).

TCA (Krebs) cycle the citric acid cycle,.step two in the production of ATP from glucose, carried out in the mitochondrial cristae.

Electron transport chain Step three in aerobic respiration wherein electrons are passed in a series of chemical reactions, eventually producing ATP.

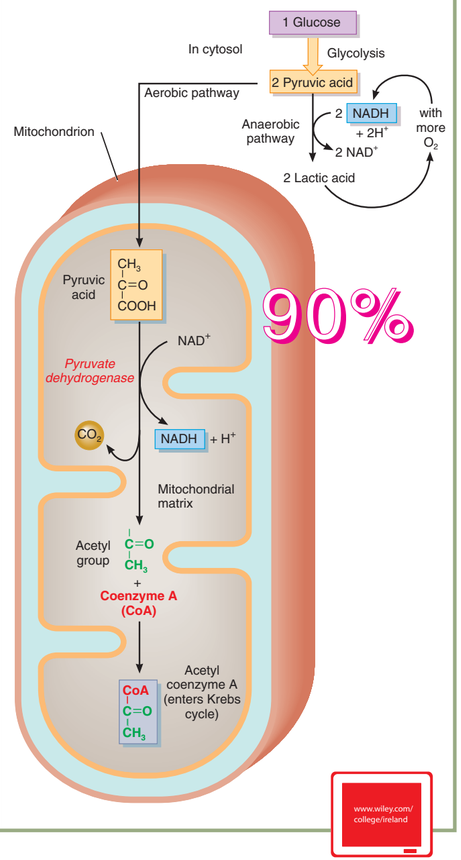


TCA cycle FIGURE 6.16

The aerobic pathway produces ATP more efficiently, but the anaerobic pathways can take over when energy demands are too high.

Process Diagram

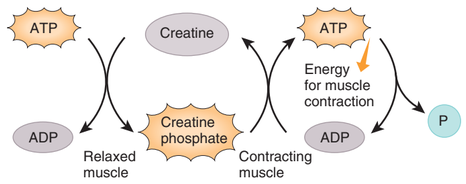
The conversion of lactic acid to pyruvic acid and then on to ATP FIGURE 6.17



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.

Oxygen debt
The amount of oxygen needed to convert the lactic acid produced by anaerobic respiration into pyruvic acid and burn it entirely to CO_2, H_2O, and energy.

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 is released when the myosin head bends toward the center, sliding the actin filament. 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.



ATP from creatine phosphate

Creatine phosphate reaction FIGURE 6.18

Creatine picks up free phosphate groups, making them available for the conversion of ADP to ATP, increasing energy available for muscle contraction. If no oxygen is present when contactions occur, two ATPs will be produced and lactic acid will be sent to the blood. Ideally, oxygen will be present in levels high enough to complete aerobic respiration. This results in the production of ATP, heat, CO_2, and water.

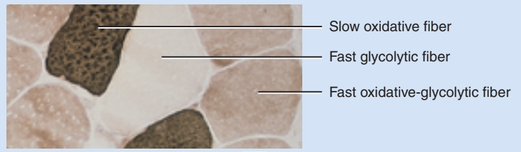
MUSCLE TWITCHES CAN BE FAST OR SLOW

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 sarcolemma, 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 of the cells, to sustain the supply of ATP within the sarcomeres. 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.

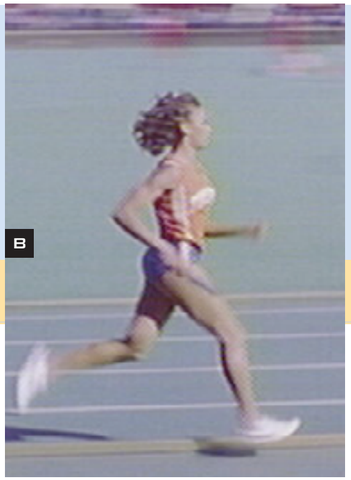
Glycogen
A large polysaccharide easily broken down to release individual glucose molecules.

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 pre-determined. 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.



Transverse section of three types of skeletal muscle fibers

A

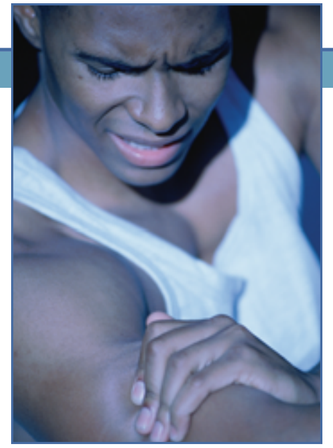


B

A Micrograph of the three types of muscle fibers
B Fast twitch and slow twitch fibers in motion FIGURE 6.19

Slow oxidative fibers are synonymous with slow twitch fibers. Note the thinner diameter and greater capillary flow through these cells as compared to the fast glycolytic fibers. Fast glycolytic fibers are the white fibers, carrying lots of glycogen and plenty of immediately available energy.

Muscle Fatigue, Muscle Woes



Ever watched the finish of the Iron Man endurance race? Hours after the front-runners pass the finish line come the also-rans. Some cross the line with a wobble-legged stagger and possibly without any control of bowel or bladder. These athletes are suffering from muscle fatigue—their muscles have stopped responding to the nervous impulse to contract.

The physical inability to contract seems to result from deficiencies in the chemicals needed for contraction. Some scientists think it is due to a brief shortage of oxygen in the contracting muscles. Others blame fatigue on a shortage of ATP, the do-it-all energy source. Still others blame fatigue on a buildup of lactic acid as a result of anaerobic respiration. As lactic acid is released into the bloodstream, it can lead to **acidosis** (lower blood pH). Acidosis affects the central nervous system and can lead to decreased contractile and metabolic functioning.

The tiredness you sometimes experience during exercise is not physical fatigue but a response to alarm signals from stressed-out muscle tissue, which may help maintain homeostasis by maintaining pH at safe levels. The exact threshold of fatigue varies widely among humans. Scientists have recently learned that women apparently use aerobic respiration more effectively than men, which could explain why women's muscles are more resistant to fatigue. Fortunately, it's fairly easy to recover from muscle fatigue (as opposed to dehydration). Rest, adequate oxygen intake, fluids, and electrolytes usually do the trick.

Exercise may play a role in other common muscle problems:

- Muscle spasms (tics or twitches) are involuntary, and often painful, muscle contractions.
- Muscle cramps are persistent spasms that may result from overuse that causes microscopic tears in muscle fibers, or from dehydration, often combined with electrolyte imbalance. Cramps often afflict muscles used for postural control—in the back and neck, for example. Fluids, electrolytes, stretching, and exercising within reason can all help prevent and treat muscle cramps.
- Delayed-Onset Muscle Soreness (DOMS) can result from an unusual increase in the severity or quantity of resistance training. DOMS is marked by temporary soreness, tenderness, and stiffness, and is associated with elevated levels of myoglobin and the enzyme creatine phosphokinase (CPK) in the blood. CPK facilitates the transfer of phosphate from creatine phosphate to ADP, and its appearance outside muscle cells is a sign of damage to those cells. DOMS is probably caused by tears in muscle tissue that damage the cells, by muscle spasms, or by tears in the connective tissue framework of muscles. DOMS usually peaks about two days after the exertion. There seems no correlation between the type of activity performed and the level of pain experienced. To prevent DOMS, build up your resistance training gradually, and warm up and stretch before exercising.

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 regime. The I Wonder . . . feature, "What are the holistic benefits of physical exercise?" outlines a few of these benefits.

I WONDER. . .

What are the holistic benefits of physical exercise?

Finally, we have enough knowledge to judge the claims of the fitness centers, and yes, exercise has health benefits. Resistance training concentrates the enzymes that help create ATP and increases the efficiency of the enzymes in the myosin heads that break down ATP, both of which help increase muscle tone. Toned muscle uses ATP continuously, and faster. The body's shape can change as it burns extra calories to sustain the muscle mass and the white muscle fibers that have enlarged through hypertrophy.

Exercise has many other specific benefits:

- The heart: The heart is a muscle, and muscles get stronger when they are used. A stronger heart is better able to resist setbacks like clogged arteries or rhythm problems that can cause major trouble in weaker hearts. Aerobic exercise can reduce blood pressure, which reduces the exposure to strokes. As the American Heart Association says, "Physical inactivity is a major risk factor for heart disease and stroke and is linked to cardiovascular mortality."
- The blood: Exercise changes the lipid profile, increasing high-density lipoprotein, which seems to protect the arteries, and reducing low-density lipoprotein and triglycerides, which are associated with hardening and narrowing of the arteries, especially in the heart.
- The immune system: Many studies show a link between physical exercise and resistance to colds and other viral infections.
- The endocrine system: Exercise is a key recommendation for slowing the onset of type II diabetes and for reducing its symptoms, probably because it increases the body's use of insulin, and reduces glucose in the bloodstream.
- The psyche: Exercise is great for reducing stress. The body makes compounds called endorphins, which are related to opiates and may have a calming effect. Curiously, recent research shows that exercise may be more reliable at reducing negative feelings like anxiety or depression than at inducing positive feelings and that the benefits appear at exercise levels that do not cause endorphin formation.
- The skeletal system: Impact exercises—especially running—help keep the bones dense, warding off osteoporosis. Increasing the muscular tug on the bones has also been shown to increase bone density.
- The individual: Exercise has an anti-aging component. Although it does not exactly reverse aging, it does help older people retain or improve their ability to do what gerontologists call the activities of daily life. Repeated studies show that exercise prevents injury and increases balance, endurance, walking speed, and rates of spontaneous physical activity throughout life.

All in all, both aerobic exercise and resistance training have a place in maintaining and restoring health. Exercise is better for you than any pill and cheaper than most health-care regimes.

TONED MUSCLES WORK BETTER, LOOK BETTER

Muscle tone
Constant partial contraction of muscle when the body is "in shape."

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.

Ethics and Issues

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 (of 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 bulk 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.

Anabolic steroids Lipid-soluble cholesterol-based compounds that stimulate increased muscle development, among other effects.

Since the 1950s, athletes have injected testosterone and related compounds to sprint faster, jump higher, and lift heavier. (The hormones must be injected because they cannot withstand stomach acid.) But anabolic steroids cause more than just muscular hypertrophy. Severe and dangerous side effects include acne, masculinization of females (the former East Germany used to be famous for its bearded women swimmers), the much publicized "'roid rage", liver dysfunction, testicular cancer, kidney disease, and kidney failure. Even diabetes and hypertension have been linked to steroid abuse. Former users have commented that steroids can be addictive: The hormones produce an energetic high that disappears when they stop using the needle.

The side effects of anabolic steroids are so severe that they are regulated by the same laws as morphine. Anabolic steroids, along with a long list of other performance-enhancing drugs, are now banned by a growing list of amateur and professional sports organizations. The bans seem to be working: After professional baseball banned steroids, some sluggers rapidly lost weight—and stopped hitting so many home runs.

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 steriod 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** (hyper = above; trophy = to grow). Scientists believe hypertrophy is caused by the addition of new myofibrils within the endomysium of individual muscle cells, which thickens individual myofibers. This means hypertrophic muscles should have thicker muscle cells, packed with more sarcomeres than other muscles 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.

Evolution of Humans
FIGURE 6.20

Only 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.

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 garb 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.

Only 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.

Throughout this unit we have explored how the skeletal and muscular systems work together to not only provide us with a structural framework but also to give us a means of locomotion. Clearly, the ability to move is critical to survival. Though the demands on the human body have changed over time, the need to move remains paramount for a successful life. In the next chapter we will explore the nervous system, which you have already seen has an intimate connection to muscles and movement.

CONCEPT CHECK

- **Why** does toned muscle use more energy than flaccid muscle?
- **Compare** fast twitch and slow twitch muscle fibers, listing similarities and differences.
- **Explain** the function of creatine phosphate in muscle.
- **What** are the side effects of anabolic steroid use?

CHAPTER SUMMARY

1 The Muscular System Has Many Functions

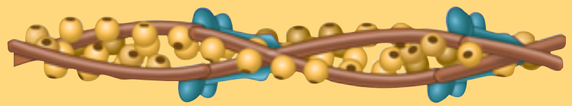
The muscular system is composed of skeletal muscle tissue. Its most obvious function is to generate movement; however, it also performs other vital functions. The muscular system generates heat, stabilizes joints, helps move lymphatic fluid through the body, and supports and protects soft internal organs.

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 surrounded 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.

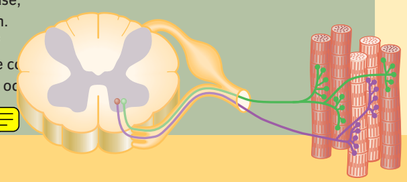
3 Form in Function: How Muscles Contract

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 troponin and tropomyosin of the actin filament. The actin active sites are exposed so they can react with the energy-rich myosin heads. ATP is used to relax the contracted muscle.



4 Whole-Muscle Contractions Emerge From Tiny Impulses

Whole-muscle contractions produce powerful movement from the combined simultaneous contraction of millions of sarcomeres. Muscle cells contract in an all-or-none 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 slack in the muscle is being taken up. During the contraction phase, the muscle visibly shortens. During the relaxation phase, the muscle returns to its original length. Tetanic contraction is a combination of many twitches, overlapping to produce constant tension in the muscle, a common occurrence in the muscles of your back and neck.



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 employed to store inorganic phosphate used in the conversion of ADP to ATP. Individual muscle cells respond differently to twitch impulses. Muscle fibers can be fast and easily 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 create ATP. Slow twitch fibers have less immediate 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** p. 000
- **anabolic steroids** p. 000
- **anaerobic pathways** p. 000
- **antagonistic (synergistic) pair** p. 000
- **electron transport chain** p. 000
- **endomysium** p. 000
- **epimysium** p. 000
- **globular** p. 000
- **glycogen** p. 000
- **graded contraction** p. 000
- **muscle tone** p. 000
- **myofibrils** p. 000
- **oxygen debt** p. 000
- **perimysium** p. 000
- **skeletal muscle** p. 000
- **t tubules** p. 000
- **TCA (Krebs) cycle** p. 000
- **threshold stimulus** p. 000
- **treppe** p. 000

CRITICAL THINKING QUESTIONS

1. In Greek mythology Achilles was an amazing warrior, undefeated in many battles. His undoing was an arrow to the tendon of the gastrocnemius muscle (see FIGURE 6.3 for the exact position). Using the terms *origin, insertion,* and *belly,* explain the location of his wound. In common language, why did the arrow end Achilles' fighting career? Anatomically speaking, what destroyed his fighting ability?

2. Briefly describe the structure of a muscle cell, starting with the sarcolemma 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 arrangement? *Hint:* Envision the cut end of a rope or cable. What happens 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 electrical source instead of the motor neurons, there is a period before 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 period 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 grueling athletic event like a marathon? Does it make sense for endurance 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 intermediate muscle fibers? Will effective training alter the proportion of these fibers?

SELF TEST

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.

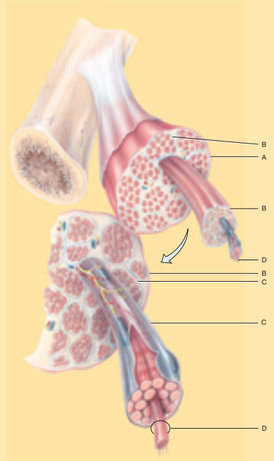
a. The humerus
b. The elbow
c. The radius
d. The carpals

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

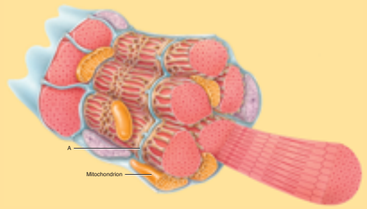
4. Identify the outermost layer of connective tissue surrounding a muscle (identified as A in the figure).

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

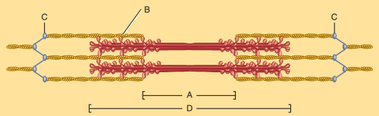


6. The contractile unit of skeletal muscle is the

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.

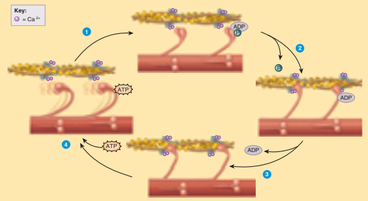
a. A band
b. I band
c. Z line
d. Middle
e. Both a and b are correct.

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

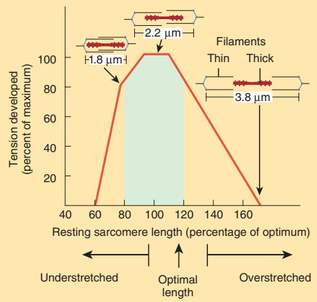
a. Actin
b. Myosin
c. Troponin
d. Tropomyosin



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.

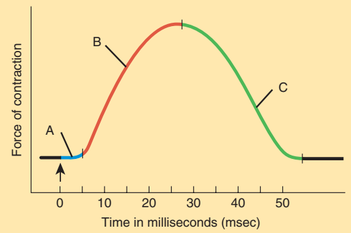
12. This graph indicates that

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 as 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