Chapter 3

Muscle Physiology

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The muscular system is comprised of three types of muscle tissue: **skeletal**, **cardiac** and **smooth**. Each performs specialized functions within the body. Skeletal muscle acts on the skeleton to maintain posture, create voluntary movement, manage force transfer, and prevent undesirable body actions. The cardiac muscle tissue, located only in the heart, pushes blood through the circulatory system. Smooth muscle comprises the muscular walls of blood vessels as well as the gastrointestinal tract, which includes the esophagus, stomach, small intestine, large intestine, and rectum. Smooth muscle moves fluids and solids, dilates and constricts small arteries, and performs a variety of other functions to help keep the body in a state of balance. For the purposes of personal training, this chapter will focus on the functions and adaptations of skeletal muscle.

How Muscles Contract

To produce the internal tensile and compression forces described in Chapter 2, skeletal muscle must contract. To do so, the body requires multiple systems to work concurrently and synergistically. Using signals primarily initiated in the brain, the nervous system stimulates the muscle, causing it to contract and produce tension. If the force requirements are ongoing, the muscle needs a continuous supply of energy and blood. In Chapter 1, we learned that the epimysium and perimysium (interwoven muscle layers) contain the nerves and blood vessels that support muscular contraction and the production of force. These networks are extremely important, as they carry the motor information via **action potentials** from the **central nervous system** and allow the vascular system to deliver energy and oxygen and remove by-product waste produced from the metabolic production of energy. The peripheral nervous system and vascular system run together through the muscle tissue, branching into smaller units all the way down to the muscle fiber, where capillaries and nerve fibers interact with the contractile proteins.

The muscle fiber is arranged like a small factory, with each structure serving a particular function to create contractile tension. Working from the inside out, the myofibrils are cylindrical structures that contain the myofilaments actin (thin filament) and myosin (thick filaments). These protein filaments are where the contractile action of the sliding filament theory takes place. This process will be explained in the next paragraph. Surrounding the myofibrils are a calcium housing network called the **sarcoplasmic reticulum** (SR), tube-like structures called **T-tubules** used to transfer nerve signals, and **mitochondria**, which will eventually be used to produce energy. The whole package is encased by the muscle fiber’s cell membrane called the **sarcolemma**. The muscle fibers are encased by the **endomysium** which is where the capillaries and nerve endings are located.

If the body needs to create tension in a group of muscle fibers, a signal is initiated in the brain called an action potential. The action potential travels via electrical current through the spinal cord and is then transferred to the peripheral nervous system. The current runs through the outer levels of the muscle tissue to very small nerve
fibers, which connect to the particular fibers to be contracted. These small nerve fibers are called motor neurons. Together, the motor neuron and all the muscle fibers it innervates are called the motor unit. Within the motor unit, the motor neuron extends branches of individual nerve fibers to individual muscle fibers. The action potential enters the individual muscle fibers at the neuromuscular junction, formed by the end of the nerve fiber and sarcolemma. Here, it stimulates the sarcolemma via an electrically-gated channel. This connection between the nerve and the muscle fiber is called an excitation-couple. The excitation-couple acts as a bridge between the nerve and the muscle, allowing the electrical impulse to jump from the nerve fiber to the muscle fiber.

Inside the muscle fiber, the action potential travels down the T-tubules and stimulates the sarcoplasmic reticulum. This initiates the contraction cycle by releasing calcium from the SR. In a relaxed state, the muscle fiber protein filaments inside the sarcomere are blocked from interacting with each other by a protein complex consisting of troponin and tropomyosin. Calcium released from the SR acts like a key to unlock the bond between the thin actin contractile filament and troponin via a conformation change of the troponin molecule. When the calcium unlocks the bond, the troponin molecule moves, rotating the tropomyosin molecule out of the way of the binding site just like opening a door. When this occurs myosin is free to attach to actin by what is referred to as a cross bridge attachment. At the myosin/actin attachment site, adenosine triphosphate (ATP) is split, and the energy released allows the muscle fiber to contract and produce force. This complex chain of interactions, allowing the actin and myosin filament proteins to slide over each other, is known as the sliding filament theory.

The movement of the myosin head resembles the movement of an oar when rowing a boat. In the same way the oar enters the water, gets pulled across the surface of the water, and is pulled out before being repositioned for the next rowing cycle, the myosin head attaches, pulls, detaches, re-cocks, and starts the process again. If the excitation is maintained and adequate ATP exists, this process can be repeated up to five times per second. The amount of tension produced is proportionate to the number of active cross bridges along a myofibril’s length.

**Force Production**

A muscle fiber is either in a state of producing maximum tension or not producing any tension at all. This is often referred to as the “all or none” principle. This suggests that the tension produced by a muscle is dependent on the number of fibers stimulated and the frequency of the stimulation. When a muscle fiber is stimulated through a single contraction-relaxation cycle, it is called a twitch. The duration of a twitch is dependent upon the fiber producing the action. Fibers are generally defined as one of two types, fast twitch or slow switch. Fast twitch fibers obviously twitch quickly (10 milliseconds), whereas slow twitch fibers take more time to complete the contraction-relaxation cycle (100 milliseconds) (5). Twitches in a skeletal muscle do not accomplish anything useful. It takes sustained muscle contractions to perform normal movements. Sustained muscle contractions occur when the rate of stimulation is increased to the point that there is no longer a relaxation phase. This is called complete tetanus, and is necessary for muscle contractions to produce force. Normal muscle contractions occur due to complete tetanus.

To produce significant tension to accomplish movement, motor units are stimulated within the desired muscle. The greater the number of motor units stimulated, the more fibers are recruited and
Muscle tone occurs because some of the motor units are always active even when the muscle is not contracted. The motor unit activation does not produce enough tension to cause movement but provides tone or firmness to the tissue. The degree of tone is dependent upon the tension created and number of motor units firing to stabilize the position of the bones and joints. The motor units are stimulated in varying patterns to prevent fatigue. When external forces act on the body, the tension in the tissue provides data to the nervous system via proprioceptors, which better enables the skeletal muscle and tendons to function in response to a sudden change in tension or body position (16). Specialized intrafusal fibers called muscle spindles aid in this response by helping the tissue manage forces (13).

Muscle spindles are clusters of specialized muscle tissue (intrafusal fibers) that lie parallel to the normal muscle fibers (extrafusal fibers) (15). The intrafusal fibers relay information to sensory neurons regarding changes in the tissue length and tension. When stretched, these tissues respond using reflex action, called the stretch reflex, to initiate a stronger contraction to reduce the imposed stretch in a shock absorbing fashion. The excitatory impulses activate agonist muscles to contract and antagonist muscles to relax in a process of rapid self-regulation. Recalling from Chapter 1, agonist/antagonist muscles are those that cause opposite movement trajectories across a joint, exemplified by the bicep and tricep muscles at the elbow joint. As the bicep muscle contracts, the triceps muscle must relax and vice versa. The reflex action aids in automatic tone adjustment which supports control of body position and posture. Because it is a reflex, the process does not require input from the brain, but rather, occurs at the level of the spinal cord, allowing for immediate compensatory adjustments during activities requiring balance and coordination. The constant supply of information from the muscle spindles through the stretch reflex is fundamental to mechanisms for neuromuscular regulation (3).

Golgi tendon organs complement muscle spindles in regulating the muscle and connective tissue tension (8). The Golgi tendons are tiny sensory receptors which exist inside the muscle tendons. They rapidly communicate information to the motor neurons in the muscles they serve to prevent excessive tension that could be potentially dangerous to the tissues’ integrity. If tension becomes too great, the Golgi tendon organs send inhibitory signals to reduce motor neuron activity and thereby reduce the force of muscular contraction. By inhibiting tension in the muscle the Golgi tendons serve to prevent tissue injury that would likely occur from the excessive tension. An example of this process occurs in the masseter muscle. Contraction of the masseter muscle causes closure of the jaw bone when one chews. The masseter muscle is capable of producing enough force in the jaw to cause fracturing of the teeth. However, the golgi tendon organs in the masseter musculotendon sense the amount of tension in the muscle and prevent the muscle from attaining this level of force, preventing damage to the teeth.

subsequently, the more tension that is produced. The total force exerted by a skeletal muscle is a factor of how many muscle fibers are recruited for the contraction. Peak tension occurs when all the motor units in the muscle are contracting in complete tetanus.

Motor units generally work in a tag team fashion because most work is not performed under peak tension. When maximal outputs are required, all the motor units are recruited at a high rate to produce tension. This level of tension can only occur for a short period of time. The muscle starts to fatigue and peak tension is reduced. When activities require force for prolonged periods, the motor units take turns firing, so some fibers recover while others work. This phenomenon suggests that firing patterns are specific to the demand of the activity (6). High output demands use synchronized firing of fast twitch fibers and high number recruitment patterns, whereas endurance activity uses asynchronous firing patterns of slow twitch fibers which are fatigue resistant to conserve motor unit potential, thereby allowing for longer periods of sustained work.

Muscle force potential as it relates to the motor unit is analogous to a crew team rowing a boat. We have identified that a muscle’s peak tension requires sustained tetanus, or the sustained firing of all muscle fibers recruited. This is analogous to everyone on a crew team rowing at a nonstop rate. The more teammates who contribute and the faster they row, the more force they will produce to move the boat across the water. The same idea applies to force production in muscle tissue. The more muscle tissue recruited, the more force potential of the contraction. Similarly, if one can get the rowers to row faster (increased firing rate) the boat will accelerate due to greater force production. If the firing rate in the motor neurons increases so does the resultant force of the muscle contraction. If all of the rowers are recruited to put forth an effort (increased recruitment) and they are coordinated to row at precisely the same time (improved synchronicity) you will attain the best performance and fastest boat speed. The motor unit works the same way. With training, the fibers are more efficiently recruited, firing rates of the motor units are enhanced, and the firing rates occur in
unison, creating synchronized tension and greater force outputs. It is an important concept to understand that all of these actions are functions of the nervous system, which becomes more efficient with training experience. The ability to increase force production within a muscle through training is dependent on adaptations that occur to both the muscle fibers and the nervous system together (1).

The example of the crew team rowing a boat explains improvements in maximal tension development. But what if the rowers want to travel long distances rather than moving at an extremely fast rate? In this case, it would make more sense for the rowers to use an alternating rowing pattern and slower stroke. If two rowers perform a synchronized stroke and then recover while two other rowers perform their stroke in an alternating fashion, the boat’s momentum will be maintained without any particular rower becoming overly fatigued. This illustrates the motor unit pattern for endurance activities described above. The more synchronized the stroke patterns and rest to work activity ratio, the more efficiently the action will be performed.

Fatigue

The ability to maintain muscle tension is dependent upon several factors, with the most notable being the intensity of the exercise (9). The more force needed, the faster the rate of fatigue. Muscle fatigue results from disruption somewhere along the chain of events in the production of force. Fatigue is defined by an inability to contract despite continued neural stimulation. The cause of fatigue can occur in the central nervous system, peripheral nervous system, at the neuromuscular junction, or in the muscle fiber itself (14). Since the fatigue is intensity-specific, the particular cause will be reflective of the activity. Short-term, high force activities cause neuromuscular fatigue due to several possible mechanisms listed below. During prolonged activities with less force output, the cause of fatigue is most often attributed to the energy supply. Muscle fatigue is cumulative, so as fibers fatigue, they disrupt the motor unit’s ability to produce the force necessary to continue the activity at the current rate. As the rate of motor unit fatigue increases, the effect becomes more pronounced, causing performance to decline proportionate to the level of fatigue (4).

Periods of recovery enable a working tissue to avoid fatigue for longer periods of time. This is evidenced by the alternating recruitment patterns used during prolonged activities. In short burst activity, the muscles perform at peak or near peak levels, which leads to rapid fatigue.

~Key Terms~

**Skeletal muscle**- A type of striated muscle, attached to the skeleton used to facilitate movement, by applying force to bones and joints via contractions.

**Cardiac muscle**- A type of involuntary mononucleated, or uninucleated, striated muscle found exclusively within the heart.

**Smooth muscle**- A type of non-striated muscle, found within the "walls" of hollow organs such as the bladder, the uterus, and the gastrointestinal tract. It also lines the lumen of the body, such as in blood vessels. Smooth muscle is fundamentally different from skeletal muscle and cardiac muscle in terms of structure and function.

**Capillaries**- Tiny blood vessels throughout the body that connect arteries and veins. Capillaries form an intricate network around body tissues in order to distribute oxygen and nutrients to the cells and to remove waste substances.

**Sarcoplasmic reticulum**- A tubular network that surrounds each individual myofibril and acts as a storage site for calcium within the skeletal muscle.
When the action is temporarily discontinued, the muscle fiber attempts to return to pre-exertion levels. The period of time between repeated actions, such as a sprint or squat performance, is called the rest period or rest interval. During this period of time, the muscle cell’s recovery is dependent upon the return of intracellular energy supply, circulatory based cellular by-product removal, and the delivery of oxygen. When the exercise bout is completely discontinued, the cell has a much longer period of time to manage the disruption caused by the activity. This is referred to as the recovery period. During the recovery period, the muscle fibers can rebuild their energy reserves, fix any damage resulting from the production of force, and fully return to normal pre-exertion levels. The duration of the recovery period required to return the cell back to normal depends upon the degree that the muscle fiber was used (7). In cases of sustained high-level output, full recovery may take as long as one week (2). Recovery between exercise bouts is an important consideration in the exercise prescription.

**Types of Muscle Contractions**

The muscle contractions produced by the stimulation of motor units contribute to different internal forces within the body. These contractions are categorized by the actions they produce. A tonic action, during which a lengthening or shortening occurs within the muscle, is called an isotonic contraction. The term isotonic is derived from the Greek *isotonos* (*iso*, meaning equal, and *tonos*, meaning tension). This term is generally used inexacty when describing dynamic muscle actions because the muscle’s effective force production across the joint changes through the movement and is not uniform. These types of contractions are visible in all movements. The shortening phase, called the concentric phase of the contraction, occurs when muscle tension force exceeds the resistance force applied to it, so positive work is attained.

This can be demonstrated with a bicep curl. As the bicep muscle contracts concentrically, the elbow flexes. When the arm returns to the start position of the curl movement, the bicep lengthens as a result of the muscle producing less tension than is necessary to accelerate the resistance in the direction of the force. When the muscle lengths under tension, it produces an eccentric contraction to perform negative work. **Concentric contractions** accelerate joint movements, while eccentric contractions decelerate movements.

If the tension created to accelerate force is equal to the resistance force no movement will occur. Although the motor units fire, the tension in the muscle is insufficient to accelerate the object in the direction of the force. This type of contraction is called an **isometric contraction**. The joint angle does not change even though the attached musculature exerts force. Isometric contractions are not commonly employed in training programs to strengthen prime movers. However, any time the body performs a movement, isometric contractions are necessary. Isometric contractions are used by stabilizing muscles to control movements and prevent undesirable actions of the body. When the body is in a stationary position, for example, the muscles acting on the skeleton must contract isometrically to prevent it from collapsing under the pull of gravity. The same types of contractions maintain posture and joint position during dynamic activities, such as the isometric contractions of the abdominals during the performance of a push-up. In effect, we use and train with isometric contractions all of the time, as they contribute to stability.

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~**Key Terms**~

**T-tubules**- The tubule that passes in a transverse manner from the sarcolemma across a myofibril of striated muscle, allowing depolarization of the membrane to quickly penetrate to the interior of the cell.

**Sarcolemma**- A thin polarized membrane enclosing a striated muscle fiber.

**Endomysium**- The fine connective tissue sheath surrounding a muscle fiber.

**Action potential**- The wave-like change in the electrical properties of a cell membrane, resulting from the difference in electrical charge between the inside and outside of the membrane, causing the muscle cell to contract.
**Muscle Fiber Types**

The type of muscle fiber recruited to produce a contraction depends upon the amount of force needed for the desired action. Muscle fibers and their respective motor units are classified by their physiologic and mechanical properties. These properties include the fiber contractile speed or twitch characteristics, force output or tension generating capacity, and ability to resist fatigue. The particular characteristics gear the motor units for either power or endurance. Motor units are either classified as fast-twitch fast-fatigue, fast-twitch fatigue-resistant, or slow-twitch fatigue-resistant. Consistent with the motor unit classification categories there are three skeletal muscle fiber types. The fiber type classifications are sometimes expressed using type distinction abbreviations or labeled according to the energy system they prefer to utilize. The high force producing fibers are called **Type IIb fibers** or fast glycolytic fibers (FG). The intermediate force producing fibers are called **Type IIa fibers** or fast oxidative/glycolytic fibers (FOG). The low power output fibers are called **Type I** or slow oxidative fibers (SO). The glycolytic or oxidative annotation refers to the type of energy source utilized to generate ATP by the muscle fiber and is described in detail in Chapter 5.

Fast twitch fibers are recognized by their characteristically large diameter size, densely packed myofibrils and large glycogen (consolidated sugar molecules for energy) reserves. They are preferentially recruited for activities requiring high power outputs and are subject to dramatic improvements in size and strength when trained under conditions of short duration and high intensity. They preferentially function using **anaerobic** metabolic systems. On the other end of the spectrum, the slow twitch muscle fibers are 50% smaller than their fast twitch counterparts and produce peak force at one third the rate upon stimulation. They primarily use **aerobic** metabolic systems and are far better suited for endurance, containing an extensive capillary network and high mitochondrial density. They also have the addition of a notably higher amount of myoglobin, which increases oxygen reserves in the cell. These characteristics make it ideal for activities of prolonged duration.

When an activity requires the combination of elevated force and prolonged duration, the intermediate fibers, Type IIA, become favored. Due to the fact that these fibers maintain properties of both fast and slow fibers, they are well suited to support both anaerobic and aerobic activities. Intermediate fibers are classified as fast twitch fibers because they contain small quantities of **myoglobin**. But, like the slow-twitch fibers, they have an extensive blood supply and are more resistant to fatigue.

In the previous section, we identified that the motor recruitment patterns were based on the tension demands of the muscle. This identifies the fact that the fiber types selected for activation depend upon the speed and magnitude of the tension required for the activity.

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**Key Terms**

**Neuromuscular junction** - The site at which nerve impulses are transmitted to muscles.

**Sarcomere** - Smallest functional unit of a muscle fiber, composed of contractile myofilaments.

**Troponin** - A protein complex found in both skeletal muscle and cardiac muscle that relays calcium sensitivity to muscle cells.

**Tropomyosin** - A group of muscle proteins that bind to molecules of actin and troponin to regulate the interaction of actin and myosin.

**Motor unit** - A motor neuron and all of the corresponding muscle fibers it innervates.
Slow-twitch fibers do not generate tension quickly, so they cannot meet the demand of high power output activities and are therefore selected to serve low level activities of varying force requirements. Activities such as jogging, cycling, and slow speed, light weight lifting involve selective recruitment of the slow-twitch fibers. When the activities are fast and powerful, the selective recruitment adds fast-twitch fibers for a greater magnitude of force production. During activities of varying intensity, such as those found with soccer, basketball, and interval training, slow twitch fibers serve the lower force outputs aerobically, while fast-twitch fibers dominate the high intensity anaerobic segments of the activity. The recruitment patterns match the fiber characteristics.

**Fiber Type Distribution**

Fiber type distribution is genetically predetermined, so no method exists to manipulate how the fibers are proportionately concentrated in the body. The distribution of fiber types within a particular skeletal muscle can be quite variable. Although certain muscles, such as those used primarily for posture, maintain higher concentrations of slow-twitch fibers. These muscles, including the soleus, deep muscles of the back, and the rectus abdominis must contract continuously to maintain upright posture. They are not designed for rapid, high force output, and therefore experience limited improvements in activities aimed at power or hypertrophy.

It has been said, “you don’t pick your sport, your sport picks you” suggesting that certain people are designed to succeed in a particular sport, whereas others are not. Fiber type distribution plays a role in this determination. As would be expected, muscle biopsies demonstrate that individuals who perform well in sprint or burst power activities have higher concentrations of fast-twitch fibers in the respective prime mover muscles necessary for their activity. Endurance athletes show higher concentrations of slow-twitch fibers in these same muscle groups. If a highly trained sprinter and marathoner switched roles for a day, neither would be very successful in the other’s event. Although training in a particular event will certainly cause anyone to improve in the activity, practice alone is not enough for a person to reach an elite status. Genetic predisposition is a powerful factor. Ultimately, the percentage of any particular fiber type within a muscle is based on the role of the tissue in movement and the genetically determined distribution pattern assigned to the muscle.

Among individuals in similar sports, distinctions in performance advantage by muscle fiber type distribution seem to be specific to the most elite athletes. However, fiber distribution patterns determine only a component of performance capacity. Although they do provide an advantage in activities that match the fiber-specific characteristics, they do not define performance outcomes because measurable performance is based on the blend of many physiological systems.

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**~Key Terms~**

**Adenosine Triphosphate (ATP)**- Serves as the major energy source within a cell to drive a number of biological processes such as muscle contractions and the synthesis of proteins.

**Cross bridge**- A myosin head that projects from the surface of the thick filament that binds to the surface of a thin filament (actin) in the presence of calcium ions.

**Complete tetanus**- Sustained skeletal muscle contraction due to repeated stimulation at a frequency which prevents relaxation.

**Muscle tone**- Unconscious nerve impulses that maintain the muscles in a partially contracted state.

**Muscle spindles**- A specialized muscle structure innervated by both sensory and motor neuron axons, functioning to send proprioceptive information about the muscle to the central nervous system in response to muscle stretching.

**Golgi tendon organs**- Kinesthetic receptors situated near the junction of muscle fibers and tendons which act as muscle-tension regulators.

**Concentric contraction**- A type of muscle contraction in which the muscles apply enough force to overcome the resistive force so that it shortens as it contracts.
Training for an activity will cause improvements in many of the physiological systems that affect the performance outcome. In response to the training stress, several components of the motor unit adapt to become better suited to the conditions. The motor units begin to more closely reflect the desired skeletal tissue type through modifications in properties and characteristics. The actual fiber type, however, does not change. In humans a slow-twitch fiber has not been shown to convert to a fast-twitch fiber and vice versa. Changes in patterns of neural stimulation, capillary and mitochondrial density, and enzyme concentration cause the muscle fiber to become better suited to the training stimulus (11). This fact is exemplified by the changes in performance with training.

Although a person may not be born with a muscle fiber type distribution that is best suited for a given activity, through specific training, they can cause changes in the recruitment pattern and muscle fibers that allow them to improve their performance despite their genetic predisposition (10).

All of the information regarding recruitment and fiber characteristics is relevant when creating the exercise prescription. Matching the stimulus to the desired adaptation response is pivotal to successful exercise programming. For instance, increasing strength and muscular size is dependent upon the magnitude and rate of the stimulus. Without employing appropriate methods to maximize these factors, the end adaptation response will be compromised to the degree that the exercise prescription is in error. This is true of any program that does not properly consider the energy system, recruitment patterns, and characteristics of the muscle involved.

**Key Terms**

**Eccentric contraction-** A type of muscle contraction in which the resistive force is greater than the force applied by the muscle so that the muscle lengthens as it contracts.

**Isometric contraction-** A contraction in which muscle tension is increased, but the joint angle is not changed because the resistance cannot be overcome. Also known as static contraction.

**Type IIb fibers-** Largest diameter muscle fiber, characterized by anaerobic metabolism and the greatest maximum tension.

**Type IIa fibers-** Large diameter muscle fiber, characterized by aerobic and anaerobic metabolism. High maximum tension.

**Type I fibers-** Smaller diameter muscle fiber characterized by aerobic metabolism and lower maximum tension.

**Myoglobin-** The oxygen-transporting protein of muscle, resembling blood hemoglobin in function.
Chapter Three References


