

Skeletal Muscle Plasticity

Joseph A. Chromiak and Jose Antonio

OBJECTIVES

On the completion of this chapter you will be able to:

1. Define the basic definitions associated with bioenergetics.
2. Understand the basic principles behind thermodynamics.
3. Develop an understanding of the concept of energy transfer.
4. Describe the biochemical reactions associated with various energy-transfer pathways in the body.
5. Explain the basics of energy expenditure, the methods for measuring energy expenditure, and the relationship of energy expenditure to exercise.

ABSTRACT

Skeletal muscle is a highly organized tissue designed to produce force for postural control, movement, and even breathing. Various architectural designs, varying amounts of muscle proteins (e.g., enzymes or myosin), and different isoforms of many muscle proteins provide for a wide range of force-producing, biochemical, and metabolic characteristics. Additionally, the ability of skeletal muscle to adapt to the demands placed upon it, such as increased mitochondrial volume associated with endurance training or increased muscle fiber cross-sectional area as a result of strength training, demonstrates a tremendous plasticity. For the sports nutritionist, a fundamental understanding of the structure and function of skeletal muscle is important inasmuch as the adaptive response to various contractile and nutritional perturbations are manifest in this tissue. It should be noted that there is a large variation among individuals with regard to the magnitude of muscle adaptability to various types of training. Differing muscle characteristics, such as muscle pennation and fiber type, and variation in degree of adaptability among individuals partially explain the wide range of differences in aspects of exercise performance, such as muscular endurance or strength.

Key Words: skeletal muscle, muscle, fiber types, fiber composition, slow twitch, fast twitch, myosin, isoforms, myosin heavy chain, muscle plasticity

Skeletal muscle has a large capacity to adapt to the demands imposed on it, which is termed plasticity. As a result of repeated bouts of endurance or aerobic exercise training, there are increases in the number and size of the mitochondria, as well as increases in the content of various enzymes involved with oxidative energy metabolism. In contrast, skeletal muscle adapts to repeated bouts of resistance exercise by increasing in size. This increase in size, termed

From: *Essentials of Sports Nutrition and Supplements*

Edited by J. Antonio, D. Kalman, J. R. Stout, M. Greenwood, D. S. Willoughby, and G. G. Haff © Humana Press, a part of Springer Science+Business Media, Totowa, NJ

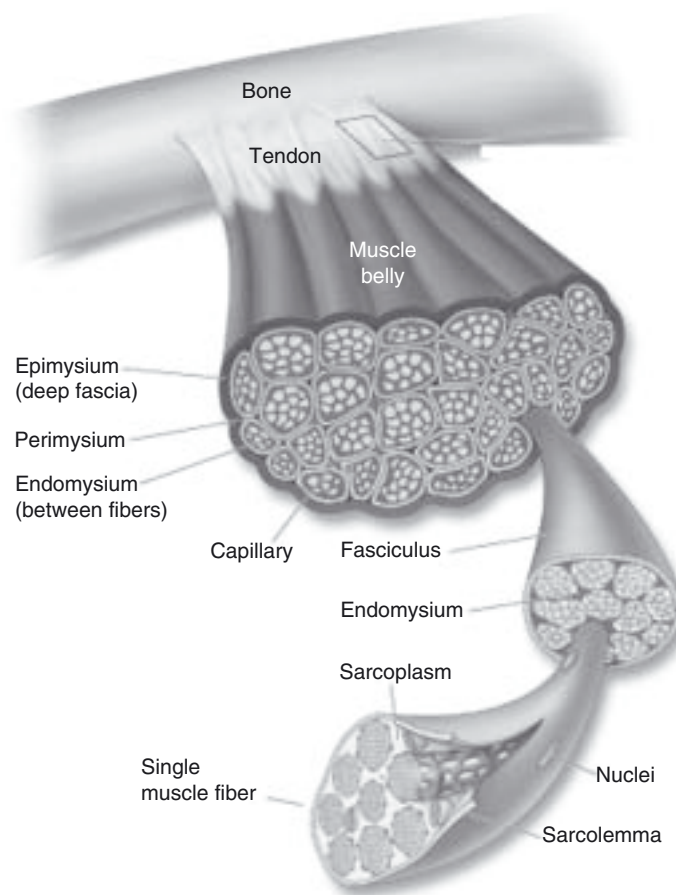
hypertrophy, is the result of an increase in the amount of contractile proteins in each muscle fiber. Consider that any given muscle may be contracting during strength training workouts for a small fraction ($<1\%$) of the total time in a week and that the other 99% of the time the muscle is not contracting forcefully. Despite the rather small proportion of the time that most muscles are developing very high amounts of tension, muscle hypertrophy occurs.¹ In this chapter, the structure and function of skeletal muscle are described followed by a discussion about the regulation of muscle action. Depending on the type of exercise training performed, additional adaptations occur that are discussed in this chapter. It is hoped that the reader will gain an appreciation for the amazing plasticity of skeletal muscle.

SKELETAL MUSCLE STRUCTURE

Skeletal Muscle Has Several Layers of Connective Tissue

Each muscle is surrounded by a layer of connective tissue called the epimysium (Figures 2.1 and 2.2). Muscles are typically divided in bundles of fibers that are referred to as fasciculi. Each fasciculus is surrounded by a tough connective tissue layer known as the perimysium. It is through this layer that the nerves and blood vessels running through the muscle are found. Each muscle fiber is surrounded by a basal lamina and a mesh-like sheath of connective tissue called the endomysium. The basal lamina serves as a scaffold for muscle fiber formation and recovery from injury. A major component of each connective tissue layer is the protein collagen although the organization of the collagen fibrils is different at each level. These connective tissue layers merge at the junction of the muscle and tendon, referred to as the myotendinous junction. The various

FIGURE 2.1. Cross-section of skeletal muscle structures and arrangement of the various connective tissue layers. The epimysium surrounds the entire muscle, the perimysium envelopes bundles of muscle fibers called fasciculi, and the endomysium surrounds each muscle fiber. (From McArdle, WD, Katch FI, Katch VL. *Exercise Physiology: Energy, Nutrition, and Human Performance*. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2001. Reprinted with permission of Lippincott Williams & Wilkins.)



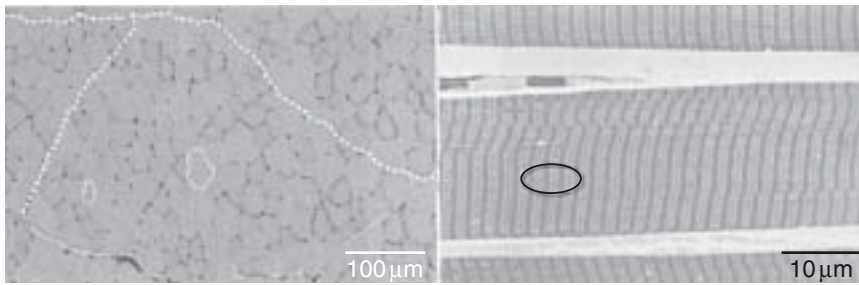


FIGURE 2.2. Muscle fibers in longitudinal view showing striated appearance and in cross-section showing polygonal shape of muscle fibers. Cross-section (left) and longitudinal section (right) of a tibialis anterior biopsy specimen. The alternating light and dark regions correspond to the A and I bands of the sarcomere. The cross-sectional view shows the polygonal shape of the densely packed muscle fibers. Each muscle fiber is surrounded by a connective tissue layer called the endomysium, which is outlined for two fibers as solid white lines. Muscle fibers are organized into fascicles that are surrounded by another layer of connective tissue referred to as the perimysium and is identified by the dashed lines. (From Lieber.²⁷ Modified and reprinted with permission of Lippincott Williams & Wilkins.)

connective tissue layers have an important function in transmission of force from the muscle fibers to the tendons.

Muscle Fibers and Muscle Architecture

Each muscle fiber is a single cell that is composed of tens to hundreds of nuclei. The terms muscle fiber and muscle cell are used interchangeably, and the term myofiber can be used also. An important characteristic of skeletal muscle fibers is that they have a polygonal shape rather than the circular or cylindrical shapes used in many textbook illustrations (Figure 2.2). This allows many more myofibers to be packed into a given volume of muscle. Another unique feature of skeletal muscle fibers is their striated appearance. The alternating dark and light bands across the surface of the myofiber are attributed to the highly organized arrangement of muscle proteins within the cell.

It is a common conception that muscle fibers run the entire length of the muscle, but this is seldom the case. In some muscles, the muscle fibers are arranged in parallel to the long axis or force-generating axis of the muscle. These muscles are referred to as fusiform muscles (Figure 2.3). Even in fusiform muscles, the myofibers frequently do not extend the length of the muscle. In some long, strap-like muscles, the myofibers often are divided into compartments by transverse bands of connective tissue called inscriptions. These inscriptions add elasticity to very long muscles and also allow for more efficient depolarization and contraction. In other muscles, muscle fibers begin at the proximal tendon and end somewhere within the belly of the muscle, whereas other myofibers begin and terminate within the belly of the muscle, and still others begin within the muscle belly and run to the distal tendon. This type of muscle architecture is referred to as serially arranged fibers. Serially arranged fibers may add elasticity to the muscle and enhance force transmission from the individual muscle fibers to the tendon.

In many muscles, the muscle fibers are oriented transversely to the long or force-generating axis of the muscle. This is referred to as a pennate fiber



FIGURE 2.3. Various architectural arrangements of muscle fibers within human skeletal muscles. In fusiform muscles, the myofibers run parallel to the long axis or force-generating axis of the muscle. In a unipennate muscle, the fibers run transversely to the long axis of the muscle, in bipennate muscles two sets of myofibers are oriented transversely to the long axis of the muscle, and in multipennate muscles three or more sets of myofibers are oriented transversely to the muscle's force-generating axis. (From McArdle, WD, Katch FI, Katch VL. Exercise Physiology: Energy, Nutrition, and Human Performance. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2001. Reprinted with permission of Lippincott Williams & Wilkins.)

arrangement. Pennation allows for more myofibers to be packed into a given volume of muscle. This increases the functional cross-sectional area of the muscle and the muscle's capacity for force generation. In some muscles, there may be two (bipennate) or more (multipennate) groups of muscle fibers each oriented transversely to the long axis of the muscle. This further increases the force-generating capacity of the muscle.

THE SKELETAL MUSCLE FIBER

The Sarcolemma

The plasma membrane of the muscle fiber is referred to as the sarcolemma. The sarcolemma is largely composed of phospholipids and some cholesterol. Many different proteins, such as channels, pumps and receptors, are embedded within the sarcolemma or span across the sarcolemma. Channels and pumps control the movement of various substances into and out of the cell. Receptor proteins allow substances outside the cell, such as epinephrine or insulin, to communicate with the interior of the cell. The Na^+ - K^+ -adenosine triphosphatase (ATPase) pumps and channels, primarily Na^+ and K^+ channels, are responsible for the development of a difference in electrical potential across the cell membrane and enable the sarcolemma to conduct a change in electric potential. The ability of the sarcolemma to propagate an action potential is very important for excitation of the cell during muscle actions.

The Neuromuscular Junction

Each muscle fiber in adult human skeletal muscle is innervated by a single motor neuron. As a motor neuron nears its target muscle fibers, the neuron branches and gives rise to the axon terminal. The ends of the neuron at the axon terminal are expanded to form the synaptic knobs or boutons. The synaptic knobs are filled with vesicles, known as the synaptic vesicles that contain the neurotransmitter acetylcholine (ACh). The motor neuron and muscle fiber are separated by a very small space referred to as the synaptic cleft. The region of the muscle fiber across from the axon terminal is highly invaginated and contains many receptors for responding to the ACh that is released from the motor neuron. This region of the myofiber is termed the motor end plate. The region of the axon terminal, synaptic cleft, and motor end plate is termed the neuromuscular junction.

The Transverse Tubules and the Sarcoplasmic Reticulum

Skeletal muscle fibers have an elaborate system of channels that are essential for activating the entire myofiber. The two components of this system of channels are the transverse or T tubules and the sarcoplasmic reticulum (Figure 2.4). At regular intervals along the muscle fiber, specifically at each A-I band junction, the sarcolemma gives rise to the transverse tubules. The T tubules, which are invaginations of the sarcolemma, enable the action potential to be propagated deep into the core of the muscle fibers. In the region where the sarcoplasmic reticulum nears the T tubules, the sarcoplasmic reticulum becomes enlarged to form the terminal cisternae. The T tubule and sarcoplasmic reticulum on either side are referred to as a triad, but the membranes of the T tubules and sarcoplasmic reticulum do not touch. Voltage-sensing proteins in the T tubule membrane known as dihydropyridine receptors trigger the release of calcium through channels on the membrane of the sarcoplasmic reticulum termed the ryanodine receptors.²

The sarcoplasmic reticulum is an extensive series of channels that run primarily with the longitudinal axis of the fibers and surround each myofibril. The sarcoplasmic reticulum also has extensive cross-connections, especially in fast-twitch fibers. The sarcoplasmic reticulum is a large reservoir for calcium

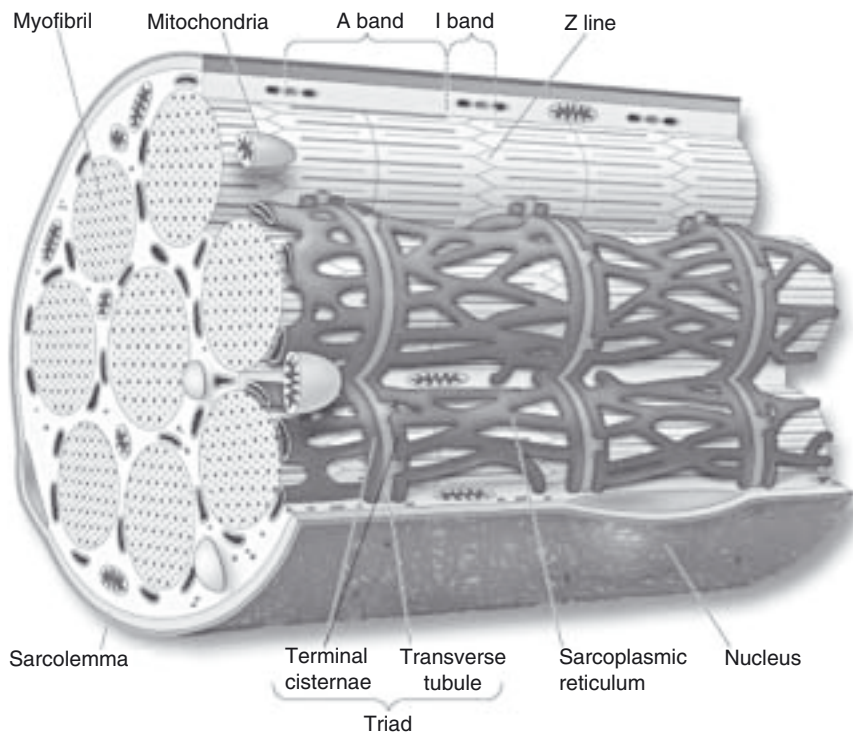


FIGURE 2.4. Cross-sectional and longitudinal illustration showing the transverse tubules and sarcoplasmic reticulum that surround each myofibril within the myofiber. The transverse tubules are invaginations of the sarcolemma that run into the core of the myofiber and are located at the A-I band junctions of the sarcomeres. The sarcoplasmic reticulum serves as a reservoir for calcium. (From McArdle, WD, Katch FI, Katch VL. *Exercise Physiology: Energy, Nutrition, and Human Performance*. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2001. Reprinted with permission of Lippincott Williams & Wilkins.)

ions. The ryanodine receptors allow calcium to diffuse rapidly into the sarcoplasm during muscle activation. During muscle relaxation, SERCA (sarcoplasmic-endoplasmic reticulum, calcium-ATPase) pumps in the membrane of the sarcoplasmic reticulum remove the calcium from the sarcoplasm by pumping it back into the sarcoplasmic reticulum.

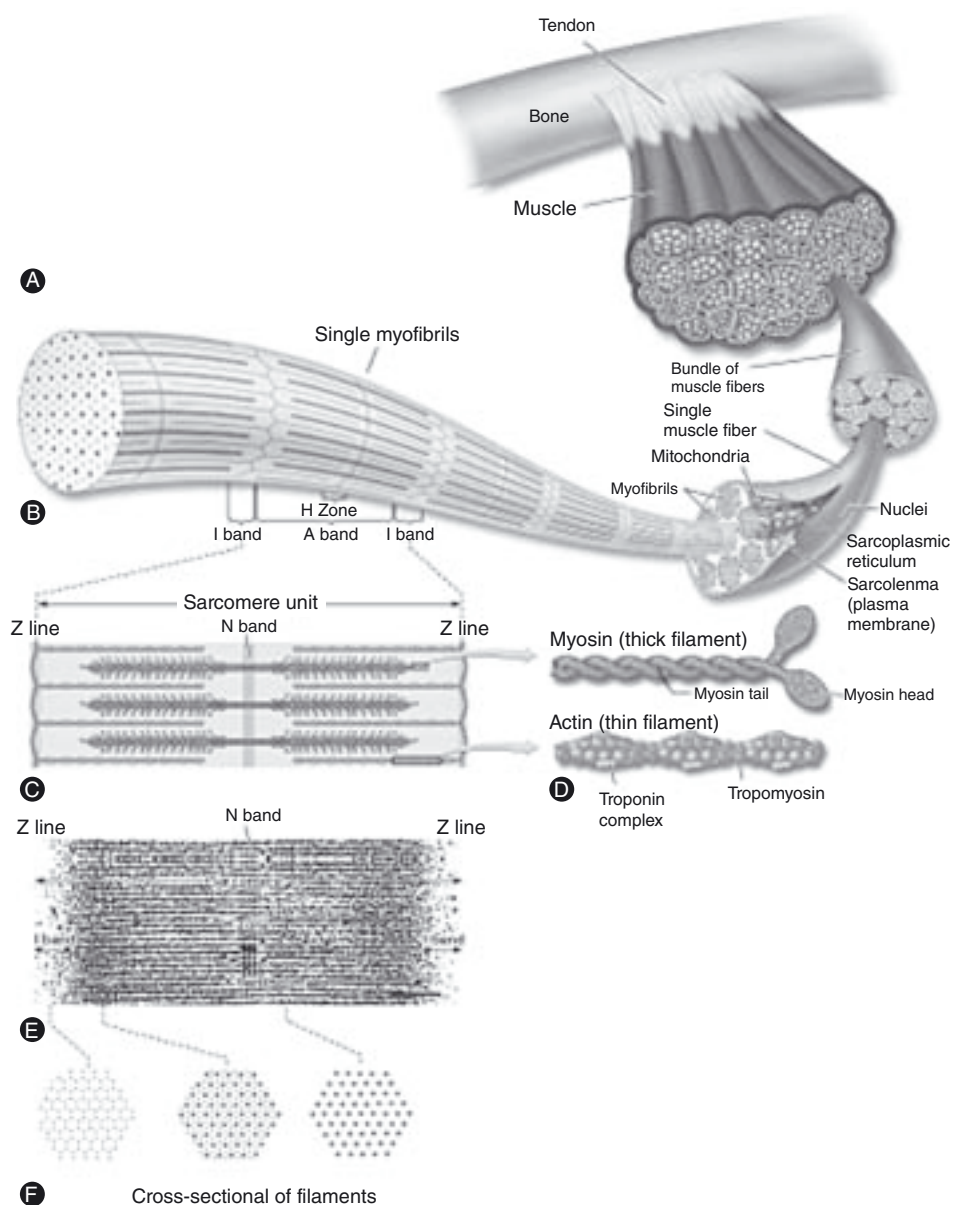
Sarcoplasm and Cellular Organelles

Various organelles, such as ribosomes and mitochondria, are located in the sarcoplasm of the muscle cell. The sarcoplasm is the gel-like fluid within the myofiber containing various ions, glycogen granules, and organelles. Mitochondria, which are often referred to as the “powerhouses of the cell,” are the site for oxidative metabolism within the myofiber.

Myofibrils and Sarcomeres: The Working Contractile Units of the Muscle Fiber

Long, cylindrical filaments known as myofibrils, which literally means “muscle thread,” extend the length of the muscle fibers (Figure 2.5). Myofibrils are the largest functional unit of a myofiber and hundreds of myofibrils may constitute a muscle fiber. A myofibril is formed by sarcomeres lined up end to end or “in series.” Sarcomeres, literally “muscle unit,” are the smallest functional unit of skeletal muscle fibers (Figure 2.5C and E). Sarcomeres are composed of the thick and thin contractile filaments (discussed below), as well as many cytoskeletal proteins. Structures termed Z lines serve as a skeleton or scaffold for the sarcomere and are located at each end of the sarcomere. The major protein of the Z lines is α -actinin. Sarcomeres are lined up end to end as the Z line of one sarcomere also serves as a Z line for the next sarcomere in series. Sarcomeres of adjacent myofibrils are said to be arranged in parallel. The number of sarcomeres in parallel within a muscle fiber is directly related to the capacity of the myofiber to produce force.

FIGURE 2.5. The gross and subcellular organization of skeletal muscle. **A:** Skeletal muscle is composed of individual muscle fibers. **B:** Muscle fibers consist of many myofibrils that are composed of numerous proteins including actin and myosin. **C:** Myofibrils are composed of sarcomeres arranged in series. **D:** Sarcomeres are composed of thick and thin filaments. **E:** Microscopic view of a sarcomere. **F:** Cross-sectional view of the thick and thin filaments showing their arrangement at different regions along the sarcomere. (From McArdle, WD, Katch FI, Katch VL. *Exercise Physiology: Energy, Nutrition, and Human Performance*. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2001. Reprinted with permission of Lippincott Williams & Wilkins.)



MUSCLE CONTRACTILE AND REGULATORY PROTEINS

The Thick or Myosin Filament

The thick filament is often referred to as the myosin filament because myosin is the only protein present (Figure 2.5D). An intact myosin molecule actually consists of two molecules of myosin heavy chain (MHC) and four myosin light chain molecules. The tail regions of the two MHC molecules coil around each other. The tail regions of about 200–250 pairs of MHC molecules are intertwined to form the thick filament, with approximately half of the myosin cross-bridges extending toward one Z line with the other half extending toward the other Z line. Each MHC molecule has a hinge region that gives rise to a globular head. The globular head is also known as the myosin cross-bridge, because it is this portion of the molecule that projects outward toward the thin filament and will bind to the actin molecules of the thin filament. An intrinsic part of the globular head of MHC is myosin ATPase activity. This enzymatic activity hydrolyzes ATP to provide energy for movement of the myosin cross-bridge, which is called the power stroke. The

thick filament is highly organized, such that every 14.3 nm along the thick filament, three pairs of myosin heads rotated 120 degrees from each other project toward the thin filament. A complete myosin molecule also consists of two regulatory and two essential myosin light chain molecules. The light chains are located near the hinge region of the MHC molecules with the two essential myosin light chain molecules located just below the globular head of the MHCs. Although the role of the myosin light chains is not completely understood, they apparently affect the power stroke by modulating the interaction between myosin and actin.³ The essential myosin light chains are believed to influence the maximal shortening velocity of the myofibers. The regulatory light chains, which can be phosphorylated, may affect force production during submaximal contractions. Phosphorylation of these light chains may increase the sensitivity of the contractile proteins to calcium, thus enhancing force generation at low, but not maximal, stimulation frequencies.⁴

The Thin Filament: Actin, Troponin, and Tropomyosin

Thin filaments begin at the Z lines and run out toward the center of the sarcomere where they interdigitate with the thick filaments to form a hexagonal lattice (Figure 2.5E). The thin filaments are often called the actin filaments because actin is the major contractile protein of this filament. The thin filament also consists of two proteins, troponin and tropomyosin, that have regulatory functions (Figure 2.5D). The actin filaments consist of long chains of individual actin molecules that have a globular shape, and are sometimes referred to as G-actin, with the “G” denoting “globular.” The long chains of G-actin molecules form a strand-like protein called filamentous or F-actin. Two F-actin strands coil around each other in an α -helix to form a thin filament. Tropomyosin runs alongside the F-actin and in the resting state fits into a groove formed by the α -helical arrangement of the two F-actin strands. The groove of the thin filament contains the active sites that myosin cross-bridges will bind during muscle contraction. Each tropomyosin molecule runs the length of seven G-actins and is closely associated with troponin. An intact troponin (Tn) molecule consists of three subunits. The troponin-tropomyosin (Tn-T) subunit links to tropomyosin. The other subunits are Tn-inhibitory (Tn-I) and Tn-calcium (Tn-C). When calcium levels in the sarcoplasm increase during muscle activation, up to four calcium molecules bind each Tn-C, inducing a change in the conformation of Tn-I. As Tn-I changes shape, it pulls on Tn-T, which in turn tugs on tropomyosin, thus rotating it away from the active sites on actin. This movement of tropomyosin out of the actin groove is called the “tropomyosin shift.” Now myosin cross-bridges can bind with actin in a “strong binding state.”

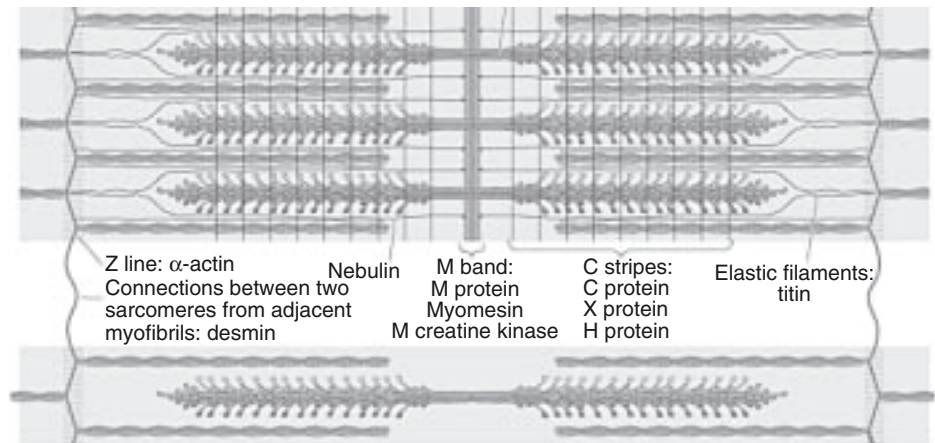
The highly organized arrangement of thick and thin filaments gives myofibers their striated appearance of light and dark bands. These regions are named based on their appearance. The A band is the region of the sarcomere where there is thick filament, which includes a region where the thick and thin filaments overlap and a region where there is only thick filament (Figure 2.5E). This latter portion is referred to as the H-zone. The I band is the region where there is only thin filament and it extends out from both sides of the Z line. Because of the nature of muscle fiber action, which is discussed below, the regions of the H-zone and I band change length during muscle contraction, but the length of the A band does not change.

THE CYTOSKELETON: THE SCAFFOLD OF THE CELL

The Endosarcomeric Cytoskeleton

To maintain the highly organized arrangement of thick and thin filaments, each sarcomere has many proteins that serve as a supporting framework (Figure 2.6). The Z line, which is composed primarily of α -actinin, can be

FIGURE 2.6. Cytoskeletal proteins associated with skeletal muscle fibers. Some of the major endosarcomeric and exosarcomeric cytoskeletal proteins are shown in relationship to the sarcomeres. (From McArdle, WD, Katch FI, Katch VL. *Exercise Physiology: Energy, Nutrition, and Human Performance*. 5th ed. Baltimore: Lippincott Williams & Wilkins: 2001. Adapted and reprinted with permission of Lippincott Williams & Wilkins.)



considered part of this endosarcomeric cytoskeleton. Titin, as the name implies, is an extremely large protein that begins at the Z line, runs parallel to the thick filaments, and may link to myosin at the M line of the sarcomere. In the region of the sarcomere where only F-actin is present (I-band region), the titin molecule is highly extensible, but as titin runs alongside the thick filament it becomes more rigid. Titin is largely responsible for the passive tension within muscle fibers and is thought to hold the myosin filament in the center of the sarcomere during muscle contraction. Additionally, titin may regulate the number of myosin molecules in the thick filament.

Nebulin extends out from the Z line, running alongside the thin filament. Nebulin may provide structural support for the thin filament, as well as regulate the number of G-actin monomers in F-actin. In the center of the sarcomere, additional proteins run perpendicular to the direction of the thick and thin filaments. These proteins constitute the M-line proteins and center the thick filaments within the sarcomere during contraction. Additional proteins referred to as the C stripes run perpendicular across the sarcomere and also may have a role in keeping the thick filaments centered within the sarcomere during muscle action.

The Exosarcomeric Cytoskeleton

Skeletal myofibers also have many cytoskeletal proteins that link adjacent sarcomeres together and connect the myofibrils at the periphery of the cell to the sarcolemma. A complete discussion of all the cytoskeletal proteins is beyond the scope of this chapter, but a few prominent proteins will be mentioned here. Desmin is part of a group of proteins termed intermediate filaments. Desmin links adjacent sarcomeres at their Z lines. Actin, which is an important contractile protein, also serves as an important cytoskeletal protein linking peripheral myofibrils to the sarcolemma.

Dystrophin is located near the sarcolemma and has a role in stabilizing the membrane during contraction.⁵ The extremely large dystrophin protein is part of a network of proteins that are essential for maintaining the integrity of the cell. A mutation of the gene that codes for dystrophin results in the well-known disease Duchenne muscular dystrophy.⁶ Muscle fibers lacking dystrophin are readily damaged during muscle use and undergo repeated cycles of degeneration and regeneration. These repetitive cycles of degeneration and repair are associated with a progressive decline in the functional capacity of the muscle because of a loss of myofibers and an accumulation of connective tissue and fat cells within the muscle.

SKELETAL MUSCLE ACTION: TYPES OF MUSCLE CONTRACTIONS

Muscles are capable of several different types of actions that can be categorized as static or dynamic. It should be noted that some sports scientists prefer the term “muscle action” rather than “contraction” (which implies shortening), because muscles may lengthen or change little in length in addition to shortening when the myofibers develop tension. Others argue that it is widely understood that “contraction” does not refer only to shortening with respect to muscle actions. “The term ‘contraction’ refers to the state of muscle activation in which cross-bridges are cycling in response to an action potential”; therefore, both terms will be used interchangeably. During static, or isometric, contractions the muscle fibers develop tension with little change in length, and the angle about the involved joints remains constant as the myofibers develop force that is equal to the external resistance, or the external resistance is stationary. Static muscle actions are common for the postural muscles of the body that act to maintain a constant position during standing.

Most muscle actions in athletics require movement and are dynamic in nature. Dynamic muscle actions include concentric, eccentric, and plyometric contractions. During concentric muscle actions, the force developed by the muscle fibers is greater than the external resistance so myofiber shortening and movement occur. During eccentric muscle actions, the myofibers lengthen while developing force. The force developed by the muscle fibers is less than the external resistance. Eccentric contractions, which are sometimes referred to as “negatives,” are popular with many athletes including bodybuilders because more weight or external resistance can be used compared with static and concentric muscle actions. Finally, during many of the rapid and powerful movements performed in sports, eccentric muscle actions are followed rapidly by concentric muscle actions. These types of actions are referred to as plyometric muscle actions. It is well known that a concentric muscle contraction is more powerful when preceded by an eccentric muscle action. Many coaches and athletes incorporate specific plyometric exercises into training programs to mimic many of the actions used in sports.

SKELETAL MUSCLE ACTION: INITIATION OF MUSCLE FIBER ACTIVATION AND EXCITATION- CONTRACTION COUPLING

Muscle actions are initiated when motor neurons within the central nervous system are excited sufficiently to develop action potentials. When depolarization of the motor neuron reaches the axon terminals, the synaptic vesicles within the synaptic knobs release their ACh into the synaptic cleft (Figure 2.7). ACh diffuses across the synaptic cleft and binds to specific ACh receptors on the motor end plate. This initiates the myofiber action potential that rapidly propagates along the sarcolemma in all directions.

Excitation-contraction coupling refers to the process of an electrical event, depolarization of the sarcolemma, inducing a mechanical event, muscle contraction. The electrical and mechanical events are coupled by the release of calcium from the sarcoplasmic reticulum. The propagation of the action potential down the T tubules triggers the release of calcium through the ryanodine receptor channels in the adjacent terminal cisternae of the sarcoplasmic reticulum. Calcium binds to troponin, inducing the tropomyosin shift allowing myosin to enter a strong binding state with actin. From the time that calcium is released into the sarcoplasm until the calcium has been resequestered in the sarcoplasmic reticulum, the muscle fiber is in the active state and tension development can occur.

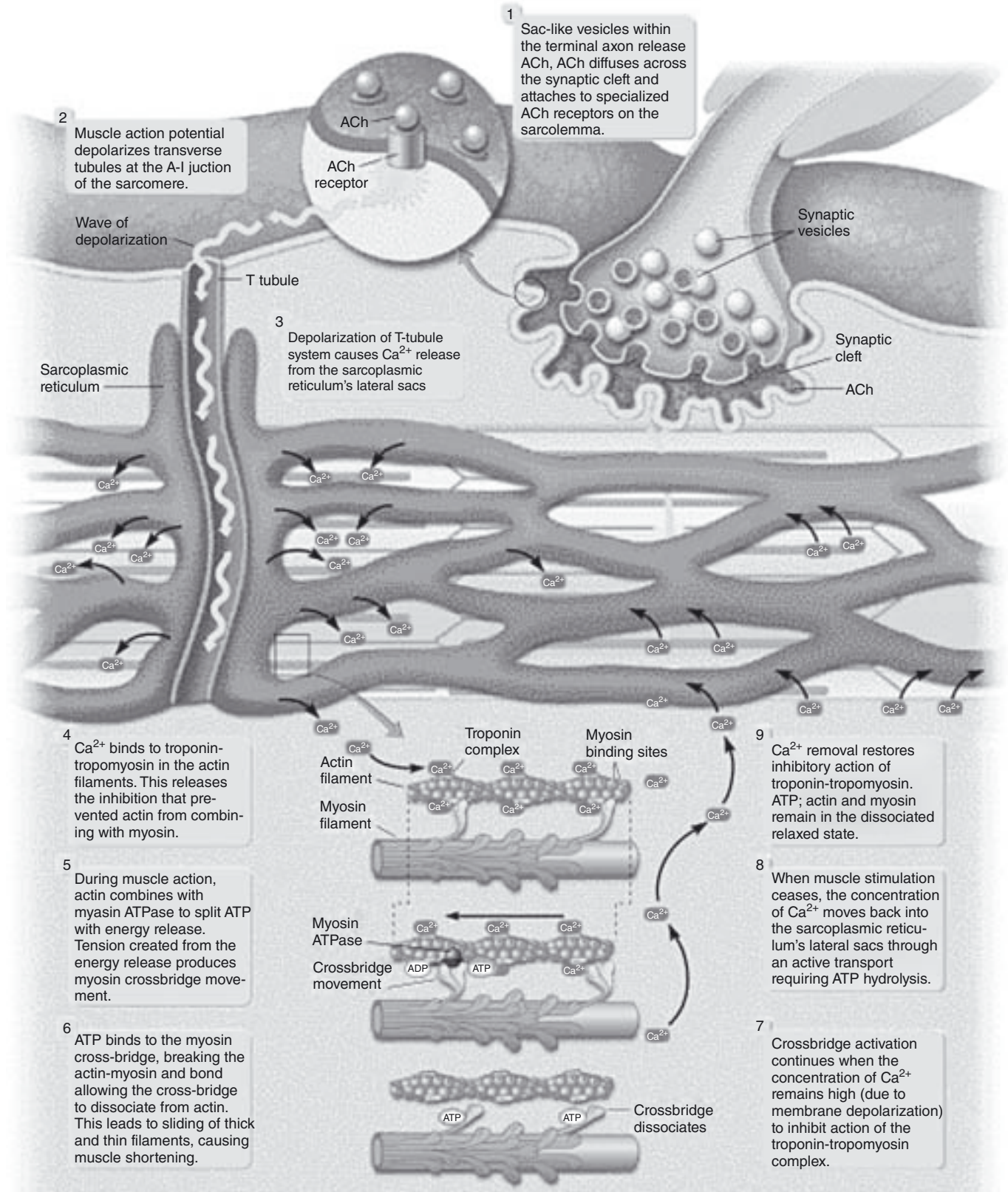


FIGURE 2.7. Illustration of the major events in muscle contraction and relaxation. The neurotransmitter acetylcholine (ACh) is released from the synaptic vesicles of the axon terminal (1). ACh diffuses across the synaptic cleft and initiates the action potential on the sarcolemma (2). Depolarization of the sarcolemma and T tubules induces calcium release from the sarcoplasmic reticulum (3). Ca^{2+} binding to troponin leads to the tropomyosin shift (4) allowing for stronger myosin-actin binding and muscle contraction.⁵⁻⁷ Muscle relaxation occurs when Ca^{2+} is resequenced in the sarcoplasmic reticulum.^{8,9} (From McArdle, WD, Katch FI, Katch VL. Exercise Physiology: Energy, Nutrition, and Human Performance. 5th ed. Baltimore: Lippincott Williams & Wilkins: 2001. Reprinted with permission of Lippincott Williams & Wilkins.)

SKELETAL MUSCLE ACTION: THE SLIDING FILAMENT THEORY AND THE CROSS-BRIDGE CYCLE

The sliding filament theory best explains the mechanism by which sarcomeres, and therefore muscle fibers, change length during muscle contraction. The thick and thin filaments do not change length, rather sarcomeres shorten or lengthen as the thin (actin) filaments slide over the thick (myosin) filaments (Figure 2.8).⁸

Recent evidence suggests that myosin cross-bridges are always attached to actin. When the muscle fibers are not contracting, the myosin cross-bridges are weakly bound to actin, the “weak binding state.” When the muscle fiber is developing tension, myosin is bound in a “strong binding state” with actin. During this strong binding state, the orientation of the myosin cross-bridges is such that when attached to actin they attempt to pull the thin filament over the thick filament.

The series of events whereby the myosin cross-bridge enters the strong binding state with actin, undergoes the power stroke, and reenters the weak binding state while the myosin cross-bridge returns to its initial orientation is termed the cross-bridge cycle. The energy for the power stroke during this cycle comes from the hydrolysis of adenosine triphosphate (ATP) by myosin ATPase. Myosin exists in an “energized” state, which means that the ATP has already been hydrolyzed to adenosine diphosphate and P_i to release energy. However, the “energized” myosin cross-bridge does not use this energy for the power stroke until it enters the strong binding state with actin. After completion of the power stroke, attachment of another ATP to the myosin cross-bridge causes it to enter the weak binding state and return to its original position. Because the total distance that a myosin cross-bridge moves the thin filament with a single power stroke is very minute, each myosin head likely undergoes multiple cross-bridge cycles during a single muscle contraction.⁹

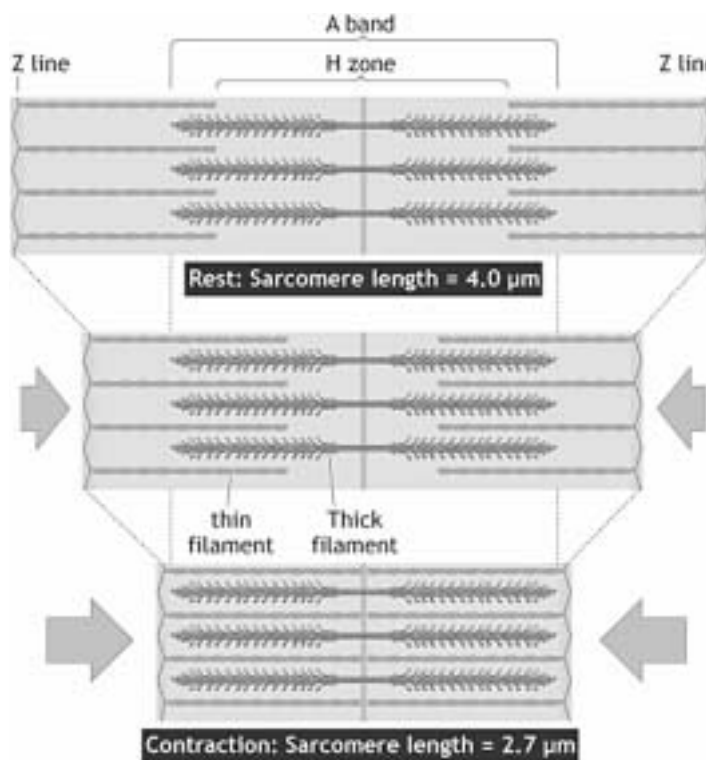


FIGURE 2.8. The sliding filament theory and sarcomere shortening. Schematic view of a sarcomere showing that shortening of the sarcomere occurs as the thin filaments are pulled closer to the center of the sarcomere by the thick filaments. (From McArdle, WD, Katch FI, Katch VL. *Exercise Physiology: Energy, Nutrition, and Human Performance*. 5th ed. Baltimore: Lippincott Williams & Wilkins: 2001. Reprinted with permission of Lippincott Williams & Wilkins.)

MUSCLE RELAXATION

Skeletal muscle fibers continue contracting until impulses from the motor neuron at the neuromuscular junction stop so that no more ACh is bound to ACh receptors at the motor end plate. Muscle relaxation occurs when the SERCA pumps have transported sufficient calcium into the sarcoplasmic reticulum to end the active state, so that tropomyosin returns to its original position over the myosin cross-bridge binding sites on actin.

THE CLASSIFICATION OF MUSCLE FIBER AND MOTOR UNIT TYPES

Several systems of categorizing muscle fibers and motor units have been developed. Three of the most frequently used schemes are presented in this chapter. Before introducing the first classification scheme, it is important to note that, although muscle fibers and motor units are placed into categories, myofibers and motor units possess a broad and nearly continuous range of contractile and metabolic properties.

Drs. James Peter, James Barnard, Reggie Edgerton and their colleagues¹⁰ collaborated to develop a classification system based on the contractile and metabolic properties of the myofibers. Fiber types designated as slow or fast contracting were identified. The slow-contracting fibers also had a very high oxidative capacity and were designated SO fibers (Table 2.1). The fast-twitch fibers were further subdivided into those with moderate to high oxidative and glycolytic capacities (FOG fibers) and fibers that had a substantial capacity for glycolytic metabolism but a low capacity for oxidative metabolism (FG fibers).

Another common classification system is based on the differential sensitivities of myosin ATPase to solutions of varying pH^{11,12} (Figure 2.9). The underlying basis for this scheme is the primary type of MHC present within the myofiber. There are three isoforms of MHC in adult, human skeletal muscle that are designated MHC I, MHC IIa, and MHC IIx.¹³ Preincubation in an acidic solution (pH 4.3) denatures the portion of the MHC IIa and IIx proteins that has the ATPase activity, so when the myofibers are stained for myosin ATPase, only those containing the MHC I isoform will stain darkly. By using solutions of various pH, three primary types of fibers labeled I, IIa, and IIx are identified. Preincubation in an alkaline solution results in the type IIa and IIx myofibers staining darkly, whereas the type I fibers stain lightly. The type of

TABLE 2.1. Biochemical, contractile, and structural properties of the three major classes of muscle fibers.

| | <i>Slow oxidative</i> | <i>Fast oxidative-glycolytic</i> | <i>Fast glycolytic</i> |
|------------------------|-----------------------|--|------------------------|
| Biochemical properties | | | |
| Myosin ATPase activity | Low | Moderately high | Highest |
| Oxidative capacity | High | Moderate to high | Low |
| Glycolytic capacity | Low | Moderate to high | High |
| Resistance to fatigue | High | Moderate to high | Low |
| Contractile properties | | | |
| Shortening velocity | Slow | Fast | Fastest |
| Relaxation | Slow | Fast | Fast |
| Specific tension | Moderate | High | High |
| Power | Low | High | Very high |
| Structural properties | | | |
| Mitochondrial density | High | Moderately high | Low |
| Z-line thickness | Wide | Intermediate | Narrow |
| M-line thickness | 5 M-bridges | 3 prominent and 2 less-prominent M-bridges | 3 M-bridges |
| Sarcoplasmic reticulum | Not extensive | Extensive | Extensive |

ATPase = adenosine triphosphatase.

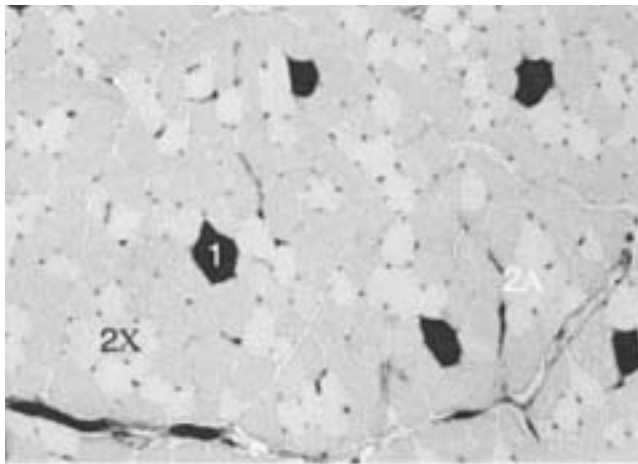


FIGURE 2.9. Myofibrillar ATPase stain using acid preincubation. Cross-section of a rabbit tibialis anterior biopsy sample showing the differential staining of type I and II fibers. Slow type I fibers stain darkly whereas the fast type IIa and IIx fibers stain lightly. (From Lieber.²⁷ Reprinted with permission of Lippincott Williams & Wilkins.)

MHC is a very important component in determining the contractile properties of the muscle fiber. The maximal velocity of muscle fiber shortening, termed V_{max} , is determined by the rate at which the myosin ATPase hydrolyzes ATP to provide energy for the power stroke. Slow-twitch fibers expressing type I MHC have a low V_{max} , whereas fast-twitch fibers expressing type IIa or IIx have high V_{max} values.

Another important classification method categorizes motor units.¹⁴ A motor unit consists of an α -motor neuron and all the muscle fibers that it innervates. In adult, human skeletal muscle, each muscle fiber is innervated by only one motor neuron. This scheme is based on the contractile properties of the motor unit and their resistance to fatigue. Using this scheme, slow contracting motor units that are highly resistant to fatigue are designated with an S. Fast contracting motor units that have a moderately high resistance to fatigue are denoted as FR, and fast contracting but highly fatigable motor units are labeled FF. The fatigue characteristics are related to the biochemical properties of the motor unit (Figure 2.10).

In general, there is a significant amount of overlap between these three classification systems. For example, the S motor units that have a high resistance to fatigue also have a very high oxidative capacity, which provides them with this fatigue resistance. Most likely, fibers classified as SO or type I would be part of S motor units. Fibers expressing either IIa or IIx MHC are likely to be FOG or FG fibers and belong to FR or FF motor units, respectively. However, caution should be used in going between the classification systems especially when categorizing the fast-contracting fibers. Remember, most properties of

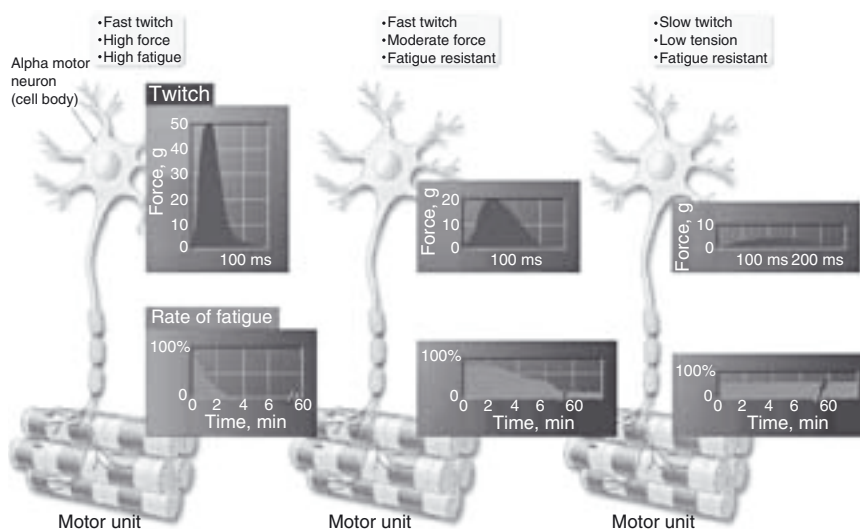


FIGURE 2.10. The contraction velocity, force, and fatigue characteristics of the fast fatigable (left), fast fatigue resistant (center), and slow (right) motor units. The upper graphs depict the twitch response to a single stimulus and the lower graphs show the fatigability of the motor units. (From McArdle, WD, Katch FI, Katch VL. Exercise Physiology: Energy, Nutrition, and Human Performance. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2001. Reprinted with permission of Lippincott Williams & Wilkins.)

Sidebar 2.1. Muscle Fiber Types, Fiber-Type Transitions, and Athletic Performance

Although muscle fiber type may be an important contributor to success in many sports, it should be recognized that many other factors including biomechanics, cardiorespiratory capacity, biochemical and psychologic characteristics determine successful athletic performance. Clearly, skeletal muscle demonstrates an enormous capacity for adaptation.^{15–19} The fast-twitch or type II muscle fibers are capable of producing greater force, especially for higher-velocity movements, compared with slow-twitch or type I fibers, and sprint performance has been correlated with the proportion of type II fibers.²⁰ Successful weightlifting performances and vertical jump power were correlated with type II fiber characteristics.²¹ In general, most muscles of elite sprinters are composed of approximately 75% fast-twitch fibers (Table 2.2). The slow-twitch or type I muscle fibers have a very high resistance to fatigue, and most successful endurance athletes have high percentages of slow-twitch fibers. However, it is possible that on occasion an athlete might be successful in endurance events with a lower proportion of slow-twitch fibers. Don Kardong was a member of the United States men's Olympic marathon team in 1976, and he was typed as having 50% slow-twitch fibers.^{22,23}

The primary factor that regulates the characteristics of muscle fibers is the motor neuron that innervates them. Experiments performed nearly 50 years ago demonstrated that when the motor nerve to a muscle that is primarily composed of slow-twitch fibers is redirected toward a muscle consisting of a majority of fast-twitch fibers that the myofibers take on the characteristics of slow-twitch fibers.¹⁵ Experiments since then have clearly demonstrated that over time, all of the biochemical, contractile, and structural characteristics of muscle fibers change when innervated by a different type of motor neuron or electrically stimulated in a manner similar to the other motor neuron type.¹⁷ Although these experiments do not truly

mimic the exercise training of athletes, they do show the tremendous plasticity of muscle fibers.

Both endurance- and strength-training studies have shown that the IIx fibers readily transition to IIa fibers. In fact, a significant decrease in the proportion of IIb myofibers in the vastus lateralis muscle of women occurred after only 2 weeks (4 workouts) of strength training.¹⁹ (Recent research shows that the IIb myosin isoform is not expressed in human skeletal myofibers. So fibers that were typed previously as IIb myofibers are truly IIx myofibers.)

The extent of transitions between the type I and IIa myofibers in response to exercise training is more controversial. An increase in the proportion of type I fibers and decline in the percentage of type II fibers during endurance training consistent with a transition from IIa to I fibers has been reported.¹⁶ It might be significant to note that these studies are relatively short in duration compared with the years of training for many elite athletes. A progressive increase in the percentage of type I fibers with years of training has been reported in professional road cyclists.²⁴ It is likely that the very high percentage of type I myofibers in the muscles of some elite endurance athletes is attributable primarily to genetics with some contribution from training-induced fiber-type transitions (Table 2.2). The extent of this transition to type I fibers is unclear, but may depend on the total amount of endurance training performed as well as the underlying genetic potential or resistance of the fibers to transition. Whether significant transition of slow-twitch to fast-twitch fibers occurs in sprinters is even less clear, because there are few reports of type I to type II transitions in humans.²⁵ Finally, the fiber-type composition of athletes in many sports, such as soccer, hockey, and football, has not been studied to a large extent. The effect of any fiber-type transitions on performance is unclear, but at the elite levels of sport, small differences may have a large impact on athletic success.

TABLE 2.2. Fiber type percentages for elite endurance athletes, sprinters, and untrained individuals.

| Study | Sport and group | Muscle | % Type I | % Type IIa | % Type IIx |
|------------------------------------|--------------------------------|------------------|----------|---------------------------|------------|
| Costill et al., ¹⁷ 1976 | Best American distance runners | Gastrocnemius | 79.0 | 21.0 (all type II fibers) | |
| | Untrained men | | 57.7 | 42.3 (all type II fibers) | |
| Costill et al., ¹⁷ 1976 | Sprinters, male | Gastrocnemius | 24.0 | 76.0 (all type II fibers) | |
| | Sprinters, female | | 27.4 | 72.6 (all type II fibers) | |
| Howald et al., ¹⁶ 1982 | Distance runners | Vastus lateralis | 78.0 | 19.0 | 2.5 |
| | Controls | | 51.0 | 41.0 | 7.1 |
| Baumann et al., 1987 ²⁶ | Professional cyclists | Vastus lateralis | 80.0 | 17.0 | 0.6 |
| | Sedentary controls | | 53.0 | 33.0 | 13.0 |

myofibers and motor units are a continuum rather than discrete points, so myofibers and motor units might not always fit neatly into a given category.

FACTORS DETERMINING MUSCULAR STRENGTH: BIOMECHANICS

Various biomechanical and biochemical factors affect a muscle's ability to produce force and move or lift objects. Skeletal muscles along with the bones to which they attach operate as levers. The length of a limb and the point of tendon attachment on a bone are important determinants of an individual's ability to exert force and move objects. Elbow flexion involving the biceps brachii muscle and the radius provides a good example of how limb length and tendon insertion points affect the ability to lift a weight. During an arm curl, the biceps brachii must develop tension and shorten in order to cause rotation at the elbow joint resulting in flexion. For this movement, the axis of rotation is at the elbow and the resistance, such as a dumbbell, is held in the hand. The longer the limb, the greater the force that muscles would need to produce in order to lift an object at the end of the limb. Also, the further out on the limb that the biceps tendon attaches to the radius, the heavier the resistance that can be moved for a given amount of force the muscle produces.

FACTORS DETERMINING MUSCULAR FORCE PRODUCTION: SARCOMERE LENGTH-TENSION RELATIONSHIP

The ability of a muscle to produce force throughout a range of motion is dependent on muscle length. For each muscle, there is a range of muscle lengths that are optimal for force production based on sarcomere length. Sarcomeres produce the greatest amount of force when there is the greatest possible number of myosin cross-bridge interactions with action. This is termed optimal length and designated as L_0 (Figure 2.11). When the muscle is

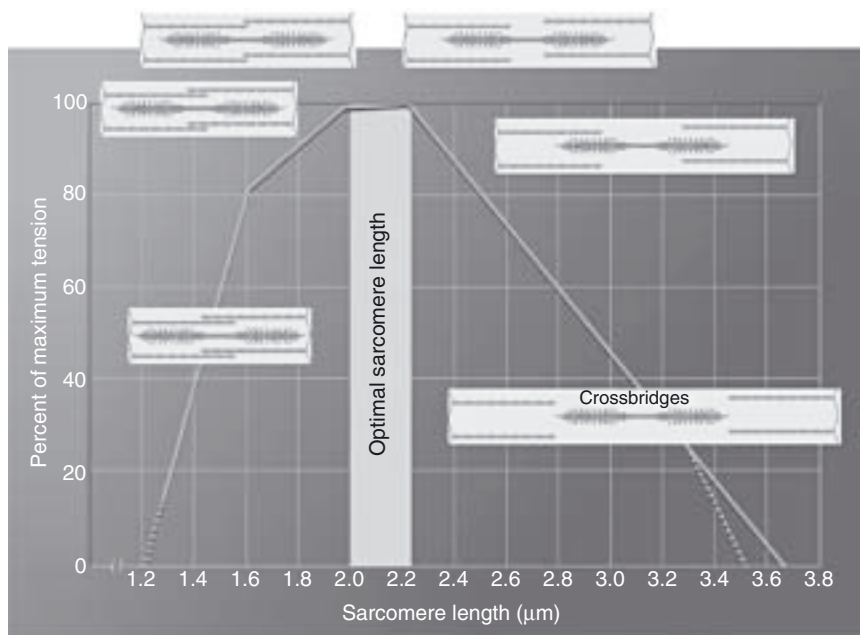


FIGURE 2.11. The relationship between sarcomere length and tension development under static conditions. Optimal sarcomere length (2.0–2.25 μm) results in the maximal tension production because the greatest number of myosin cross-bridges can bind to actin. Tension output decreases as sarcomere length decreases or increases beyond optimal length. (From McArdle, WD, Katch FI, Katch VL. Exercise Physiology: Energy, Nutrition, and Human Performance. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2001. Reprinted with permission of Lippincott Williams & Wilkins.)

lengthened beyond L_0 , force production decreases as the thin filaments are pulled away from the thick filaments and the potential number of myosin-actin interactions declines. When the muscle is shortened to less than L_0 , force also declines as the thin filaments from the opposing Z lines of the sarcomere overlap. This overlap may interfere with the binding of myosin to actin.

FACTORS DETERMINING MUSCULAR FORCE PRODUCTION: FORCE-VELOCITY RELATIONSHIP

The force that a muscle can produce is a function of the type of contraction and the velocity of movement. The velocity at which a muscle can contract is determined by the force acting against it. The force-velocity relationship is often described with reference to a static muscle action. For concentric muscle actions, there is a decline in muscle force production as the velocity of shortening increases. Initially, rather small increases in shortening velocity result in a dramatic decrease in force production (Table 2.3). For example, the force produced by a muscle declines by 25% or more when going from a static muscle contraction to a velocity of shortening that is only 6% of the maximum shortening velocity. When resistances greater than the maximal force-producing capacity of the muscle are used, an eccentric muscle action results. Initially, as the velocity of lengthening increases a small amount, there is a fairly large increase in muscle force production. Finally, as lengthening velocity continues to increase, muscle force production levels off.

The force-velocity curve differs among the three major myofiber types. Specific tension is the amount of force produced per unit cross-sectional area of muscle, and allows for comparison of the force-production capabilities of muscle fibers of different sizes. Recent research using rat muscle shows that for static muscle actions, fast-twitch fibers are capable of producing greater specific tension than slow-twitch fibers.²⁸ Secondly, the slope of the initial decline in force as shortening velocity increases is greatest for type I fibers, intermediate for type IIa fibers, and least for IIx fibers. Therefore, for any given velocity of shortening, type IIx fibers produce the greatest amount of force and type I fibers produce the lowest force.

Power is the product of force and velocity and is a very important factor determining successful performance in many sports. The peak power generated by a muscle or muscle fibers is related to the velocity as well as the force of muscle contraction. Maximal power production occurs at approximately one third of maximal force production as well as one third of maximal shortening velocity. Because fast-twitch fibers are capable of greater force production at any given contraction velocity compared with slow-twitch fibers, the fast-

TABLE 2.3. Relative muscle force at various relative contraction velocities.

| <i>Muscle force (% of maximal static contraction)</i> | <i>Velocity of shortening (% of maximal shortening velocity)</i> |
|---|--|
| 100 | 0 |
| 95 | 1 |
| 90 | 2.2 |
| 75 | 6.3 |
| 50 | 16.6 |
| 25 | 37.5 |
| 10 | 64.3 |
| 5 | 79.1 |
| 0 | 100 |

Source: Adapted from Lieber.²⁷

twitch fibers are capable of greater power production than slow-twitch fibers.

REGULATION OF MUSCLE FORCE PRODUCTION

Muscle fibers are recruited as groups known as motor units, which are the functional units of the neuromuscular system. When an α motor neuron is excited sufficiently to develop an action potential, all myofibers that are innervated by the motor neuron are activated. This is referred to as the all-or-none principle. In general, the slow (S) motor units are the smallest having the lowest innervation ratios, which is the number of fibers innervated per motor neuron. The neurons of S motor units typically have the least synaptic input and the smallest soma and axon diameters. Fast, fatigue-resistant (FR) motor units have intermediate innervation ratios, and the soma and axon are intermediate in size. Typically, fast fatigable (FF) motor units have the greatest innervation ratios, their neurons have the greatest synaptic input, and the soma and axon diameters are the largest.

For static and concentric muscle actions, motor units are recruited on the basis of size beginning with the smallest motor units and as more force is needed larger motor units are recruited. This is known as Henneman's size principle of motor unit recruitment. It should be noted that this orderly recruitment of motor units is both sequential and additive. More recent evidence suggests that motor unit recruitment occurs in reverse order beginning with larger motor units for eccentric muscle actions.²⁹ Also noteworthy is that motor unit recruitment has been studied primarily for contractions and movements much less powerful and complex than many of the ballistic, multi-joint movements observed in sports. Many contractions in sports are plyometric in nature. The manner of motor unit recruitment for these types of actions is not entirely clear.

Force production by a muscle can vary over a very wide range, which is essential for smooth, coordinated movements. The neuromuscular system uses two major strategies to regulate force production during muscular contractions. The first strategy involves the recruitment of motor units in an orderly manner as described above and is called multiple motor unit summation. Simply stated, as more force is needed, additional motor units are recruited. A second strategy involves rate coding or recruiting motor units at various frequencies in order to vary the force output by the muscle fibers of that motor unit. This strategy is termed wave summation.

To better understand wave summation, an understanding of the response of muscle fibers to neural stimulation is essential. When the myofibers of a motor unit are stimulated, they develop tension then relax. This is referred to as a twitch (see Figure 2.13). If a second stimulus occurs before complete myofiber relaxation, then the second twitch results in greater force than the first twitch. As the frequency of motor unit stimulation increases, the force of the individual twitches begins to add up or summate. If the frequency of motor unit firing is sufficient, the individual twitches merge and force output increases to a maximal value. The increased force in response to a series of stimuli is referred to as tetanus. The underlying physiologic explanation of wave summation is related to the amount of time needed for the SERCA pumps to resequester calcium into the sarcoplasmic reticulum. With increasing frequencies of neuromuscular stimulation, there is inadequate time to pump the calcium that had been released back into the sarcoplasmic reticulum. With each additional stimulus, additional calcium is released into the sarcoplasm. As calcium concentrations in the sarcoplasm increase, the amount of calcium bound to troponin increases, which exposes more binding sites on actin so more force can be produced. It is important to note that even though muscle twitches are discussed, muscle contractions during human movements involve repeated and sustained contractions rather than twitches.

An increased synchronization of motor unit firing has been observed in strength-trained individuals^{30,31}; therefore, it has been speculated that motor unit synchronization is a third strategy used by the neuromuscular system to increase force production. Synchronization refers to an increased temporal coincidence of action potentials by the motor neurons. Research suggests that this strategy does not change maximal muscle tension during static contractions.³² Synchronization may increase the rate of muscle force production thus allowing the muscle to achieve maximal force output more rapidly or it may serve as a mechanism to coordinate the activity of multiple muscles synergistically.³³

Based on the current understanding of motor unit recruitment, some important applications to the training of athletes can be made. Athletes need to incorporate contraction types and movement patterns into their training that are as similar as possible to those in their sport in order to optimize neuromuscular recruitment. Concentric, eccentric, and plyometric muscle actions must be included in the training of athletes to induce neuromuscular adaptations that result in optimal motor unit recruitment for these various contraction types. Maximal muscle contractions need to be incorporated into strength-training workouts in order to recruit and thus induce adaptations of all motor units and muscle fibers.

MUSCULAR FATIGUE

Fatigue is defined as an inability to maintain the desired intensity of exercise. Fatigue can result from many factors that can be categorized as central or peripheral. Also, the factors contributing to fatigue vary depending on the intensity and duration of exercise. With regard to central fatigue, many factors such as decreased blood glucose concentrations or sensation of pain may increase the difficulty of voluntarily exciting the motor nerves in the motor cortex of the brain sufficiently. At the muscular level, several factors may contribute to an inability to maintain a given effort during very-high-intensity exercise. The depletion of ATP and phosphocreatine (PCr) during supramaximal exercise causes a decline in exercise intensity. Lactic acid, or more accurately the H^+ ions associated with it, has long been considered the major cause of fatigue during high-intensity, anaerobic exercise. This view has been challenged by evidence demonstrating that inorganic phosphate (Pi) is the major contributor to fatigue at the level of the myosin cross-bridge.^{34,35} A role for H^+ as a contributor to fatigue cannot be completely discounted because buffering H^+ ions by bicarbonate loading has been shown to improve run times for races ranging from 400 to 1500 meters.³⁶⁻³⁸

During longer-duration aerobic exercise, the almost complete depletion of intramuscular glycogen is a dramatic cause of fatigue. In highly trained athletes, whose nutritional practices are sound, complete depletion of intramuscular glycogen rarely occurs. However, depletion of glycogen within individual fibers may occur. When this happens, myofibers associated with larger motor units must be recruited to maintain intensity. These larger motor units are more difficult to excite voluntarily, thus increasing the difficulty of maintaining the desired intensity of exercise. Because carbohydrates are the primary substrate for high-intensity exercise, carbohydrate consumption during exercise prolongs time to exhaustion.^{39,40}

The inability of elite athletes to maintain a given level of effort during long-distance races is likely attributable to multiple peripheral and central factors. One interesting factor that may be involved is excitation-contraction coupling failure induced by an accumulation of K^+ ions with the lumen of the T tubules. A buildup of K^+ may result in failure of action potentials to propagate down the T tubules resulting in a reduction in the amount of calcium released from the sarcoplasmic reticulum. Decreased calcium release results in fewer myosin cross-bridges interacting with actin in the strong binding state, thus reducing force production.

Sidebar 2.2. Sensory Receptors in Skeletal Muscle

There are several types of sensory receptors associated with skeletal muscle that are responsive to various types of stimuli including chemicals (chemoreceptors), mechanical forces (mechanoreceptors), pain-producing substances (nociceptors), and temperature (thermoreceptors).

Free nerve endings: Free nerve endings are the simplest type of sensory receptor and are found in most tissues of the body. Different types of free nerve endings are sensitive to each of the categories of stimuli listed above. Free nerve endings that are responsive to chemicals include those that are sensitive to changes in the level of extracellular H^+ , K^+ , O_2 , and CO_2 . Chemoreceptors send information about the local chemical environment via afferent or sensory neurons to the central nervous system. Chemoreceptors may be involved in the sensation of muscular discomfort and in cardiorespiratory responses during exercise.

Proprioception: Muscles and their associated joints contain several types of receptors that relay information about muscular dynamics and limb movements to the central nervous system. Proprioception enables the central nervous system to track a sequence of movements and provides a means for modifying subsequent motor behavior if needed. In skeletal muscle, Golgi tendon organs (GTOs) and muscle spindles are important proprioceptors.

Golgi tendon organs: GTOs are a type of mechanoreceptor that are located at the musculotendinous junction and are very sensitive to force development by the muscle fibers (Figure 2.12). GTOs act to protect the myofibers from damage that might occur from excessive muscular force output. When excited by high force production, GTOs transmit an inhibitory signal via a type Ib sensory or afferent neuron to the spinal column. Within the

spinal column, this inhibitory input depresses motor neuron excitability, thus increasing the amount of excitatory input necessary to stimulate the motor neuron sufficiently to develop an action potential. This is likely to cause a decrease in muscle force production. One of the early neural adaptations to strength training is the ability to more readily overcome the inhibitory effects of the GTOs.

Muscle spindles: Muscle spindles are referred to as stretch receptors and are the most complex sensory receptors in skeletal muscle (Figure 2.13). In response to rapid lengthening of the muscle, they can trigger a reflex muscle contraction, which is called a stretch or myotatic reflex. Muscle spindles are mechanoreceptors that contain specialized muscle fibers called intrafusal fibers encapsulated within a connective tissue sheath. Muscle spindles are located throughout the muscle and run in parallel with the other myofibers, which are referred to as extrafusal fibers. Muscle spindles contain two types of sensory nerve endings. Primary nerve endings are sensitive to dynamic changes in muscle length, whereas secondary nerve endings provide information about muscle length. Muscle spindles are even more complex because they are innervated by γ -motor neurons. When α motor neurons stimulate the extrafusal fibers to contract, γ -motor neurons stimulate the intrafusal fibers to contract in order to keep them at a length consistent with that of the muscle and thus sensitive to further length changes. When the primary nerve endings are excited by muscle lengthening, they transmit an excitatory impulse to the spinal cord. At the spinal level, the sensory neuron excites the motor neurons innervating the same muscle, which can initiate a reflex contraction of the muscle. Muscle spindles have important roles in postural control and regulation of movement.

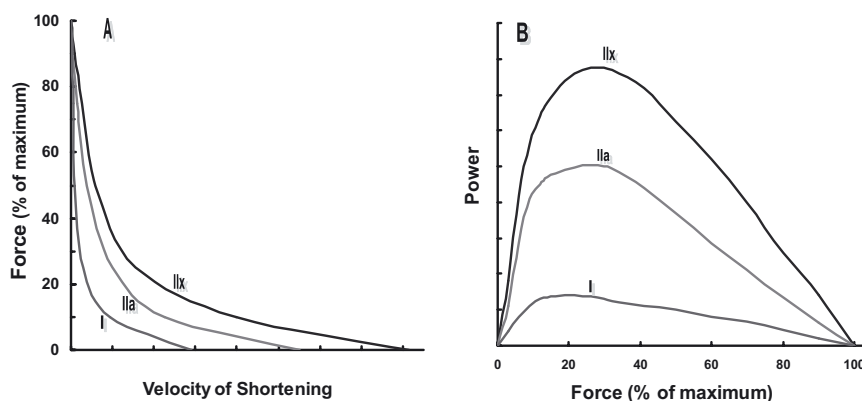
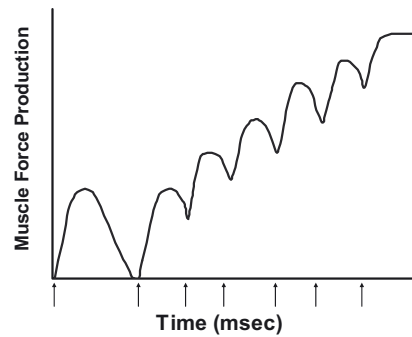


FIGURE 2.12. The relationship of (A) force and velocity and (B) power and force for the three adult human fiber types. **A:** Muscle fiber force production decreases rapidly from a static muscle action (0 velocity) to slow shortening velocities. For any given velocity of shortening, type IIx fibers are capable of the greatest force output and type I fibers produce the lowest force. **B:** Type IIx fibers are capable of greater power production than type IIa or I fibers, and type I fibers produce the lowest power outputs.

FIGURE 2.13. A twitch response and wave summation. A single stimulation of a muscle (shown as \uparrow) results in a twitch response. Repetitive stimuli result in summation until maximal force output by the muscle is achieved at tetanus.



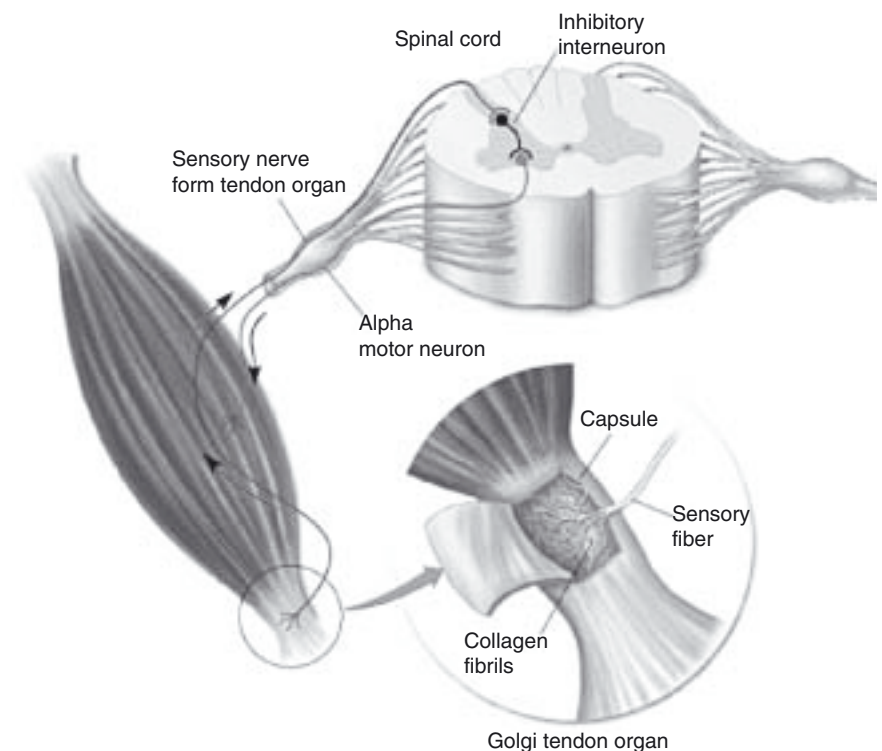
RESPONSES AND ADAPTATION OF SKELETAL MUSCLE TO EXERCISE TRAINING

Delayed-Onset Muscle Soreness

A common experience for fitness enthusiasts and athletes alike is the sensation of muscular pain or discomfort beginning approximately 16–24 hours after a workout. This delayed-onset muscle soreness (DOMS) usually peaks about 24–48 hours postexercise before beginning to subside. Depending on the training status of the individual and the rigor of the workout, the pain may have dissipated within 72 hours, but in cases of more severe damage can last several days. DOMS is accompanied by decreases in the maximum force capabilities of the muscle.⁴¹

The primary cause of DOMS is muscle fiber damage that may include tension-induced disruption of the sarcomeres and sarcolemma, as well as increased intracellular calcium, which activates enzymes that degrade muscle proteins.^{42–46} Eccentric contractions are much more likely to cause myofiber damage and DOMS than static or concentric muscle actions. Although DOMS is most often associated with strength-training exercises, endurance-type exercise with a significant eccentric component, such as running downhill, can cause DOMS also. The most common finding after eccentric exercise-induced muscle damage is disruption of the myofibrillar material, especially at the Z disk^{41,43} (Figure 2.14). Studies also show that there is disruption of the proteins

FIGURE 2.14. The Golgi tendon organ and its neural connections. Golgi tendon organs are responsive to muscle tension development. Golgi tendon organs function as a protective sensory mechanism to detect and subsequently reduce excess strain at the musculotendinous junction. Excessive tension within the muscle activates the Golgi tendon organs inducing a reflex inhibition of the muscle. (From McArdle, WD, Katch FI, Katch VL. *Exercise Physiology: Energy, Nutrition, and Human Performance*. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2001. Reprinted with permission of Lippincott Williams & Wilkins.)



Sidebar 2.3. Reducing Delayed-Onset Muscle Soreness: Regular Exercise Is Recommended But Long-Term Use of Nonsteroidal Antiinflammatory Drugs Should Be Avoided

Anytime an individual performs exercise to which they are not accustomed, DOMS is likely to occur. Mild DOMS is not uncommon for athletes and fitness enthusiasts who perform strenuous workouts, but the soreness is not usually as great as the first time that DOMS is experienced. The most effective means of reducing DOMS is to exercise on a regular basis. Even a single bout of exercise has a significant protective effect against muscle soreness during subsequent bouts of similar exercise.^{48,49} This phenomenon is called the repeated bout effect.

Aspirin and other nonsteroidal antiinflammatory drugs (NSAIDs) reduce the sensation of muscular pain; however,

longer-term use may slow recovery. Drs. Jan Friden, Richard Lieber, and colleagues induced muscle damage in rabbits by repetitive stretching of the contracting muscles of the anterior compartment of the leg.⁵⁰ Initially, there was a more rapid recovery of contractile strength by the leg muscles of rabbits treated with the NSAID flurbiprofen, but there was a longer-term deficit in muscle force production compared with untreated rabbits. Based on histologic observation, muscles from the treated animals showed a less effective regenerative response. Although the use of NSAIDs may reduce DOMS, their routine use for reducing soreness should be avoided.

that make up the cytoskeleton.^{44,47} Muscle damage leads to an inflammatory process and the accumulation of fluid and pain-producing substances within the muscle. It is important to realize that the actual amount of damage to the muscle fibers that causes significant muscular discomfort is quite small. Often, the damage within a myofiber extends for only a few sarcomeres. These localized areas of damage are readily repaired if adequate time is allowed for recovery.

Muscle Satellite Cells: Role in Muscle Repair, Regeneration, and Adaptation

Satellite cells of skeletal muscle are quiescent, myogenic stem cells located outside the myofiber sarcolemma but within its basement membrane. Approximately 1%–5% of the nuclei associated with a myofiber are satellite cell nuclei,⁵¹ and it seems that more oxidative muscle fibers have a greater density of satellite cell nuclei compared with more glycolytic myofibers.⁵² The greater percentage of satellite cell nuclei associated with oxidative or slow-twitch fibers may be attributable to their greater use (e.g., maintenance of posture, light activity), and thus greater wear and tear. Satellite cells are important for the repair of myofiber damage and regeneration of necrotic myofibers.^{51,53} Skeletal muscle fiber damage induces satellite cell activation by various mitogens that have not been clearly defined. Activated satellite cells undergo one or more cycles of mitosis to give rise to daughter cells. The fate of these additional cells depends on the chemical signals acting on the cell. Daughter cells may undergo additional cycles of mitosis, fuse with damaged fibers or with other satellite cells to form a myotube, or return to a state of quiescence. Whether myofiber damage must occur for satellite cell activation is unclear, but recent experimental work shows that satellite cells are likely to contribute additional nuclei during myofiber hypertrophy in response to strength training.^{52–54} Also, recent evidence shows that satellite cells are activated during fiber-type transformation.⁵³

Adaptations of Skeletal Muscle to Endurance Training

Repeated bouts of endurance exercise increase an individual's maximal oxygen uptake, which indicates a greater ability for the cardiorespiratory system to deliver oxygenated blood to the working skeletal muscles and for muscle fibers

to extract and use the oxygen for energy production. Within skeletal muscle, several important adaptations occur that increase the oxidative capacity of muscle, including an increased number and size of mitochondria and increases in the enzymes of metabolic pathways involved in oxidative metabolism.⁵⁵⁻⁵⁷ These enzymes include succinate dehydrogenase and malate dehydrogenase, which are enzymes in Krebs tricarboxylic acid cycle. Endurance exercise also induces a shift toward a greater reliance on lipid metabolism. As discussed earlier, a transition of type IIX fibers to type IIA fibers occurs quite readily in response to endurance training. Transitions from type II fibers to type I fibers have been reported in some studies, but the extent of these transitions is unclear.

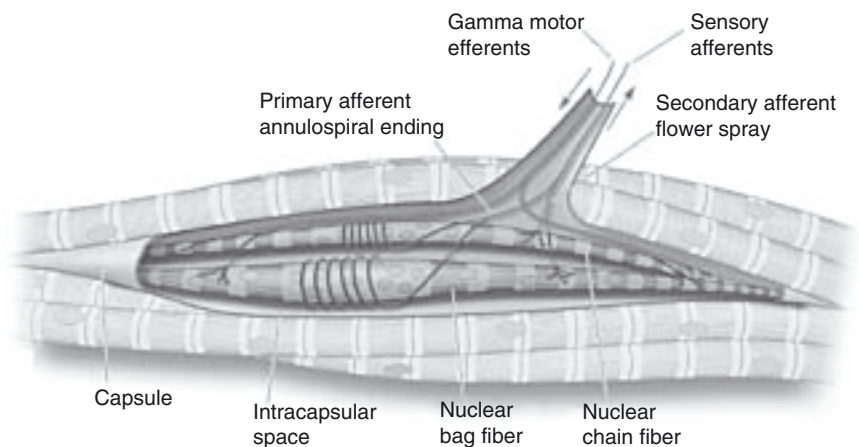
Skeletal Muscle Adaptations to Strength Training

Increases in muscular strength and size occur as a result of resistance or strength training.⁵⁸⁻⁶¹ Strength gains during the first few weeks of strength training are largely the result of adaptations within the nervous system. Some of the adaptations include reduced activation of antagonistic muscles and enhanced ability to overcome the inhibitory effects of the GTOs. These neural adaptations allow the individual to use heavier resistances during a training session, thus loading the muscle to a greater degree.

Longer-term increases in muscle strength result primarily from muscle hypertrophy, although nervous system adaptations are always important. Increased muscle size is important because the force that a muscle can produce is directly related to its cross-sectional area. The primary way that muscle hypertrophy occurs is by growth of individual muscle fibers. This is a result of altering protein turnover in favor of net protein synthesis (Figures 2.15 and 2.16). Strength training causes a short-term increase in protein degradation, but a longer-term increase in protein synthesis (Figure 2.17). Adequate protein and carbohydrate consumption before or after a strength-training workout can shift protein turnover further toward a positive protein balance by reducing degradation and increasing protein synthesis.^{62,63} Several studies show a greater rate of myofiber hypertrophy for the type II fibers compared with the type I fibers.^{64,65} Individuals who have a higher proportion of type II myofibers may increase muscle mass at a greater rate compared with individuals with a higher proportion of type I myofibers. This may explain the observation of many fitness enthusiasts who seem to have a difficult time increasing muscle size whereas other individuals seem to gain muscle mass more readily.

Although the primary means by which muscle size increases as a result of resistance training is myofiber hypertrophy,⁶⁴ increasing evidence suggests that some increase in the number of muscle fibers, termed myofiber hyperplasia, is possible.⁶⁶⁻⁶⁹ Initially, evidence showing that hyperplasia could occur was from experimental animal models, such as the compensatory hypertrophy of muscles

FIGURE 2.15. Structure of the muscle spindle including a detailed view of the intrafusal fibers and neural connections. The muscle spindles are stretch receptors within skeletal muscle. The two different types of intrafusal fibers within the muscle spindle are responsive to length changes or changes in the rate of change of length. (From McArdle, WD, Katch FI, Katch VL. *Exercise Physiology: Energy, Nutrition, and Human Performance*. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2001. Modified and reprinted with permission of Lippincott Williams & Wilkins.)



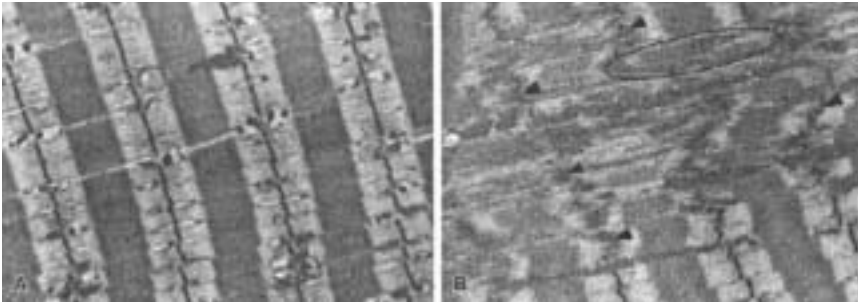


FIGURE 2.16. Ultrastructural changes in human vastus lateralis muscle after eccentric contractions. **A:** Normal muscle. **B:** Muscle obtained 3 days after eccentric contraction-induced injury. It is important to note that the disruptions are localized and primarily in the region of the Z disk. (From Lieber.²⁷ Reprinted with permission of Lippincott Williams & Wilkins.)

that occurred after ablation (removal) of the synergists and the wing-stretch model in chickens and quail. Although these models were criticized for not being similar to strength training in humans, they did demonstrate that muscle fiber formation was possible in adult animals. The research of Dr. William Gonyea and colleagues⁶⁹ in which cats were trained to perform resistance-training exercise in order to obtain a food reward added additional support for myofiber hyperplasia. Cats that performed resistance-training exercise for an average of 101 weeks had a 9% greater myofiber number in the flexor carpi radialis muscle of their trained limb compared with their untrained limb. Obviously, these types of experiments cannot be done for ethical reasons in humans; however, a substantial body of indirect evidence supports the likelihood of muscle fiber hyperplasia in humans as a result of strength training,^{70,71} although the extent of the hyperplasia is unclear.

With regard to fiber-type transitions, a shift of type IIx fibers to IIa fibers occurs quite rapidly in response to heavy strength training. In women performing strength-training exercises, a shift from type IIx to IIa fibers was observed after only four workout sessions.¹⁹ A shift of type II to type I fibers or vice versa has not been reported with resistance training.

Skeletal Muscle Adaptations to Sprint Training

A variety of sprint-training workouts can be achieved by altering the duration or distance of the sprint, workout intensity, the duration of the recovery interval, and training frequency. Energy for sprinting exercise is derived largely from the ATP/PCr and glycolytic/glycogenolytic energy systems.^{72–74} However, when repetitive sprints are performed with short recovery intervals or when sprint duration is increased, the contribution of aerobic energy metabolism increases.^{73,75}

Although there is substantial variation among studies, adaptations to sprint exercise training include increases in enzymes associated with all three energy systems and improved muscle buffering capacity.⁷⁶ Differences among studies may be attributable in part to differences in sprint duration, duration of the

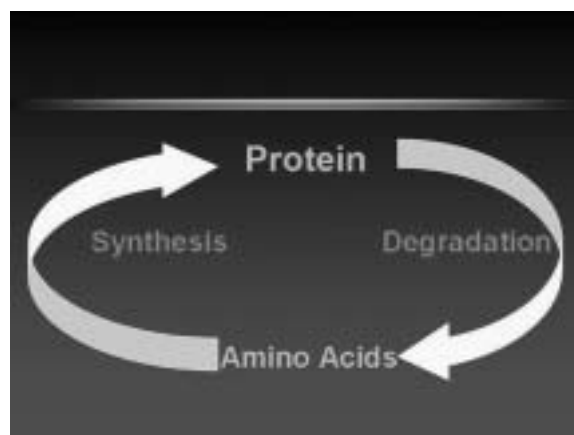


FIGURE 2.17. Schematic representation of the relationship of protein synthesis and degradation with muscle protein and amino acids. Muscle hypertrophy associated with strength training results largely from an increase in protein synthesis. Postexercise nutrition may promote greater increases in protein synthesis and reduce degradation.^{62,63}

recovery interval, and training volume. Increases in the activities of enzymes of the phosphagen energy system, myokinase and creatine phosphokinase, have been reported after sprint training.⁷⁶ Interestingly, the majority of studies have shown no increase in the amount of intramuscular ATP and PCr after sprint training; however, the ability to resynthesize ATP may be more important than the absolute muscle content.⁷⁶ Increases in the enzymes of the glycolytic/glycogenolytic pathway are often observed after sprint training. For example, significant increases in the activity of hexokinase (+56%) and phosphofructokinase (+49%) were observed in vastus lateralis muscle after training with repeated bouts of 30-second sprints on a cycle ergometer for 7 weeks.⁷⁷ Other studies have reported increases in the rate-limiting enzyme of glycolysis, phosphofructokinase, as well as glycogen phosphorylase and lactate dehydrogenase.⁷⁶

It is important to point out that increases in maximal oxygen consumption⁷⁸ as well as increases in enzymes involved in oxidative metabolism have been reported after sprint or interval-type training.⁷⁶ This is significant for the conditioning of athletes in sports that require high degrees of strength and power, because aerobic-type training can attenuate training-induced gains in strength and power.^{79–81} The necessary degree of aerobic conditioning for athletes in many sports characterized by strength–power or a high anaerobic component might be achieved by repeated bouts of short duration and very-high-intensity exercise.

In addition to the metabolic changes that have been discussed, adaptations in fiber size, fiber type, and morphology have been observed in response to sprint training. Increases in myofiber cross-sectional area of 5%–16% have been reported for type I and II fibers after 8 weeks to 8 months of sprint training.⁷⁶ The volume of the sarcoplasmic reticulum may increase in response to sprint training.^{76,82} Finally, transition of type IIx fibers to IIa frequently occurs after sprint training. A decrease in the proportion of type I fibers and increase in the percentage of type IIa fibers suggests that sprint training can induce a type I to IIa fiber-type transition.^{25,76} However, changes suggestive of a IIa to I shift have been reported also.^{83,84} Differences among studies may be related to longer sprint durations or a greater training frequency.⁷⁶

Concurrent Strength and Endurance Training: Beneficial for Endurance Athletes But Not Strength–Power Athletes

A frequently asked question in sports is whether athletes competing in sports requiring a large amount of strength and power should establish a conditioning base with aerobic-type exercise. The classic work of Dr. Robert Hickson⁸⁰ clearly demonstrated that endurance exercise can hinder the development of muscular strength. It is possible that adaptations and responses necessary for improving strength and power, including neuromuscular recruitment,⁸⁵ myofiber hypertrophy,⁸⁶ and hormonal levels,⁸⁶ are compromised when concurrent strength and endurance exercise is performed.⁷⁹ Athletes participating in strength–power sports can improve aerobic capacity through the use of high-intensity, short-duration work intervals with short rest periods.⁷⁶

Interestingly, endurance athletes may benefit from strength training. After 10 weeks of training, individuals performing concurrent endurance and strength training had increased running or cycling times to exhaustion despite no increase in aerobic capacity.^{81,87} The addition of strength training improves running and cycling performance by enhancing movement economy.^{88,89} Also, the addition of explosive-strength training that included sprints and plyometric exercises to an endurance training program improved 5-kilometer time in well-trained endurance athletes without changes in their maximal oxygen uptake. This improvement was attributed to improved neuromuscular characteristics and enhanced running economy.⁹⁰ Interestingly, strength training does not seem to substantially improve swim performance.⁹¹ It is important to note that endurance athletes should avoid a substantial increase in lean body mass, because the additional body weight is likely to have a detrimental impact on performance.

Because most research has been done on sedentary or moderately trained individuals who are not elite, there is some debate as to whether highly trained

or elite athletes can benefit from strength training. It has been suggested that the neuromuscular recruitment patterns of elite athletes are so efficient that strength training will not improve movement economy.⁹² At this time, it can be concluded that the addition of an appropriately designed strength-training program can improve the performance of many fitness enthusiasts and athletes. However, additional research is necessary to determine whether the appropriate application of strength training can enhance the performance of elite athletes.

SUMMARY

Skeletal muscle is a highly organized tissue designed to produce force for postural control, movement, and even breathing. Various architectural designs, varying amounts of muscle proteins (e.g., enzymes or myosin), and different isoforms of many muscle proteins provide for a wide range of force-producing, biochemical, and metabolic characteristics. Additionally, the ability of skeletal muscle to adapt to the demands placed on it, such as increased contractile activity associated with endurance training or increased loading attributable to strength training, demonstrates a tremendous plasticity. It should be noted that there is a large variation among individuals with regard to the magnitude of muscle adaptability to various types of training. Differing muscle characteristics, such as muscle pennation and fiber type, and variation in degree of adaptability among individuals partially explains the wide range of differences in aspects of exercise performance, such as muscular endurance or strength.

PRACTICAL APPLICATIONS

Effective exercise training programs must be designed to induce adaptations necessary for success in a given sport or achieving individual goals. The specificity of training principle states that training should be as specific as possible to the event in which an athlete competes. For example, for increasing strength and power, athletes must include maximal muscle contractions using movement patterns that are as similar as possible to those in their sport in order to recruit all motor units and to optimize neuromuscular recruitment. Also, endurance, strength, and sprint training tend to induce different adaptations in skeletal muscle although there is some degree of overlap depending on the design of the training program. For example, repeated bouts of very-high-intensity exercise (sprinting) with short rest periods will increase the oxidative capacity of skeletal muscle.^{93, 94} Familiarity with the characteristics of skeletal muscle that contribute to success in various types of athletic events, as well as knowledge of the adaptations of skeletal muscle to different types of exercise training programs enables athletes, coaches, and sports nutritionists to design more effective training programs.

QUESTIONS

1. What is the innermost layer of connective tissue that surrounds each individual muscle fiber?
 - a. Endomysium
 - b. Perimysium
 - c. Epimysium
 - d. Myomysium
2. Which of the following is the type of muscle action during which the muscle develops tension and lengthens?
 - a. Concentric
 - b. Static
 - c. Eccentric
 - d. Isometric

3. Skeletal muscles are divided in bundles of muscle fibers. Which term refers to these bundles of muscle fibers?
 - a. Sarcomeres
 - b. Myofibrils
 - c. Synergists
 - d. Fasciculi
4. What is the name of a very large protein in muscle fibers that keeps myosin centered within the sarcomere?
 - a. Z disk
 - b. Titin
 - c. Troponin
 - d. Sarcoplasmic reticulum
5. If a football player begins a strength-training program, which of the following is most accurate regarding muscle hypertrophy?
 - a. The type I muscle fibers will hypertrophy at the greatest rate.
 - b. The type II muscle fibers will hypertrophy at the greatest rate.
 - c. Usually the type I and II muscle fibers hypertrophy at the same rate.
 - d. The primary means by which muscle hypertrophy occurs is muscle fiber hyperplasia.
6. The thick filaments of the sarcomere are composed of which of the following?
 - a. Myelin
 - b. Actin
 - c. Myosin
 - d. Tropomyosin
7. Justin Gatlin won the gold medal in the 100-meter sprint at the recent Olympic games. If you could study his leg muscles, you would likely find which of the following?
 - a. His muscles have a very high percentage of slow-twitch muscle fibers.
 - b. His muscles have a very high percentage of fast-twitch muscle fibers.
 - c. His muscles have about 50% fast-twitch muscle fibers.
 - d. There is no relationship between muscle fiber type and sprinting performance.
8. Which term refers to the most basic contractile element of skeletal muscle?
 - a. Myofibrils
 - b. Sarcomeres
 - c. Filaments
 - d. Mitochondria
9. Which of the following is the best description of how muscle fibers shorten during a concentric muscle action?
 - a. Muscle shortening occurs as the thick (myosin) filaments shorten and pull the thin filaments toward the center of the sarcomere.
 - b. Muscle shortening occurs as the thin filaments shorten.
 - c. Muscle shortening occurs as the myosin cross-bridges slide the thin filaments over the thick filaments.
 - d. Muscle shortening occurs as the thin filaments are pulled away from the thick filaments.
10. When calcium is released, what is the protein on the thin filament with which it interacts?
 - a. Actin
 - b. Titin
 - c. Troponin
 - d. Tropomyosin
11. Which of the following group of athletes would be expected to have the highest percentage of slow-twitch fibers in the muscles of their legs?
 - a. Sprinters
 - b. Shot putters

- c. Football players
 - d. Soccer players
 - e. Long-distance runners
12. Which of the following is not a factor in determining the amount of force that a muscle can produce?
- a. The size of the muscle
 - b. The number of motor units activated
 - c. The amount of mitochondria within the muscle
 - d. The speed of the muscle contraction
13. Which of the following statements most accurately describes strength gains during the initial 6–8 weeks of resistance training?
- a. Strength gains are attributable largely to neural adaptations
 - b. Strength gains are attributable largely to muscle fiber hypertrophy
 - c. Strength gains are attributable almost equally to neural adaptations and muscle fiber hypertrophy
 - d. Strength gains are minimal during the initial 6–8 weeks of strength training
14. Which of the following is the type of muscle contraction that is most likely to cause delayed-onset muscle soreness?
- a. Concentric
 - b. Static
 - c. Eccentric
 - d. Isometric
15. Which of the following is the most likely cause of delayed-onset muscle soreness?
- a. Structural damage to the muscle
 - b. High levels of lactic acid in the muscle
 - c. Depletion of muscle glycogen
 - d. Increased muscle spindle activity
16. In human adult skeletal muscle, each muscle fiber is typically innervated by which number of motor neurons?
- a. One
 - b. Two or three
 - c. About five
 - d. More than ten
17. Which of the following terms is used to refer to the order in which motor units are recruited during a concentric muscle action?
- a. Size principle
 - b. Saltatory conduction
 - c. Principle of contraction-type specificity
 - d. Static recruitment
18. Which of the following muscle fiber types has the greatest oxidative (aerobic) capacity?
- a. Type I
 - b. Type Ib
 - c. Type IIa
 - d. Type IIx
19. What is the extensive series of channels that run throughout the skeletal muscle fiber and is a site for calcium storage?
- a. Transverse tubules
 - b. Myofibrils
 - c. Sarcolemma
 - d. Sarcoplasmic reticulum
20. What is the type of muscle contraction during which the muscle develops force but there is no rotation about a joint?
- a. Eccentric
 - b. Static

- c. Plyometric
 - d. Concentric
21. What is the structure within a muscle cell that is formed by lining up sarcomeres end to end?
- a. Myofibrils
 - b. Fasciculi
 - c. Z lines
 - d. Sarcoplasmic reticulum
22. Which of the following types of muscle sensory receptor is responsive to force (tension) development by the muscle?
- a. Muscle spindles
 - b. Golgi tendon organs
 - c. Free nerve endings
 - d. Nociceptors
23. Which of the following is an example of a skeletal muscle adaptation that occurs in response to endurance training?
- a. Increased muscle fiber size
 - b. Decreased percentage of type I fibers
 - c. Increased number of myofibrils
 - d. Increased size and number of mitochondria
24. Which of the following types of receptors is sensitive to painful stimuli or chemicals?
- a. Nociceptors
 - b. Mechanoreceptors
 - c. Thermoreceptors
 - d. Golgi tendon organs
25. Which term refers to an increase in the number of muscle fibers within a muscle?
- a. Hypoplasia
 - b. Hypertrophy
 - c. Hyperplasia
 - d. Atrophy
26. Which of the following proteins link the Z lines of adjacent sarcomeres together?
- a. α -Actinin
 - b. Dystrophin
 - c. Nebulin
 - d. Desmin
27. What is the chemical that is found in the numerous synaptic vesicles located in the axon terminals of motor neurons?
- a. Epinephrine
 - b. Calcium
 - c. Acetylcholine
 - d. Norepinephrine
28. Which of the following factors is a major determinant of the velocity of muscle fiber shortening?
- a. The number of mitochondria within the muscle fiber
 - b. The type of myosin ATPase activity
 - c. The amount of calcium released from the sarcoplasmic reticulum
 - d. The size of the muscle fiber
29. Based on recent research, which of the following is the most likely cause of muscle fatigue during very-high-intensity exercise?
- a. H^+ ions from lactic acid
 - b. Depletion of muscle glycogen
 - c. Low blood glucose levels
 - d. Accumulation of inorganic phosphate within the muscle fiber

30. Which of the following statements most accurately represents muscle fiber type alterations with exercise training?
- Transitions from type IIX to type IIA occur with either aerobic training or strength training
 - Transitions from type IIX to type IIA occur with aerobic training, but not with strength training
 - Transitions from type IIA to type IIX occur with either aerobic training or strength training
 - Transitions from type IIA to type IIX occur with strength training, but not with aerobic training

REFERENCES

- Wong TS, Booth FW. Protein metabolism in rat tibialis anterior muscle after stimulated chronic eccentric exercise. *J Appl Physiol* 1990;69:1718–1724.
- Franzini-Armstrong C. The sarcoplasmic reticulum and the control of muscle contraction. *Faseb J* 1999;13(Suppl 2):S266–270.
- Lowey S, Waller GS, Trybus KM. Skeletal muscle myosin light chains are essential for physiological speeds of shortening. *Nature* 1993;365:454–456.
- Sweeney HL, Bowman BF, Stull JT. Myosin light chain phosphorylation in vertebrate striated muscle: regulation and function. *Am J Physiol* 1993;264:C1085–1095.
- Petrof BJ, Shrager JB, Stedman HH, Kelly AM, Sweeney HL. Dystrophin protects the sarcolemma from stresses developed during muscle contraction. *Proc Natl Acad Sci USA* 1993;90:3710–3714.
- Hoffman EP, Brown RH Jr, Kunkel LM. Dystrophin: the protein product of the Duchenne muscular dystrophy locus. *Cell* 1987;51:919–928.
- Enoka RM. Activation order of motor axons in electrically evoked contractions. *Muscle Nerve* 2002;25:763–764.
- Huxley AF, Niedergerke R. Structural changes in muscle during contraction: interference microscopy of living muscle fibres. *Nature* 1954;173:971–973.
- Kitamura K, Tokunaga M, Iwane AH, Yanagida T. A single myosin head moves along an actin filament with regular steps of 5.3 nanometres. *Nature* 1999;397:129–134.
- Peter JB, Barnard RJ, Edgerton VR, Gillespie CA, Stempel KE. Metabolic profiles of three fiber types of skeletal muscle in guinea pigs and rabbits. *Biochemistry* 1972;11:2627–2633.
- Brooke MH, Kaiser KK. Three “myosin adenosine triphosphatase” systems: the nature of their pH lability and sulfhydryl dependence. *J Histochem Cytochem* 1970;18:670–672.
- Brooke MH, Kaiser KK. Muscle fiber types: how many and what kind? *Arch Neurol* 1970;23:369–379.
- Smerdu V, Karsch-Mizrachi I, Campione M, Leinwand L, Schiaffino S. Type IIX myosin heavy chain transcripts are expressed in type IIB fibers of human skeletal muscle. *Am J Physiol* 1994;267:C1723–1728.
- Burke RE, Levine DN, Zajac FE 3rd. Mammalian motor units: physiological-histochemical correlation in three types in cat gastrocnemius. *Science* 1971;174:709–712.
- Buller AJ, Eccles JC, Eccles RM. Interactions between motoneurons and muscles in respect of the characteristic speeds of their responses. *J Physiol* 1960;150:417–439.
- Howald H, Hoppeler H, Claassen H, Mathieu O, Straub R. Influences of endurance training on the ultrastructural composition of the different muscle fiber types in humans. *Pflugers Arch* 1985;403:369–376.
- Pette D. Historical perspectives: plasticity of mammalian skeletal muscle. *J Appl Physiol* 2001;90:1119–1124.
- Pette D, Staron RS. Transitions of muscle fiber phenotypic profiles. *Histochem Cell Biol* 2001;115:359–372.
- Staron RS, Karapondo DL, Kraemer WJ, et al. Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. *J Appl Physiol* 1994;76:1247–1255.
- Esbjornsson M, Sylven C, Holm I, Jansson E. Fast twitch fibres may predict anaerobic performance in both females and males. *Int J Sports Med* 1993;14:257–263.
- Fry AC, Schilling BK, Staron RS, Hagerman FC, Hikida RS, Thrush JT. Muscle fiber characteristics and performance correlates of male Olympic-style weightlifters. *J Strength Cond Res* 2003;17:746–754.

22. Costill DL, Daniels J, Evans W, Fink W, Krahenbuhl G, Saltin B. Skeletal muscle enzymes and fiber composition in male and female track athletes. *J Appl Physiol* 1976;40:149–154.
23. Costill DL, Fink WJ, Pollock ML. Muscle fiber composition and enzyme activities of elite distance runners. *Med Sci Sports* 1976;8:96–100.
24. Rodriguez LP, Lopez-Rego J, Calbet JA, Valero R, Varela E, Ponce J. Effects of training status on fibers of the musculus vastus lateralis in professional road cyclists. *Am J Phys Med Rehabil* 2002;81:651–660.
25. Jansson E, Esbjornsson M, Holm I, Jacobs I. Increase in the proportion of fast-twitch muscle fibres by sprint training in males. *Acta Physiol Scand* 1990;140:359–363.
26. Baumann H, Jaggi M, Soland F, Howald H, Schaub MC. Exercise training induces transitions of myosin isoform subunits within histochemically typed human muscle fibres. *Pflugers Arch* 1987;409:349–360.
27. Lieber RL. *Skeletal Muscle Structure, Function, and Plasticity: The Physiological Basis of Rehabilitation*. 2nd ed. Baltimore: Lippincott Williams & Wilkins; 2002.
28. Bottinelli R, Canepari M, Reggiani C, Stienen GJ. Myofibrillar ATPase activity during isometric contraction and isomyosin composition in rat single skinned muscle fibres. *J Physiol* 1994;481(Pt 3):663–675.
29. Nardone A, Romano C, Schieppati M. Selective recruitment of high-threshold human motor units during voluntary isotonic lengthening of active muscles. *J Physiol* 1989;409:451–471.
30. Milner-Brown HS, Stein RB, Yemm R. The contractile properties of human motor units during voluntary isometric contractions. *J Physiol* 1973;228:285–306.
31. Semmler JG, Nordstrom MA. Motor unit discharge and force tremor in skill- and strength-trained individuals. *Exp Brain Res* 1998;119:27–38.
32. Yao W, Fuglevand RJ, Enoka RM. Motor-unit synchronization increases EMG amplitude and decreases force steadiness of simulated contractions. *J Neurophysiol* 2000;83:441–452.
33. Semmler JG. Motor unit synchronization and neuromuscular performance. *Exerc Sport Sci Rev* 2002;30:8–14.
34. Stackhouse SK, Reisman DS, Binder-Macleod SA. Challenging the role of pH in skeletal muscle fatigue. *Phys Ther* 2001;81:1897–1903.
35. Westerblad H, Allen DG, Lannergren J. Muscle fatigue: lactic acid or inorganic phosphate the major cause? *News Physiol Sci* 2002;17:17–21.
36. Bird SR, Wiles J, Robbins J. The effect of sodium bicarbonate ingestion on 1500-m racing time. *J Sports Sci* 1995;13:399–403.
37. Goldfinch J, McNaughton L, Davies P. Induced metabolic alkalosis and its effects on 400-m racing time. *Eur J Appl Physiol Occup Physiol* 1988;57:45–48.
38. Wilkes D, Gledhill N, Smyth R. Effect of acute induced metabolic alkalosis on 800-m racing time. *Med Sci Sports Exerc* 1983;15:277–280.
39. Ivy JL. Role of carbohydrate in physical activity. *Clin Sports Med* 1999;18:469–484.
40. Jacobs KA, Sherman WM. The efficacy of carbohydrate supplementation and chronic high-carbohydrate diets for improving endurance performance. *Int J Sport Nutr* 1999;9:92–115.
41. Friden J, Sjostrom M, Ekblom B. Myofibrillar damage following intense eccentric exercise in man. *Int J Sports Med* 1983;4:170–176.
42. Morgan DL. New insights into the behavior of muscle during active lengthening. *Biophys J* 1990;57:209–221.
43. Friden J. Delayed onset muscle soreness. *Scand J Med Sci Sports* 2002;12:327–328.
44. Lieber RL, Friden J. Morphologic and mechanical basis of delayed-onset muscle soreness. *J Am Acad Orthop Surg* 2002;10:67–73.
45. Crenshaw AG, Karlsson S, Styf J, Backlund T, Friden J. Knee extension torque and intramuscular pressure of the vastus lateralis muscle during eccentric and concentric activities. *Eur J Appl Physiol Occup Physiol* 1995;70:13–19.
46. Crenshaw AG, Thornell LE, Friden J. Intramuscular pressure, torque and swelling for the exercise-induced sore vastus lateralis muscle. *Acta Physiol Scand* 1994;152:265–277.
47. Lieber RL, Thornell LE, Friden J. Muscle cytoskeletal disruption occurs within the first 15 min of cyclic eccentric contraction. *J Appl Physiol* 1996;80:278–284.
48. Evans WJ, Meredith CN, Cannon JG, et al. Metabolic changes following eccentric exercise in trained and untrained men. *J Appl Physiol* 1986;61:1864–1868.
49. Newham DJ, Jones DA, Clarkson PM. Repeated high-force eccentric exercise: effects on muscle pain and damage. *J Appl Physiol* 1987;63:1381–1386.
50. Mishra DK, Friden J, Schmitz MC, Lieber RL. Anti-inflammatory medication after muscle injury. A treatment resulting in short-term improvement but subsequent loss of muscle function. *J Bone Joint Surg Am* 1995;77:1510–1519.
51. Allbrook D. Skeletal muscle regeneration. *Muscle Nerve* 1981;4:234–245.

52. Schultz E. Satellite cell behavior during skeletal muscle growth and regeneration. *Med Sci Sports Exerc* 1989;21:S181–186.
53. Russell B, Dix DJ, Haller DL, Jacobs-El J. Repair of injured skeletal muscle: a molecular approach. *Med Sci Sports Exerc* 1992;24:189–196.
54. Vierck J, O'Reilly B, Hossner K, et al. Satellite cell regulation following myotrauma caused by resistance exercise. *Cell Biol Int* 2000;24:263–272.
55. Holloszy JO, Booth FW. Biochemical adaptations to endurance exercise in muscle. *Annu Rev Physiol* 1976;38:273–291.
56. Hawley JA. Adaptations of skeletal muscle to prolonged, intense endurance training. *Clin Exp Pharmacol Physiol* 2002;29:218–222.
57. Hoppeler H, Fluck M. Plasticity of skeletal muscle mitochondria: structure and function. *Med Sci Sports Exerc* 2003;35:95–104.
58. Tesch PA, Larsson L. Muscle hypertrophy in bodybuilders. *Eur J Appl Physiol Occup Physiol* 1982;49:301–306.
59. Dudley GA, Tesch PA, Miller BJ, Buchanan P. Importance of eccentric actions in performance adaptations to resistance training. *Aviat Space Environ Med* 1991;62:543–550.
60. Tesch PA, Thorsson A, Essen-Gustavsson B. Enzyme activities of FT and ST muscle fibers in heavy-resistance trained athletes. *J Appl Physiol* 1989;67:83–87.
61. Tesch PA. Skeletal muscle adaptations consequent to long-term heavy resistance exercise. *Med Sci Sports Exerc* 1988;20:S132–134.
62. Lemon PW, Berardi JM, Noreen EE. The role of protein and amino acid supplements in the athlete's diet: does type or timing of ingestion matter? *Curr Sports Med Rep* 2002;1:214–221.
63. Wolfe RR. Protein supplements and exercise. *Am J Clin Nutr* 2000;72:551S–557S.
64. McCall GE, Byrnes WC, Dickinson A, Pattany PM, Fleck SJ. Muscle fiber hypertrophy, hyperplasia, and capillary density in college men after resistance training. *J Appl Physiol* 1996;81:2004–2012.
65. Antonio J, Gonyea WJ. Skeletal muscle fiber hyperplasia. *Med Sci Sports Exerc* 1993;25:1333–1345.
66. Antonio J, Gonyea WJ. Progressive stretch overload of skeletal muscle results in hypertrophy before hyperplasia. *J Appl Physiol* 1993;75:1263–1271.
67. Antonio J, Gonyea WJ. Muscle fiber splitting in stretch-enlarged avian muscle. *Med Sci Sports Exerc* 1994;26:973–977.
68. Alway SE, Winchester PK, Davis ME, Gonyea WJ. Regionalized adaptations and muscle fiber proliferation in stretch-induced enlargement. *J Appl Physiol* 1989;66:771–781.
69. Gonyea WJ, Sale DG, Gonyea FB, Mikesky A. Exercise induced increases in muscle fiber number. *Eur J Appl Physiol Occup Physiol* 1986;55:137–141.
70. Larsson L, Tesch PA. Motor unit fibre density in extremely hypertrophied skeletal muscles in man. Electrophysiological signs of muscle fibre hyperplasia. *Eur J Appl Physiol Occup Physiol* 1986;55:130–136.
71. MacDougall JD, Sale DG, Elder GC, Sutton JR. Muscle ultrastructural characteristics of elite powerlifters and bodybuilders. *Eur J Appl Physiol Occup Physiol* 1982;48:117–126.
72. Gaitanos GC, Williams C, Boobis LH, Brooks S. Human muscle metabolism during intermittent maximal exercise. *J Appl Physiol* 1993;75:712–719.
73. Bogdanis GC, Nevill ME, Boobis LH, Lakomy HK. Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. *J Appl Physiol* 1996;80:876–884.
74. Bogdanis GC, Nevill ME, Lakomy HK, Boobis LH. Power output and muscle metabolism during and following recovery from 10 and 20 s of maximal sprint exercise in humans. *Acta Physiol Scand* 1998;163:261–272.
75. McCartney N, Spriet LL, Heigenhauser GJ, Kowalchuk JM, Sutton JR, Jones NL. Muscle power and metabolism in maximal intermittent exercise. *J Appl Physiol* 1986;60:1164–1169.
76. Ross A, Leveritt M. Long-term metabolic and skeletal muscle adaptations to short-sprint training: implications for sprint training and tapering. *Sports Med* 2001;31:1063–1082.
77. MacDougall JD, Hicks AL, MacDonald JR, McKelvie RS, Green HJ, Smith KM. Muscle performance and enzymatic adaptations to sprint interval training. *J Appl Physiol* 1998;84:2138–2142.
78. Dawson B, Fitzsimons M, Green S, Goodman C, Carey M, Cole K. Changes in performance, muscle metabolites, enzymes and fibre types after short sprint training. *Eur J Appl Physiol Occup Physiol* 1998;78:163–169.
79. Chromiak JA, Mulvaney DR. The effects of combined strength and endurance training on strength development. *J Appl Sport Sci Res* 1990;4:55–60.

80. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol* 1980;45:255–263.
81. Hickson RC, Rosenkoetter MA, Brown MM. Strength training effects on aerobic power and short-term endurance. *Med Sci Sports Exerc* 1980;12:336–339.
82. Ortenblad N, Lunde PK, Levin K, Andersen JL, Pedersen PK. Enhanced sarcoplasmic reticulum Ca(2+) release following intermittent sprint training. *Am J Physiol Regul Integr Comp Physiol* 2000;279:R152–160.
83. Cadefau J, Casademont J, Grau JM, et al. Biochemical and histochemical adaptation to sprint training in young athletes. *Acta Physiol Scand* 1990;140:341–351.
84. Simoneau JA, Lortie G, Boulay MR, Marcotte M, Thibault MC, Bouchard C. Human skeletal muscle fiber type alteration with high-intensity intermittent training. *Eur J Appl Physiol Occup Physiol* 1985;54:250–253.
85. Dudley GA, Djamil R. Incompatibility of endurance- and strength-training modes of exercise. *J Appl Physiol* 1985;59:1446–1451.
86. Kraemer WJ, Patton JF, Gordon SE, et al. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol* 1995;78:976–989.
87. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, Foster C. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol* 1988;25:191–200.
88. Millet GP, Jaouen B, Borrani F, Candau R. Effects of concurrent endurance and strength training on running economy and VO(2) kinetics. *Med Sci Sports Exerc* 2002;34:1351–1359.
89. Johnston RE, Quinn TJ, Kertzer R, Voman NB. Strength training in female distance runners: impact on running economy. *J Strength Cond Res* 1997;11:224–229.
90. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol* 1999;86:1527–1533.
91. Tanaka H, Swensen T. Impact of resistance training on endurance performance. A new form of cross-training? *Sports Med* 1998;25:191–200.
92. Hawley J, Burke L. Peak Performance. Training and Nutritional Strategies for Sport. St. Leonards, Australia: Allen & Unwin; 1998.
93. Burgomaster KA, Hughes SC, Heigenhauser GJ, Bradwell SN, Gibala MJ. Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *J Appl Physiol* 2005;98:1985–1990.
94. Gibala MJ, Little JP, van Essen M, Wilkin GP, Burgomaster KA, Safdar A, Raha S, Tarnopolsky MA. Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *J Physiol* 2006;575:901–911.



<http://www.springer.com/978-1-58829-611-5>

Essentials of Sports Nutrition and Supplements

Antonio, J.; Kalman, D.; Stout, J.R.; Greenwood, M.;

Willoughby, D.S.; Haff, G.G. (Eds.)

2008, XVII, 691 p., Hardcover

ISBN: 978-1-58829-611-5

A product of Humana Press