CHAPTER 2

Skeletal Muscle Physiology and Its Application to Occupational Ergonomics

Robert G. Cutlip and Sharon S. Chiou

CONTENTS

2.1 INTRODUCTION

In the United States, work-related musculoskeletal disorders account for approximately 38% of cases involving days away from work [1], thus making it an enormous economic and health care burden. A large component in musculoskeletal disorders is acute and chronic contraction-induced skeletal muscle injury [2]. In order to address this issue, there have been extensive studies to-date on acute contraction-induced muscle injury using both animals and humans. Occupationally related musculoskeletal disorders have been associated with exposure to excessive physical loads, repetitive movements, awkward postures, and vibration [3]. A number of different tissues, including skeletal muscles, can be injured by exposure to these various factors [3]. To understand how exposure to these factors results in muscle injury, it is necessary to understand the biological and physiological mechanisms that allow skeletal muscles to generate movement, maintain posture, and support loads. The goal of this chapter is to provide a basic description of skeletal muscle physiology, injury mechanics, and motor control with application to occupational musculoskeletal disorders.

2.2 MUSCLE PHYSIOLOGY AND ANATOMY

Individual skeletal muscles are comprised of bundles of muscle cells or myofibers (Figure 2.1). Each myofiber is surrounded by a collagenous basement membrane (basal lamina) in addition to a cellular membrane called the sarcolemma. Myofibers are similar to other cells in the body, but they have a couple of unique features. First, myofibers contain a modified endoplasmic reticulum called a sarcoplasmic reticulum (SR). The SR functions as a protein processing and distribution organelle, and it regulates the levels of free intracellular calcium (Ca^{2+}) within the myofiber. Second, most of the intracellular space within the myofiber comprises the contractile elements or myofibrils (80% of a muscle's volume) (Figures 2.1 and 2.2). Each myofibril comprises thick and thin filaments. Each thick filament (12–18 nm diameter) is composed of several hundred myosin proteins. Within the thick filaments, each myosin protein has a projection or a globular head. These globular heads have binding sites that can interact with and form crossbridges with the thin filaments, and an ATPase binding site. Thin filaments (5–8 nm diameter) are made of actin molecules that are organized in two strands twisted together to form a helix, that are covered by threadlike tropomyosin molecules and spherical troponin molecules. Thin and thick filaments are organized in a specific pattern which is repeated down the length of the muscle. It is this patterning that gives skeletal muscle its striated appearance [4]. Myofibers are wrapped in a connective tissue sheath called the endomysium, bundles of myofibers are wrapped in an additional sheath (the perimysium), and whole muscle is wrapped in the epimysium (Figure 2.2). Each repeated segment of thin and thick fibers forms a sarcomere [4]. The sarcomere is defined as the area between the Z-disk or Z-line (Figure 2.3). Each sarcomere comprises dark areas (A bands), that contain the thick filaments, and light areas (I bands), that contain the ends of the thin filaments that do not overlap with the thick filaments (Figures 2.3 and 2.4). At each end of the sarcomere is a three-dimensional (3D) structure referred to as a Z-disk or Z-line. Muscle contractions are produced when crossbridges are formed between overlapping thin and thick fibers in the sarcomere, making the sarcomere the smallest contractile unit in the myofiber. The protein titin attaches the A-band to the Z-disk (Figures 2.3 and 2.4).

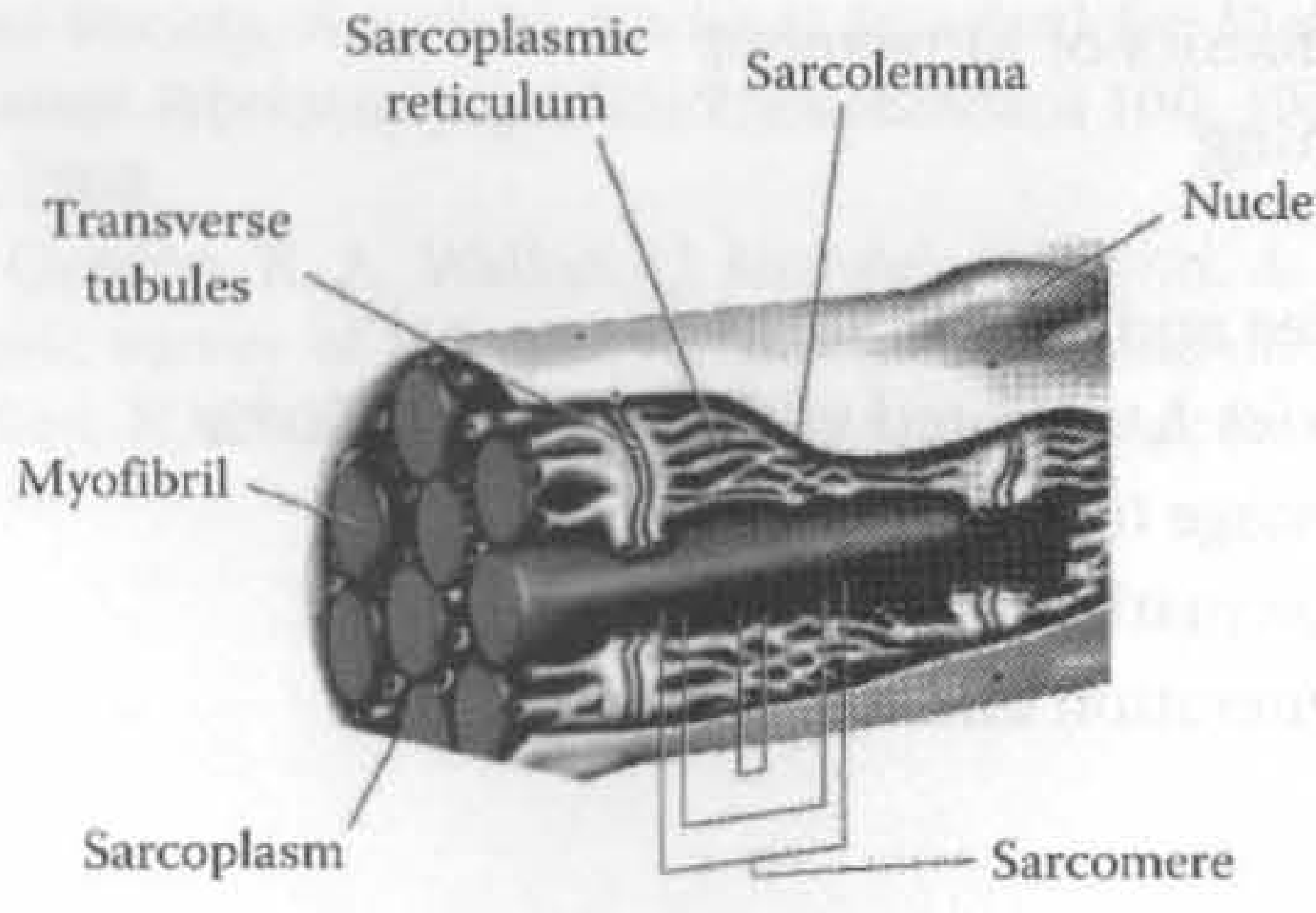


FIGURE 2.1 Organization of a skeletal muscle cell showing the sarcolemma, sarcoplasm, sarcomere, and transverse T-tubules.

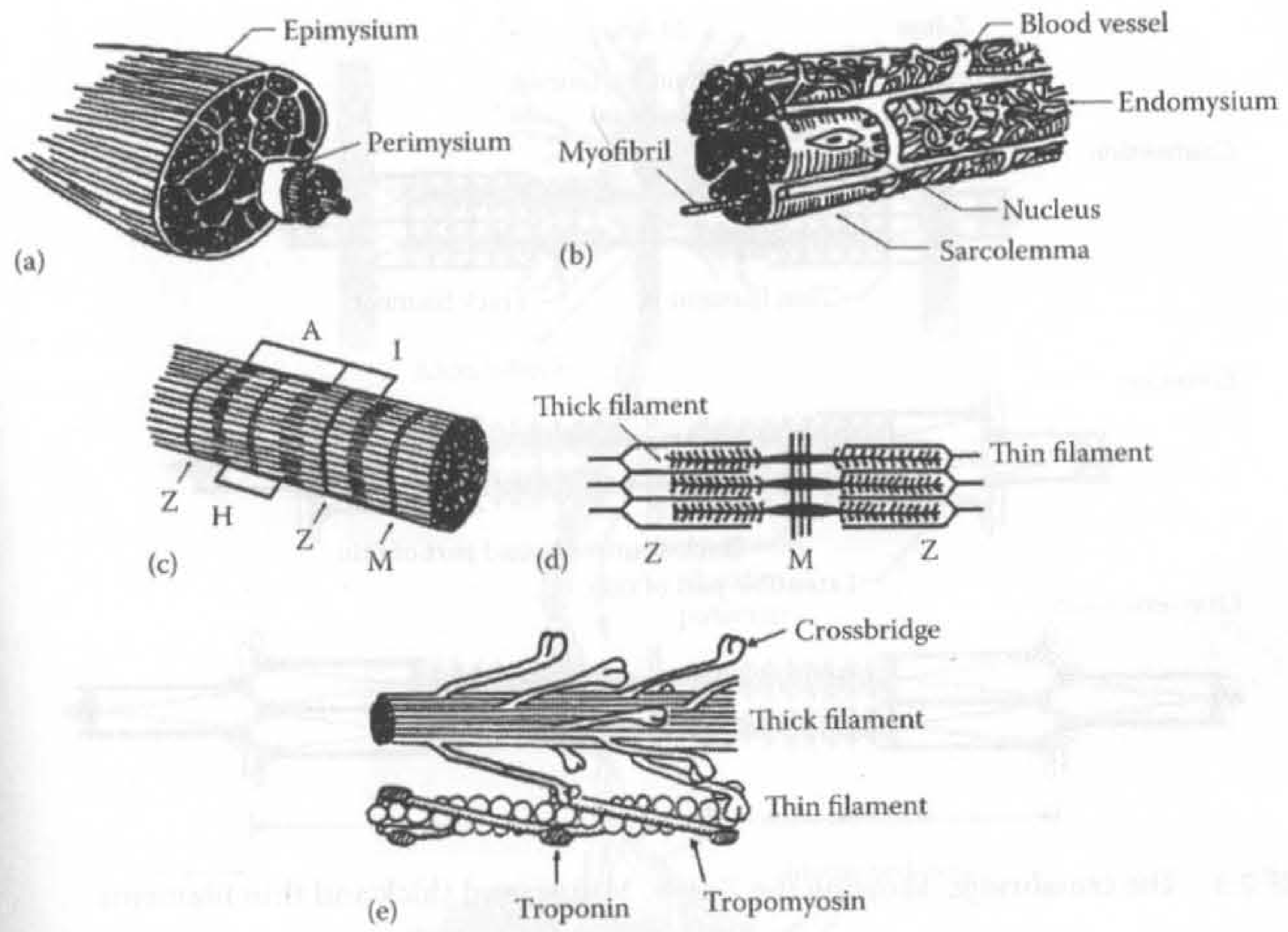


FIGURE 2.2 Skeletal muscle organization from (a) epimysium and perimysium, (b) the endomysium and myofibrils, (c) the myofilaments, (d) the crossbridge, (e) the contractile and regulatory proteins.

2.3 SOMATIC NERVOUS SYSTEM

Skeletal muscle is innervated by motor neurons that control activation and subsequent contraction. The somatic nervous system which innervates skeletal muscle has nerve fibers that are continuous from their origin in the cell bodies on the spinal cord to their termination

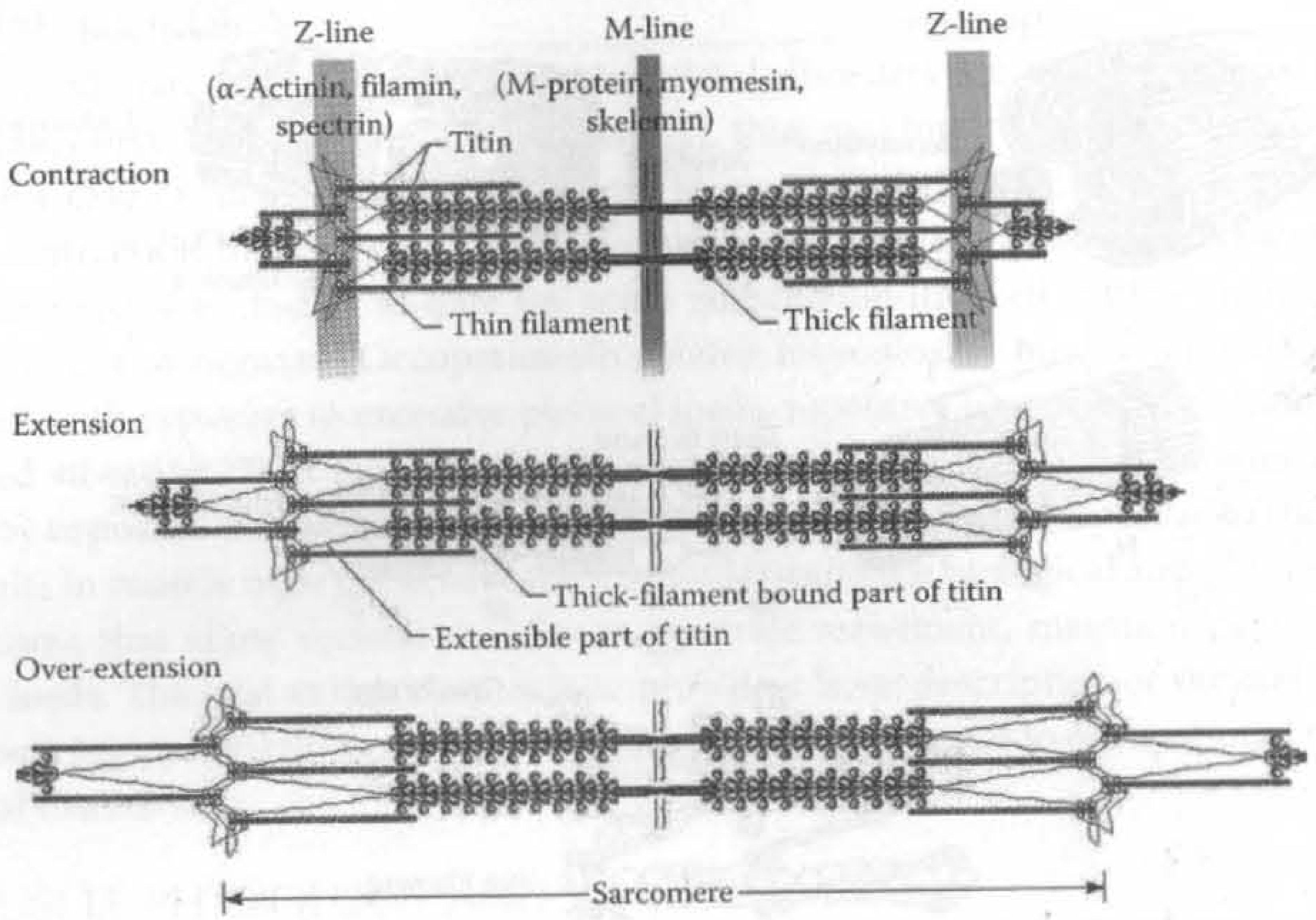


FIGURE 2.3 The crossbridge, showing the Z-line, M-line, and thick and thin filaments.

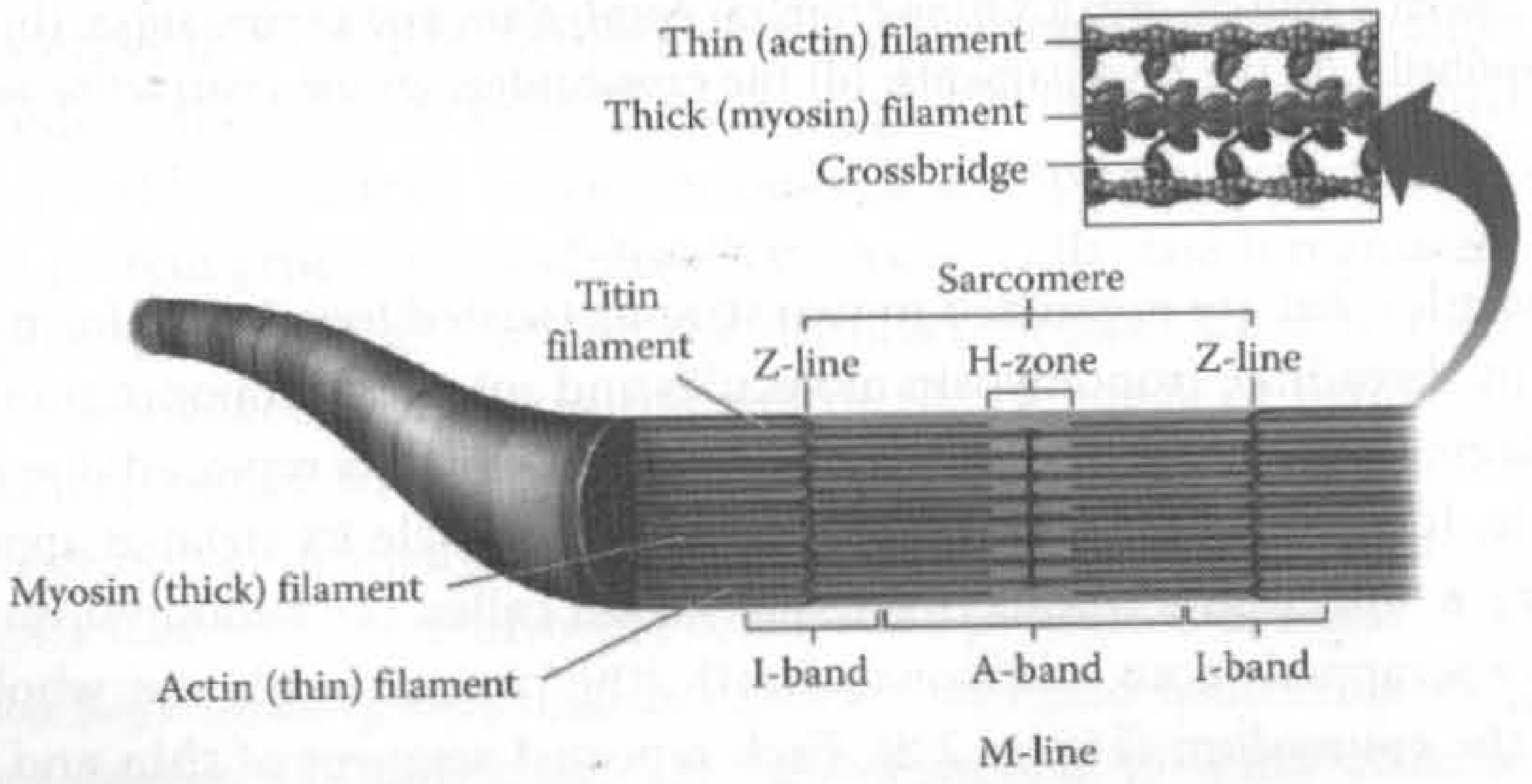


FIGURE 2.4 The crossbridge, showing the I-band, A-band, titin filaments, and Z-line.

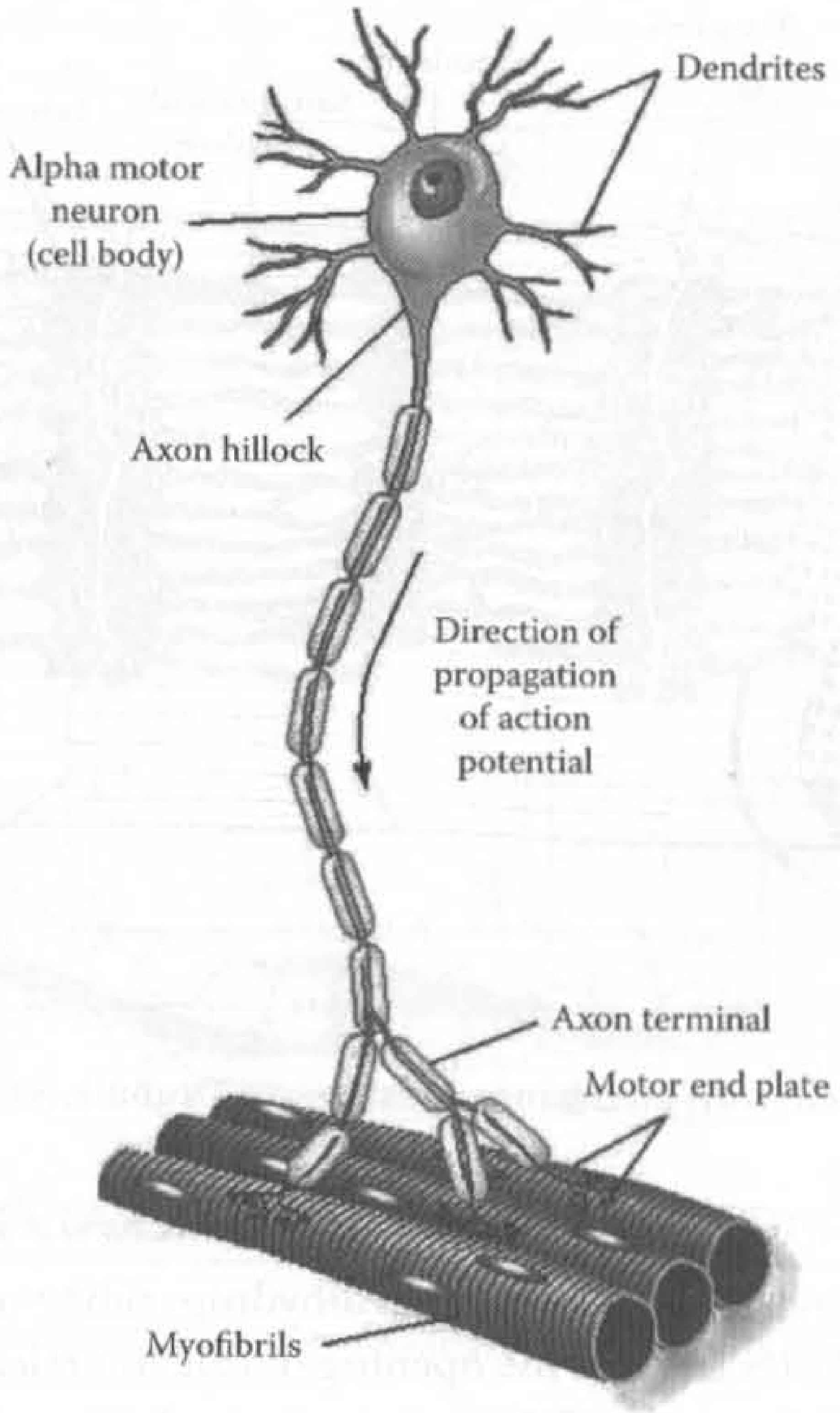


FIGURE 2.5 The motor unit that consists of the alpha motor neuron, motor end plate, and the myofibrils it innervates.

on skeletal muscle at the myofibrils (Figure 2.5). This is in contrast to the autonomic nervous system, which contains two neuron chains of preganglionic and postganglionic fibers used to innervate cardiac and smooth muscles. To initiate a muscle contraction, myofibers must receive stimulation from motor neurons located in the ventral horn of the spinal cord. This stimulation is based on total synaptic input at the cell body from inhibitory postsynaptic potentials (IPSPs) and excitatory postsynaptic potentials (EPSPs) produced by presynaptic inputs originating from diverse sites in the brain. Presynaptic inputs can be influenced by many peripheral sensory receptors in the ascending pathways that can influence descending pathway output via the motor neurons. These inputs can either be excitatory or inhibitory. Areas of the brain that control skeletal muscle activity are motor regions of the cortex, basal nuclei, brain stem, and cerebellum. When summed at the cell body on the spinal cord, if EPSP's are more dominant, an action potential is then initiated. Alpha motor neurons are considered the final common pathway where skeletal muscle activity can be governed only by input from these neurons; thus, it is considered the final common pathway (Figure 2.5). Other parts of the nervous system can only affect skeletal muscle activity by influencing the motor neurons in the somatic nervous system. While skeletal muscle is under voluntary control, lower brain centers control involuntary activity that assists in bringing about the voluntary action that is typically controlled by motor regions in the higher brain centers. Indeed, much of skeletal muscle control is involuntary.

When a motor neuron is activated, an action potential is propagated down the nerve axon and terminates on the neuromuscular junction (NMJ). The NMJ is a space where the action potential cannot cross from the nerve axon to the muscle fibers it innervates. Thus, a chemical messenger is used to transmit the signal from the nerve axon to the muscle fibers. As the signal is transmitted down the nerve axon, voltage-gated channels open to release calcium into the terminal button of the NMJ. This facilitates the release of the chemical messenger acetylcholine (ACH) that crosses the space to the motor end plate. This causes an ionic shift which results in the propagation of the action potential down the basement membrane of the muscle fiber and then down the transverse tubule (T-tubules) of the muscle cell (Figure 2.6).

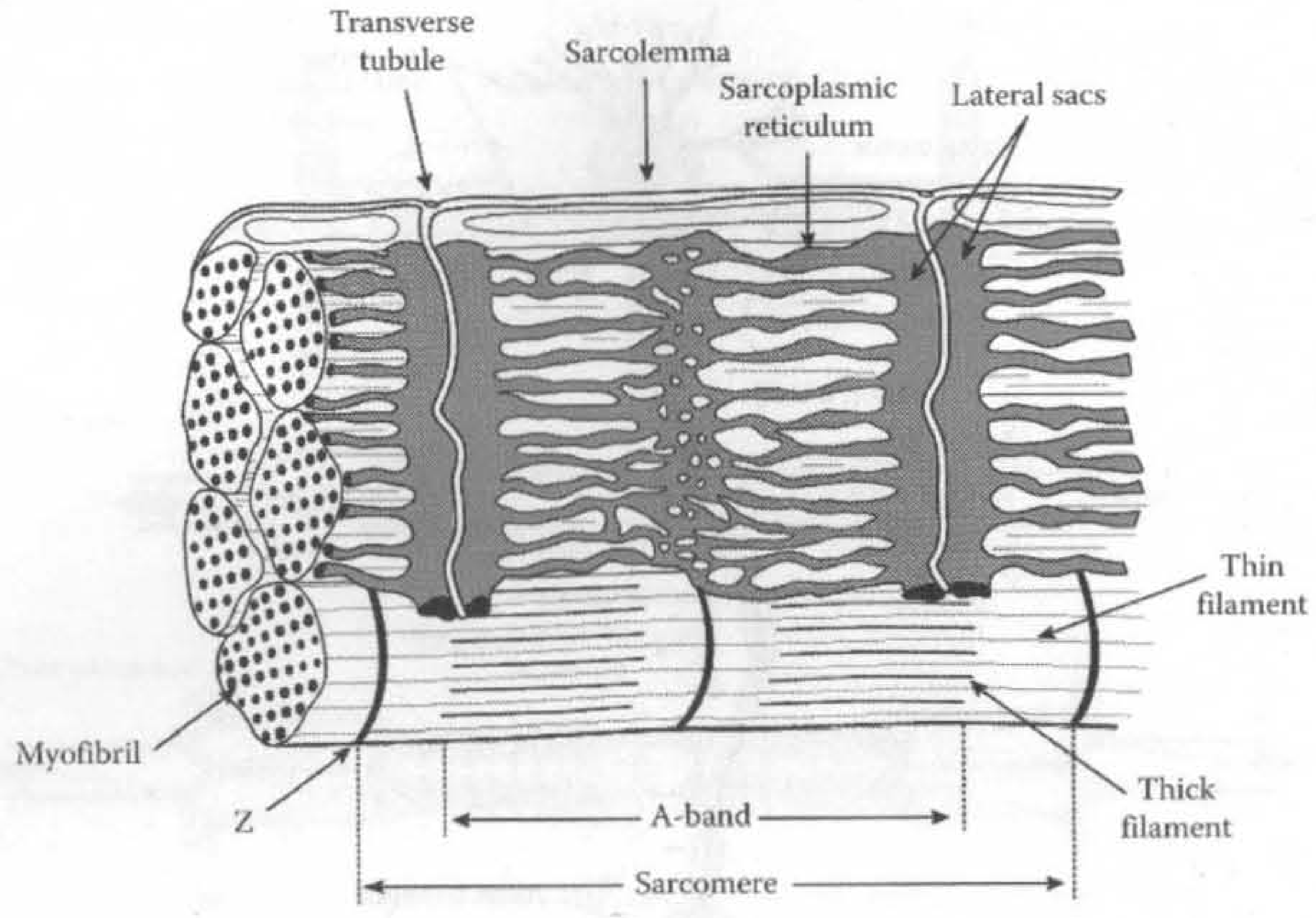


FIGURE 2.6 The muscle cell, with sarcolemma, transverse T-tubule, SR, and myofibrils.

2.4 MUSCLE CONTRACTION AND FORCE GENERATION

The action potential activates the voltage-gated dihydropyridine receptors in the T-tubule. This change in the T-tubules triggers the opening of calcium release channels (ryanodine receptors) on the SR. Ca^{2+} leaves the SR lateral sacs through the ryanodine receptors, enters the cytoplasm, and binds to troponin, one of the proteins on the thin filaments (Figure 2.6). Troponin has three polypeptide units: one binds to tropomyosin, one binds to actin, and a third which binds to Ca^{2+}. Under resting conditions, tropomyosin is bound to actin and it blocks the myosin binding site on the actin protein, preventing the formation of crossbridges (Figure 2.7). However, when free Ca^{2+} rises in the cytoplasm of a myofiber, it binds to troponin and tropomyosin is pulled away from the myosin binding site on actin, leaving it open for crossbridge formation. Once crossbridges are formed, the ATPase located on the myosin head increases its activity and hydrolyzes ATP. This causes the crossbridge to break, and Ca^{2+} then dissociates from its binding site on tropomyosin. When Ca^{2+} is removed, tropomyosin slides back into the blocking position and the muscle relaxes. Thus, troponin and tropomyosin are referred to as regulatory proteins in muscle contraction (Figure 2.7).

One of the main functions of skeletal muscle is to generate and transmit force. Force, or muscle tension, is directly related to the number of actin and myosin crossbridges that are formed and the frequency of stimulation. A single action potential results in a single muscle contraction referred to as "twitch". As the frequency of stimulation increases, the resultant twitch tension increases with increasing stimulation frequency until a force plateau results. Force is produced at each attached crossbridge, so the total force development is proportional to the number of attached crossbridges. The number of crossbridges that can be formed depends upon the degree of overlap between the thin and thick filaments. When a sarcomere is overstretched or compressed, the area over which thin and thick filaments overlap is reduced, and thus there is a decrease in the number of crossbridges that can be formed resulting in a reduction in force (Figures 2.3 and 2.8). Thus, maximal force is generated when sarcomeres are at a length that produces the optimal overlap between thin and thick fibers. Passive tension is due to connective tissue and increases dramatically as the length increases, usually outside of the normal physiological range. The total tension in the muscle is the sum of the active and passive tension (Figure 2.8).

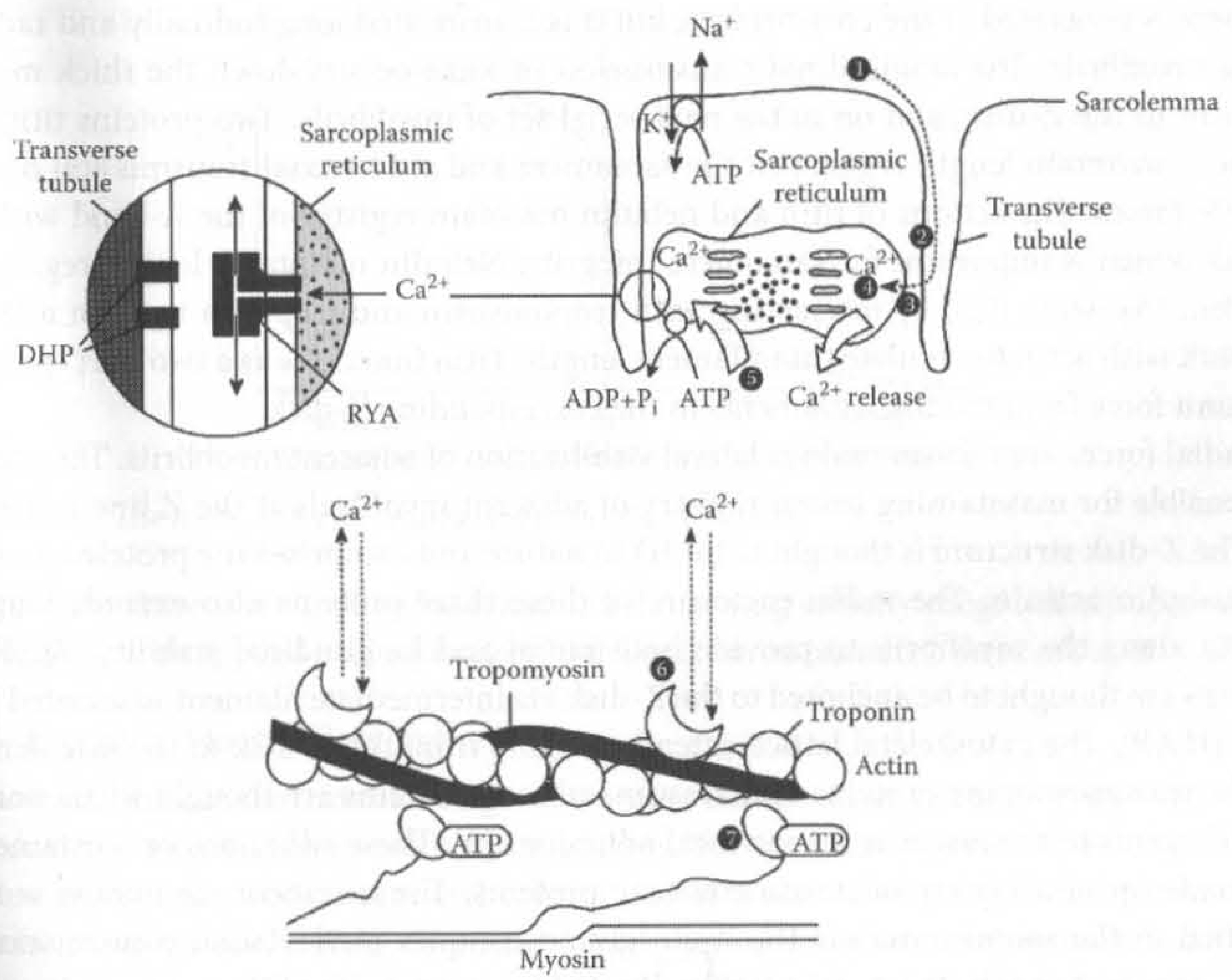


FIGURE 2.7 The NA-K pump on the cell membrane, and the binding of calcium to the tropomyosin molecule.

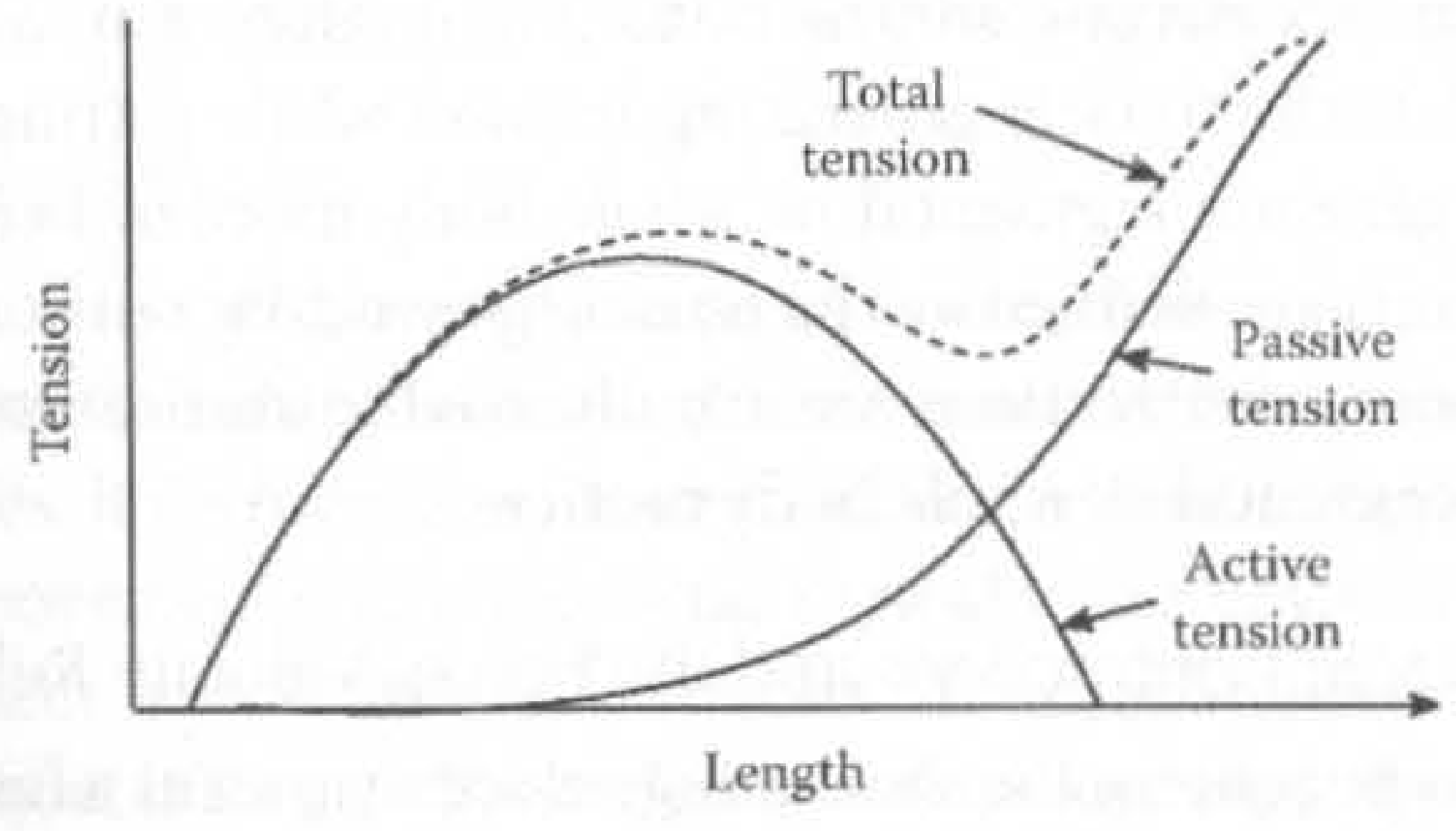


FIGURE 2.8 The length–tension relationship of skeletal muscle.

Force is generated at the crossbridges, but it is transmitted longitudinally and radially along myofibrils. The longitudinal transmission of force occurs down the thick myosin filament to the Z-disk, and on to the next serial set of myofibrils. Two proteins titin and nebulin, maintain length registry of the sarcomere and aid in axial transmission of contractile forces. The actions of titin and nebulin maintain registry of the A-band with the Z-disk which is important for sarcomere integrity. Nebulin maintains length registry of the thin filaments [5,6] by interacting with tropomyosin and troponin to form a lateral network with actin to regulate thin filament length. Titin functions as a two part spring to transmit force from the thick filaments to the corresponding Z-disk.

Radial forces are transmitted via lateral stabilization of adjacent myofibrils. The protein responsible for maintaining lateral registry of adjacent myofibrils at the Z line is desmin [7]. The Z-disk structure is thought to be 3D in nature and comprises the proteins desmin, actin, and α-actinin. The radial enclosure of these three proteins also extends longitudinally along the myofibrils to provide both radial and longitudinal stability [8]. These proteins are thought to be anchored to the Z-disk via intermediate filament-associated proteins (IFAP). The cytoskeletal lattice extends radially from the Z-disk to the sarcolemma via the transmembrane proteins. The transmembrane proteins are thought to anchor the myofilaments to the sarcolemma via focal adhesions [9]. These adhesions or "costameres" are made up of a variety of transmembrane proteins. The basement membrane is then attached to the sarcolemma via the dystroglycan complex [8,9]. Radial transmission of forces occurs through structural proteins located in and outside of the sarcomeric region via the intermediate filament network, and to the sarcolemma via the transmembrane proteins [8]. Capability of radial force transmission is necessary for redundancy in case of fiber injury. Thus, force can be transmitted in any direction in relation to the axis of the muscle fibers via endosarcomeric and exosarcomeric protein lattices.

2.4.1 Types of Muscle Contractions

There are three primary types of muscle contractions. These contraction types are distinguished by how the muscle length changes during the contraction [10,11]. Isometric contractions are defined as muscle activity where tension is generated without a change in length. This is also referred to as a static contraction where muscle is generating tension but does not result in a change in length, and thus, there is no segmental (about a single joint) or whole body motion. Shortening contractions (often referred to as concentric contractions [10] are defined as the muscle generating tension while getting shorter. Concentric contractions usually generate segmental or whole body motion. Lengthening (or eccentric) muscle contractions are defined as the muscle generating tension while the muscle is lengthening. Lengthening contractions are usually used to absorb work or energy, thereby applying braking to segmental or whole body motion.

2.4.2 Concentric Muscle Contractions and the Force–Velocity Relationship

During concentric muscle actions, the shortening velocity varies as a function of applied load to the muscle, thus shortening velocity progressively decreases as applied load is increased. The resultant relationship is hyperbolic (Figure 2.9). The maximum shortening velocity occurs when there is no applied load, and the shortening velocity progressively approaches zero velocity at an applied load equivalent to the maximum isometric force of the muscle [12].

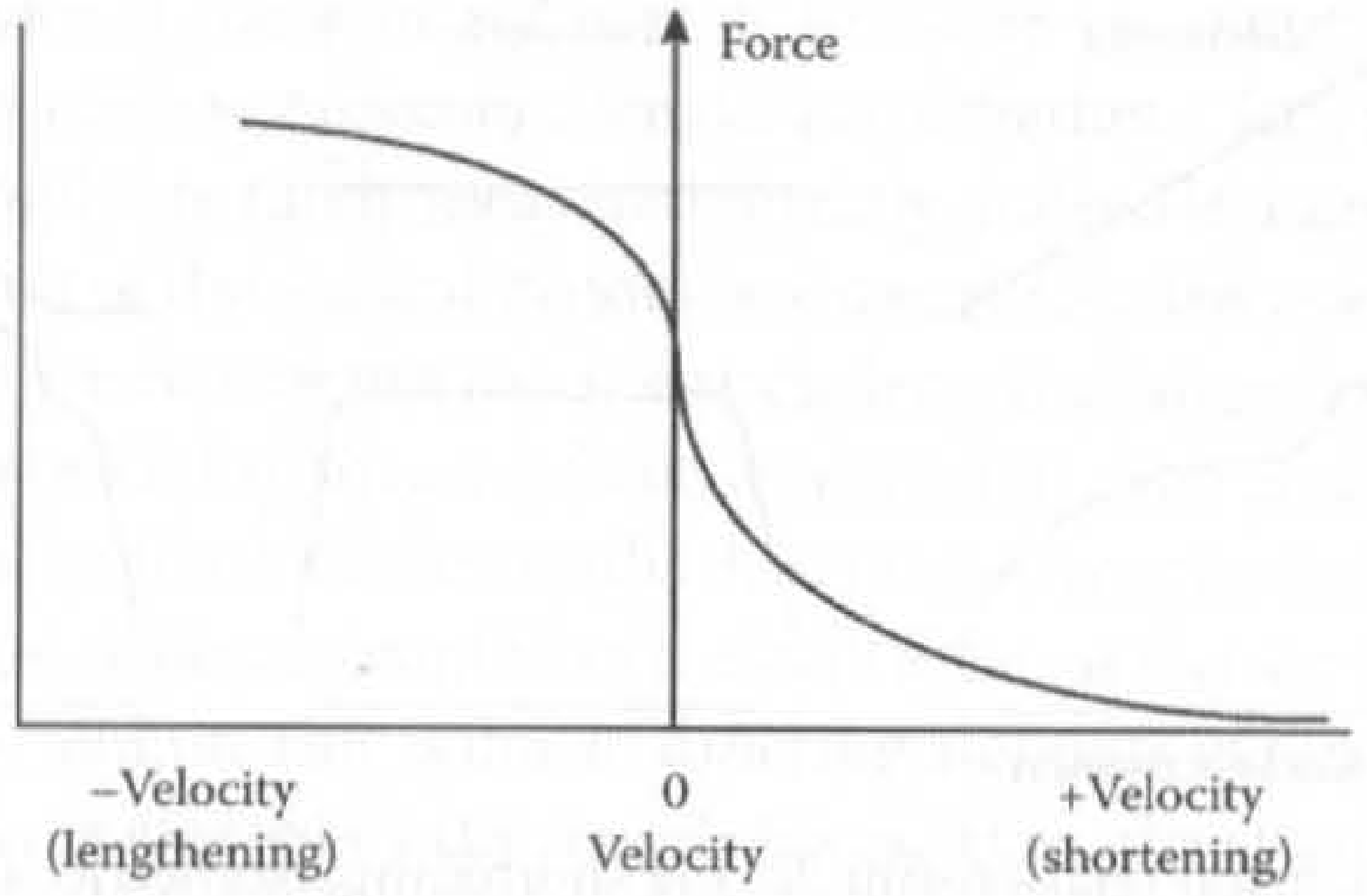


FIGURE 2.9 The force–velocity relationship of skeletal muscle.

2.4.3 Eccentric Muscle Contractions

It is now well known that muscle can generate more tension during eccentric muscle actions than during concentric or isometric contractions. This was first reported in a study involving human muscles under volitional control [13]. It is also interesting that while muscles generate more tension during eccentric muscle actions than concentric muscle actions, EMG activity is less in muscles during stretch than during shortening at the same tension. During maximal effort, the EMG signature remains constant and force varies due to the length–tension relation of that specific muscle or muscle group; however, force during volitional eccentric activity never exceeded 140% of maximal shortening forces [14]. In animal studies that employ electrical stimulation to activate the muscle of interest, forces of 180% of maximum isometric force are typical [15]. High eccentric forces in humans with spastic paresis have been attained to levels similar as those seen in animal studies [16]. In addition, if muscles in humans are stimulated by external electrical stimulators, as in the case of spinal cord injured patients, the external forces generated during eccentric muscle actions are nearly 200% of the forces generated concentrically using the same electrical stimulation paradigm [17]. Thus, exogenous electrical stimulation overrides the inhibitory influences that moderate muscle output force. The force–velocity relationship during lengthening is near linear as the force does not increase as the lengthening velocity increases (Figure 2.9).

2.4.4 Stretch-Shortening Cycles

Stretch-shortening cycles (SSCs) are a type of muscle action that incorporates both concentric and eccentric muscle actions. Natural movement usually comprises SSCs. In most sports-related activities, it involves a prior stretch before shortening to enhance the shortening phase of the movement. Activities that typically use SSCs are jumping, walking, running, and movement in and around obstacles. In occupational-related activities, it is most related to reciprocal lifting and lowering activities and repetitive lift and carry tasks. It is an excellent model to study physiological muscle function [18]. It also allows for simultaneous study of concentric and eccentric muscle function and their synergism.

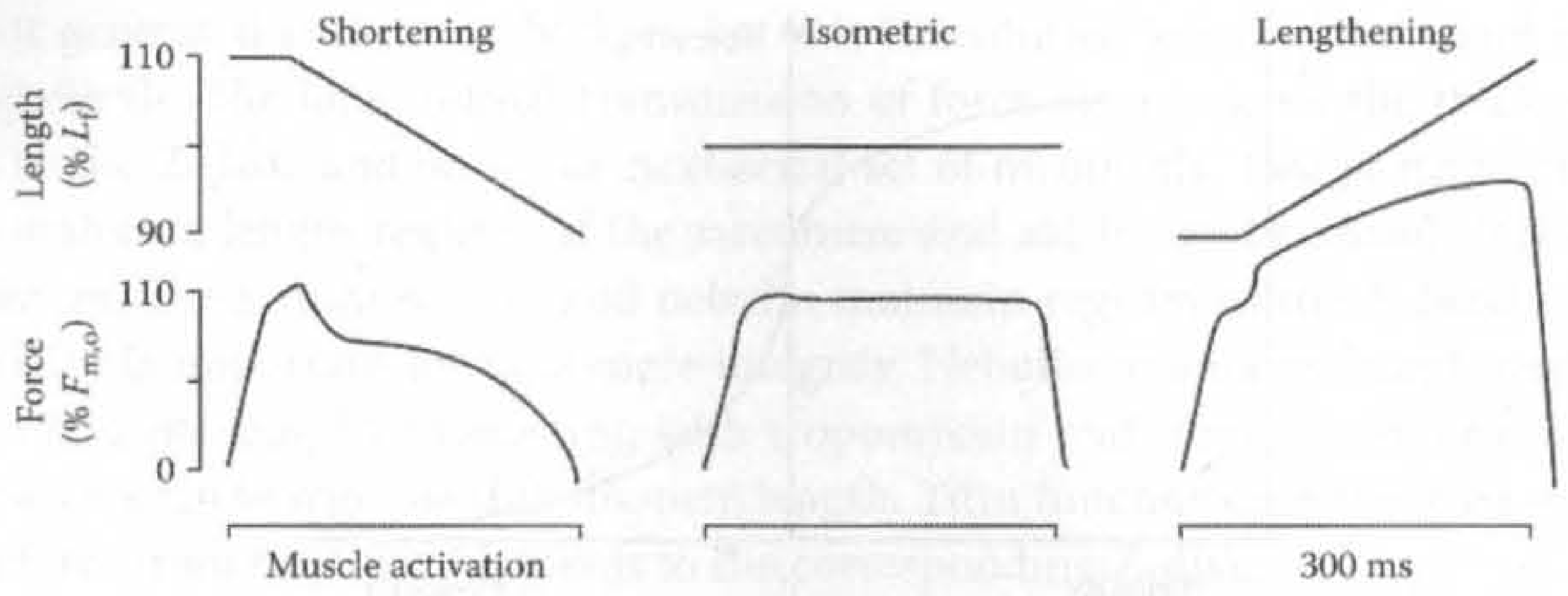


FIGURE 2.10 Length–tension relationship during shortening, isometric, and lengthening muscle actions.

2.4.5 Length–Tension Relationship

During isometric muscle contractions, it is well understood that force varies as a function of muscle length while the muscle is shortening or lengthening (Figure 2.10). Also, peak muscle tension reaches a plateau during maximal isometric contractions. It has been shown that muscle tension is lowest at very short and very long muscle lengths and develops higher tension in the intermediate lengths [19,20]. This is due to the degree of sarcomere overlap in the crossbridge. Thus, the length–tension curve has an ascending and descending limb as length increases (see Figure 2.8). The ascending limb, defined as the increase in force with increase in length, is due to more actin binding sites being available to bind with the myosin filaments. As tension plateaus, this is thought to be due to all the actin binding sites being bound to the myosin filaments. The descending limb, defined as the decrease in muscle tension with increasing length, is due to less actin binding sites being available as the actin filaments are pulled out of register with the myosin filaments. Thus, the length–tension relationship of muscle is due to myofilament overlap in the sarcomere (as shown in Figures 2.3 and 2.8).

2.5 MUSCULOTENDON ACTUATOR

Muscle and tendon have typically been studied in isolation although they function synergistically. Their integrative function has been defined as the musculotendon actuator [21]. While physiologists have long recognized that muscle and tendon act in a synergistic fashion, they have studied those tissues in isolation to better understand the function of muscle and tendon separately. The musculotendon actuators interact with body segments to produce movement and the dynamics of movement are dependent upon the contraction dynamics of the actuator. This system also functions as a feedback loop where the dynamics of body segments affect the force output of the actuator via the length and velocity of the actuator and the inherent compliance [21].

Tendon compliance affects the contraction dynamics of the muscle. In actuators with highly compliant tendons, a length change of the actuator would be mostly realized by the length change in the tendon, with very little concomitant length change in muscle. Compliance of an actuator is defined by the ratio of tendon slack length to muscle fiber length. Muscle length changes will be commensurate with length perturbations of the musculotendon actuator if the actuator is stiff. However in compliant actuators, muscle length changes will not follow exogenous length perturbations. This is quite relevant since changes in muscle length are rarely measured directly, indeed in human studies of muscle function the kinematics of the musculotendon are measured. The assertion that changes in musclotendon length are representative of muscle length changes may be incorrect, particularly for actuators with highly compliant tendons [21]. The active and passive force–length relation of muscles that have been published to-date may be erroneous due to the fact that muscle fibers are at different lengths in the active versus passive state even though the actuator is at the same length. This is due to differing amounts of tendon stretch which are caused by different forces exerted by the muscle fibers. Thus, the stretch of the tendon must be accounted for to accurately represent muscle stretch [22]. The muscle tendon interface (at the aponeurosis) exists in a state of dynamic equilibria, where force transients are equalized via stretch of the tendon and muscle activation and muscle length change. The dynamic equilibria also are governed by the response time of the tendon and muscle which are often different. Actuator compliance varies depending on the muscle group and animal species. In humans, actuator compliance appears to be highest on the plantar flexor group and lowest on proximal groups such as biceps and triceps [23–25]. In summary, one must think in terms of the musculotendon when investigating in vivo muscle function or reviewing scientific studies of in vivo function. While most studies refer specifically to muscle function, the measurements are typically made on the musculotendon group. Thus, one must be cognizant of the influence of tendon mechanics on muscle function and the musculotendon unit.

2.6 ENERGETICS OF MUSCLE CONTRACTIONS

Skeletal muscle is an electro-chemical-mechanical transducer. In other words, muscle activity is governed by electrical input from the somatic nervous system evoking chemical changes that provide energy for the contractile activity, and the subsequent mechanical output which results from the contractile activity. Muscle activity is fueled by several metabolic pathways; each pathway is most suited for a type of muscle contraction. Muscle fibers have these alternate pathways that generate adenosine triphosphate (ATP), the fuel for muscle contraction. Myosin ATPase splits ATP to provide energy for the power stroke of the crossbridge (Figure 2.11). To repeat the cycle, a fresh molecule of ATP binds to the myosin thick filament to allow detachment from the actin filament. This ATP is then split to recycle the bridge for the next stroke. The active resequestration of calcium back into the SR is also fueled by ATP. ATP is the only energy source used for muscle activity and must be supplied at a continuous rate for activity to be maintained. Limited supplies of ATP are located in the muscle, but three additional pathways provide supply of fresh ATP as needed during activity. The three pathways are (1) creatine phosphate pathway which donates high energy phosphates to ADP to form ATP, (2) oxidative phosphorylation (citric acid cycle and the electron transport chain), and (3) glycolysis. Creatine phosphate is the first storehouse tapped during muscle contractile activity. The reversible reaction is based on the donation of a high energy phosphate from creatine phosphate to ADP in the presence of the enzyme creatine kinase to form creatine and ATP. As energy reserves are built up in resting muscle, the high energy phosphate is transferred to creatine phosphate, thus

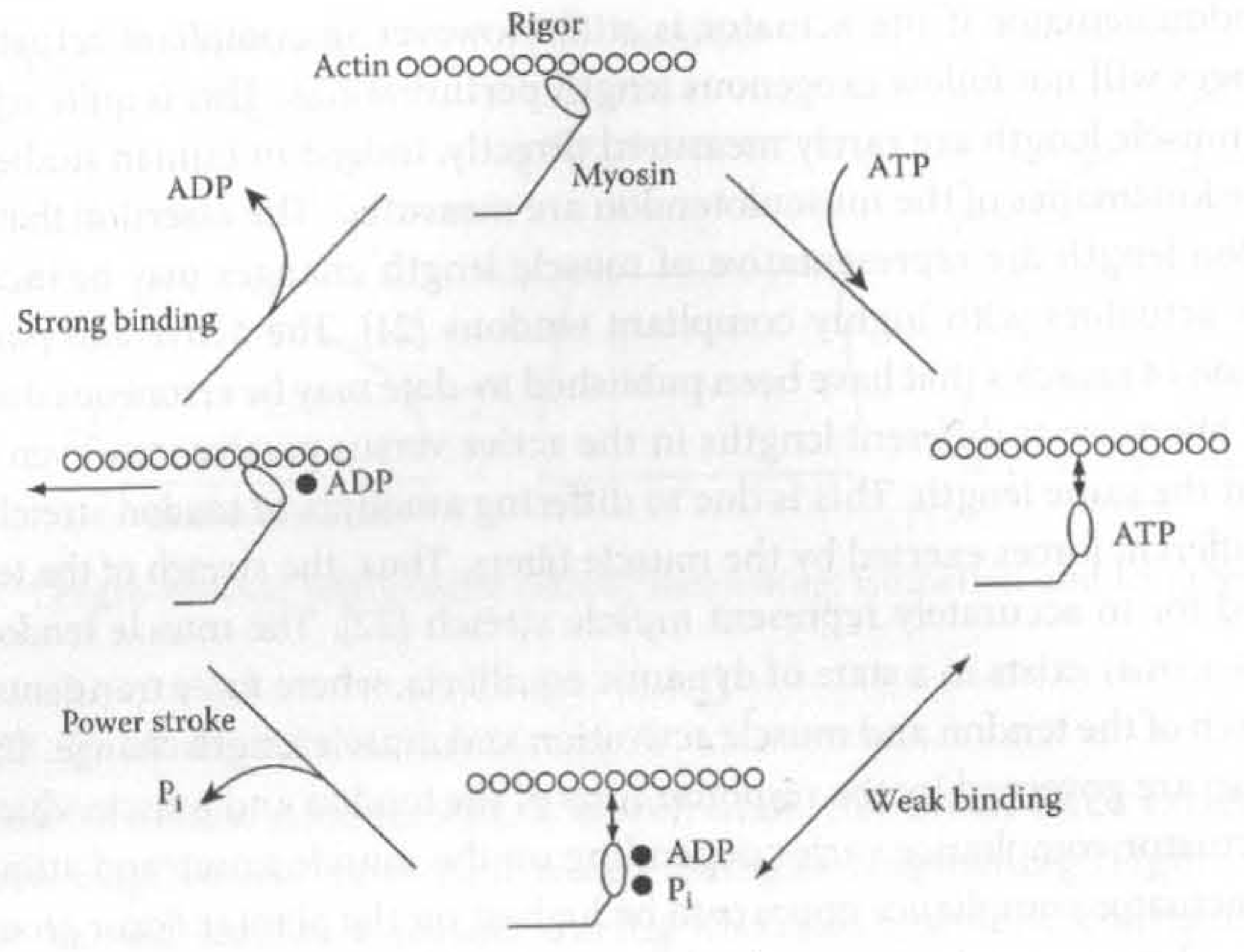


FIGURE 2.11 Crossbridge cycling and the role of ATP.

a rested muscle contains five times as much creatine phosphate as ATP. When the small pools of ATP are utilized at the onset of muscle contractile activity, the creatine phosphate pools can be rapidly converted to ATP to fuel the muscle activity. This energy pathway is mostly tapped during short, high intensity activity such as sprints, jumping, or lifting of objects for a short duration. Longer duration activities will use alternative energy pathways of oxidative phosphorylation and glycolysis to produce ATP. Oxidative phosphorylation provides a rich yield of 36 ATP molecules for each molecule of glucose. This pathway is slow, due to the number of intermediate steps. Sufficient oxygen is needed in the muscle mitochondria to fuel this pathway. Long-term, lower intensity activities such as repetitive motion tasks typical in manufacturing or manual materials handling, or walking would use this pathway provided that sufficient oxygen and nutrient supplies are available. This would be categorized as an aerobic pathway since it is done in the presence of oxygen. Oxygen is transported to the active muscles by the bloodstream. The flow of oxygen is potentiated by increased inotropic and chronotropic actions of the heart to pump more blood, vasodilation of the blood vessels to increase mass flow rate, and increased pulmonary activity to provide more oxygen to the bloodstream. Slow twitch muscle fibers have more myoglobin for storage of oxygen to assist in transfer of oxygen to active muscle fibers. Nutrient fuel can also be transported by the blood for use by active muscle or stored in glucose chains for later use.

Cardiovascular performance can limit the amount of oxygen that can be delivered to active muscle. During maximal activity, vasoconstriction occurs and the relatively slow oxidative phosphorylation pathway cannot keep up with the task demands for delivery of ATP to the muscle. When this occurs, muscles will rely on glycolysis to meet energy demands. Using this pathway, a glucose molecule is broken down into two ATP molecules and two pyruvic acid molecules. In the presence of oxygen, the pyruvic acid molecules can

then enter the oxidative phosphorylation cycle to yield more nutrient fuel. However, the glycolytic pathway can proceed in the absence of oxygen to produce two ATP molecules for every glucose molecule. This is not as rich of ATP yield as produced by the oxidative phosphorylation pathway; however, this pathway is much faster and can proceed in the absence of oxygen, thus an anaerobic pathway. This pathway is best suited for short duration, intense physical activity. However, this pathway rapidly depletes the muscles' small supply of glycogen and in the absence of oxygen, the molecules of pyruvic acid are converted into lactic acid, thus promoting muscle soreness and metabolic acidosis leading to significant muscle fatigue. In most occupational tasks that require manual material handling, this pathway is probably not used since most tasks in the industrial setting are of lower intensity and longer duration.

2.7 MUSCLE FIBER TYPES

There are three types of skeletal muscle fibers that differ by their contractile speed and the ATP enzymatic processes used. There are slow oxidative fibers (Type I), fast oxidative fibers (Type IIa), and fast glycolytic fibers (Type IIb) (Figure 2.12). The faster fibers (Type IIa and IIb) are also referred to as fast myosin-ATPase for their ability to process ATP more rapidly. This also means that the crossbridge cycles more rapidly, resulting in a faster contractile velocity. Type IIa and IIb fibers are also referred to as fast-twitch-fatigue resistant and fast-twitch fatigable, respectively. Type I muscle fibers are slow twitch fibers that have a greater capacity to form ATP, are richer in mitochondria that contain enzymes in the oxidative phosphorylation pathway, and are richer in myoglobin due to the fiber's dependency on oxygen for contractile activity. This gives Type I muscles a red color. Type I muscles are typically used to maintain posture, and for long duration, low-intensity tasks that are typically found in many work environments. Type I muscles are better equipped for oxidative phosphorylation, a slow ATP synthesizing pathway. The rich yield of ATP in this pathway does not readily deplete energy stores, and also does not accumulate lactic acid since this pathway always operates in the presence of oxygen; thus, they are more fatigue resistant. Fast fibers have far fewer mitochondria than their slower twitch counterparts and have more stored glycogen and the enzymes necessary to break down glycogen into ATP.

	Type I	**Type IIA**	**Type IIB**
Other names	Red, slow twitch (ST) Slow oxidative (SO)	White, fast twitch (FT) Fast oxidative glycolytic (FOG)	Fast glycolytic (FG)
Speed of contraction	Slow	Fast	Fast
Strength of contraction	Low	High	High
Fatigability	Fatigue resistant	Fatigable	Most fatigable
Aerobic capacity	High	Medium	Low
Anaerobic capacity	Low	Medium	High
Motor unit size	Small	Larger	Largest
Capillary density	High	High	Low

FIGURE 2.12 The characteristics of muscle fiber types. (Adapted from Simon S.R. (ed.), *Orthopaedic Basic Science*, American Academy of Orthopaedic Surgeons, Rosemont, IL, 1994. With permission.)

They also have much less myoglobin than the Type I fibers, gives them a white color. They also have less capillary density since they do not rely on oxygenation for contraction. They have a higher myosin-ATPase content, and are typically larger in diameter than their Type I counterparts and have more myofilaments of actin and myosin to produce greater tension. Thus, the Type II glycolytic fibers are most suited for tasks that require high power output for a short duration, due to their dependence on glycogen to fuel the activity. Type IIa fibers are hybrids between the Type I and Type IIb fibers. They have both the high ATPase capacity of the Type IIb fibers and the higher oxidative capacity of the Type I fibers. Their contraction velocity is higher than the slow twitch Type I fibers and can maintain contraction for longer than the Type IIb fibers. However, their contractile activity needs more ATP than the oxidative phosphorylation pathway can provide, they do rely somewhat on the glycolytic pathway to meet the contractile demands, thus they fatigue more rapidly than their Type I counterparts.

Whole muscles contain a mixture of fiber types, dependent upon the intended use of the muscle. Muscles that have a large percentage of fast twitch glycolytic fibers are used for short duration, higher intensity tasks, while those that have a larger percentage of slow twitch fibers are used more for maintenance of posture. The fiber type composition can vary from muscle to muscle and person to person. For example, elite marathon runners have a higher population of slow twitch fibers than elite strength athletes. Strength athletes normally have a high population of Type II fibers to generate power for short durations.

2.8 MOTOR CONTROL

Motor control is the system that controls and coordinates human movements. It involves a dynamic process that regulates the ability of the human body to move, adapt, learn, use tools, conduct occupational tasks, and carry out many more activities. Motor control functions involve continuously processing sensory information related to body movements (e.g., force magnitude, directions, etc.) and environment (e.g., floor slipperiness, lighting, etc.), and initiating the commands necessary for successful task completion.

Factors affecting motor control are complex. The study of motor control is generally considered multidimensional; as such, it necessarily includes many dimensions of control, theoretical perspectives, approaches, and disciplinary methods. Such complexity of approaches reflects the fact that human activities—from the simple to the most complex—rely on physiological functions that cross numerous boundaries, and that draw on complex control functions within the human brain, nervous system, and musculoskeletal system, and that rely on the body's ability to dynamically integrate sensory information and control functions. Traditionally, research on motor control has focused on the function of the nervous system and how it controls body movements. More current research clearly establishes that motor controls arise from the interaction between neural and biomechanical dynamics [26].

2.8.1 Structure of the Motor Control System

The part of nervous system pertaining to motor control includes the brain, spinal cord, motor nerves, sensory nerves, and proprioceptors. The brain and the spinal cord comprise the central nervous system, which initiates and controls human movement.

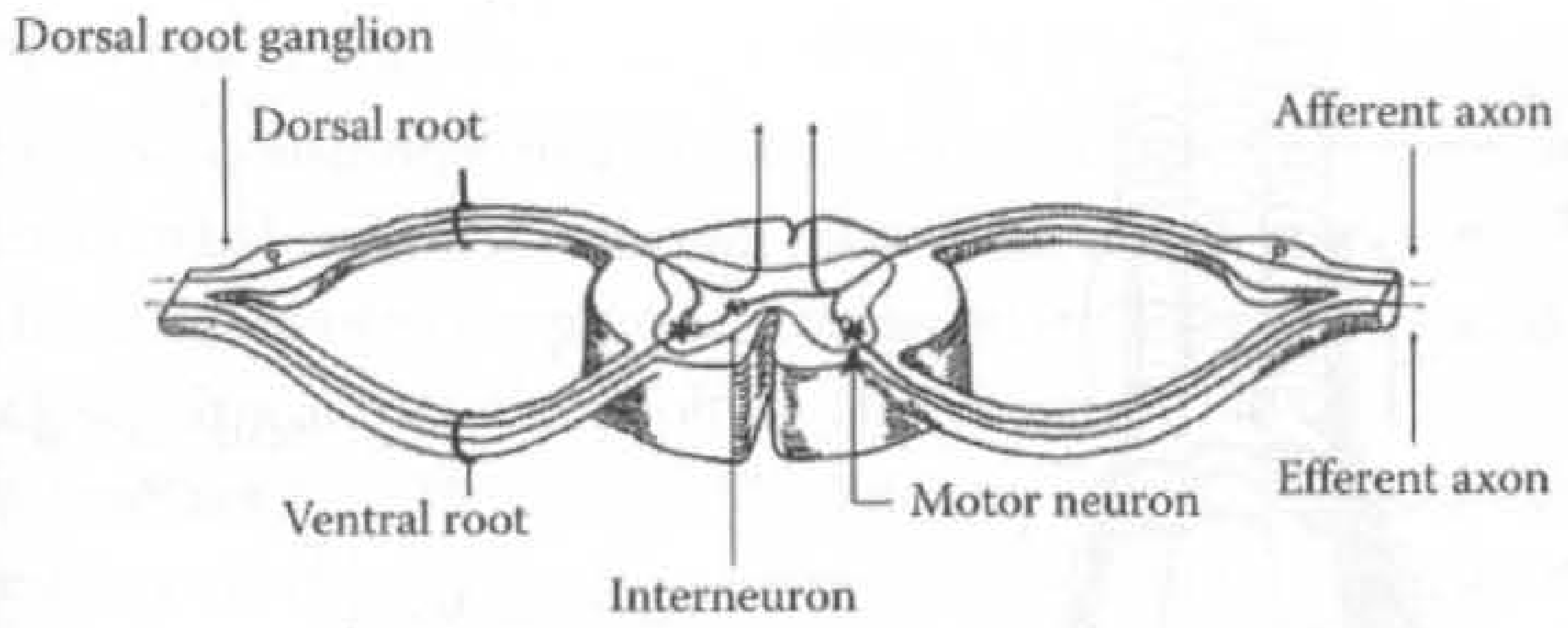


FIGURE 2.13 The afferent and efferent axons from the motor neuron and the ventral and dorsal root ganglia.

Human muscles are connected to the central nervous system by both motor and sensory nerves. The motor nerves exit the spinal cord on the ventral side or front side of the cord while the sensory nerves enter the spinal cord from the dorsal or back side (Figure 2.13). The motor nerves, also called efferent nerves, carry impulses outward from the central nervous system to the muscles. This pathway is termed the efferent or descending pathway. The sensory nerves, also known as the afferent nerves, transmit impulses inward from the muscles, joints, skin, and other sensory organs to the central nervous system. This pathway is termed afferent or ascending pathway.

Proprioceptors are sensory receptors located in the muscles, joints, and tendons that transform mechanical distortion of the muscle or joint into nerve impulses to provide the central nervous system with information on the changing conditions of the musculoskeletal system, such as muscle length and joint position. Proprioceptors include muscle spindles and Golgi tendon organs. The muscle spindles lie parallel with the muscle fibers in the belly of the muscle and are activated by the gamma motor neurons to stay in synchronization with the muscle fibers. They provide inputs about muscle length to the central nervous system. Golgi tendon organs monitor forces and tensions in the muscle; they lie at the muscle–tendon junctions (Figure 2.14). Another important proprioceptor is the semicircular canals of the inner ear that sense the position of the body. Collectively, these receptors provide continuous input to the nervous system to determine how many muscle fibers should be recruited to perform a task. In addition to proprioceptors, vision plays an important role in motor control. Research evidence suggests that vision is used to define the trajectory and kinematics of movements while proprioceptor is critical in the transmission of the plan into motor commands sent to the muscles [27,28]. The interactive process can explain how the human body maintains postural balance and how human gait is accomplished.

2.8.2 Control of Postural Balance

The maintenance of postural equilibrium is a complex process. In daily life or in an occupational setting, postural equilibrium is constantly challenged by perturbations arising from environmental changes, sudden movement of body segments, or task demands. These perturbations could be visual, vestibular, or mechanical changes resulting in conditions that may displace the body away from its equilibrium.

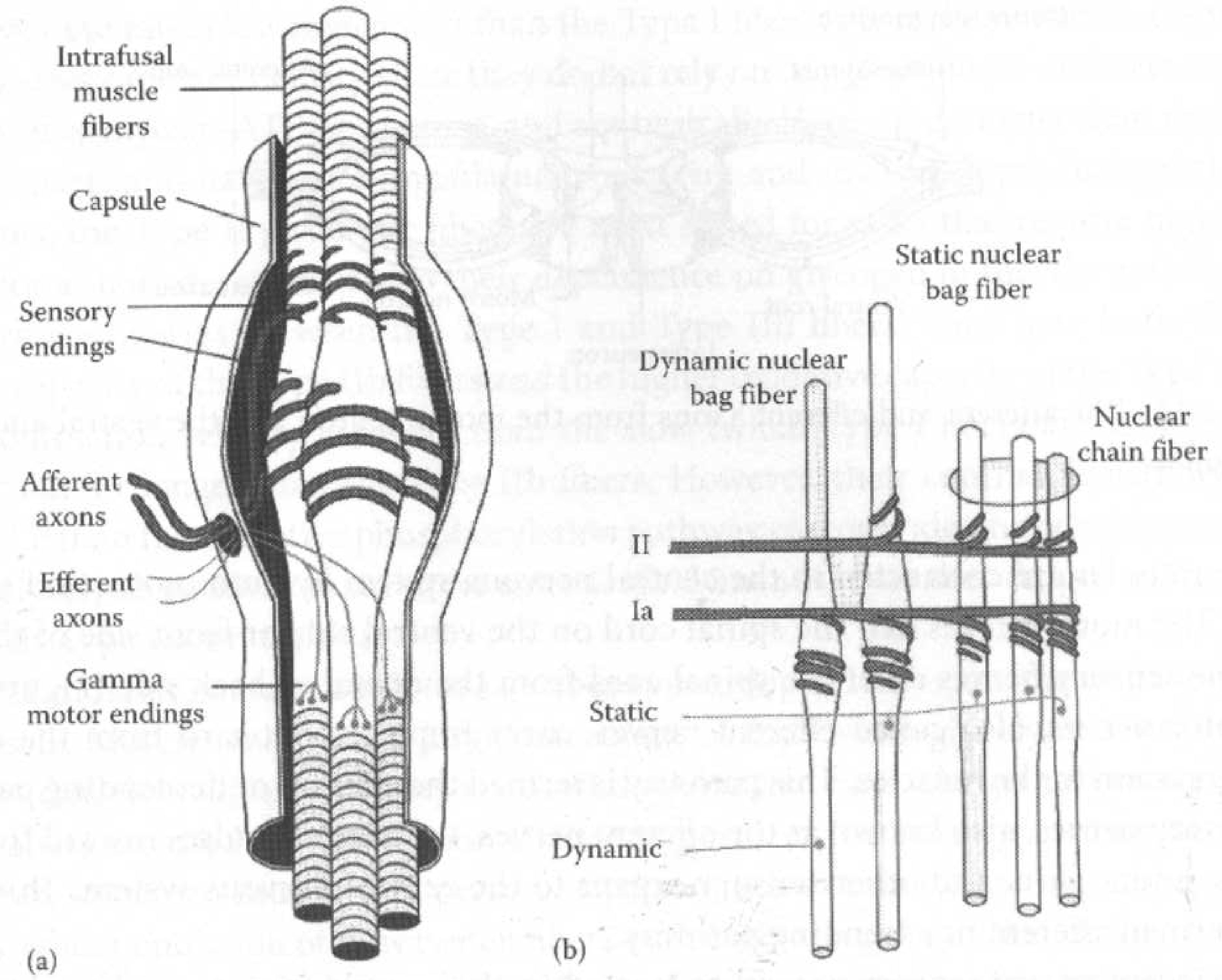


FIGURE 2.14 Intrafusal fibers complete with (a) gamma motor neurons and (b) sensory endings.

Biomechanically, the body's equilibrium is achieved when all forces acting on the body segments are balanced and the center of mass is well controlled within the base of support. The maintenance of postural balance is dependent on both sensory and motor processes. When the body's center of mass is shifted near the outer perimeter of the basal support due to perturbations, the instability is detected via afferent inputs from muscles, joints, vestibular system, and vision. Subsequently, motor processes coordinate the muscle actions into discrete synergies to minimize postural sway and keep the body's center of mass within the base of support [29,30]. If the static balance cannot be maintained, a rapid step or additional external support such as holding onto a guard rail is needed to reestablish the base of support.

Research on the human body's responses to postural perturbations provides important views of postural control mechanisms. In order to obtain a measure of the relative importance of the participating afferent inputs, experiments were designed to enhance, weaken, or exclude one or more afferent inputs [27,31–33]. For example, the role of the vestibular system becomes more important when the standing surface is uneven and the vision input is excluded. Despite the availability of multiple sensory inputs for healthy adults, the preferred sensory input for balance control is the proprioceptors at the feet [34]. Although the central nervous system generally relies on one sense at a time for balance, when one source is reduced, alternative sensory inputs are used for balance [35]. Postural balance is widely used as an indicator of susceptibility to loss of balance or fall. The control of postural stability plays an important role in fall prevention among elderly as well as among individuals performing workplace activities.

2.8.3 Control of Human Gait

Human gait is the most common human movements which occur subconsciously; however, the control mechanism behind such common movement is little understood by most people. Gait requires an integration of a complex neuromuscular-skeletal system as well as the coordination of muscles acting across many joints. This dynamic balance could be disturbed by traumatic injury, neurological damage, gradual degeneration, and even fatigue [36]. It can also be challenged by perturbations arising from environmental changes, that is, floor slipperiness and compliance, or job-task requirements, such as working at heights [37–40].

To achieve safe and efficient locomotion, previous studies indicated that major motor functional requirements needed to be met. Upright posture and total body balance must be maintained [41] and the upper body should be fully supported against the force of gravity during locomotion. Foot trajectory needs to be well controlled to achieve safe ground clearance [42]. In addition, sufficient mechanical energy needs to be generated by the body to maintain forward velocity during progression [43]. Moreover, the motor patterns at the hips, knees, and ankles have the major function of absorbing and generating energy [43] and the central nervous system must integrate and coordinate efferent commands with proprioceptive feedback and vestibular and visual inputs to generate the correct patterns of moment of force at each joint.

Previous studies on gait [38,44,45] have documented that people changed their gait as they approached and encountered slippery surfaces. Humans can adjust their gait to perceived changes indicated by sensory feedback, and can safely negotiate many different friction-surface levels. The typical protective gait strategy adopted in response to increased slipperiness includes shorter steps, and increased knee flexion to reduce vertical acceleration and forward velocity [46]. Gait changes are also observed in poorly lit environments. Subjects experiencing these conditions walked significantly slower, and exhibited decreased incoming velocity and heel contact angle [38]. It is the sudden and unanticipated changes in surface slipperiness or other environmental factors that cause most slips and falls.

2.8.4 Muscle Mechanics of Movement

The motor unit is the most fundamental element of the neuromuscular system; it consists of a group of muscle fibers that are innervated by the same motor neurons (Figure 2.15). When a single motor neuron is stimulated to exceed the threshold of contraction, all fibers of the motor unit will contract [47]. A large motor unit with a larger number of muscle fibers can exert greater force than a small motor unit. Other factors affecting the force output of a muscle are the muscle fiber length, muscle cross-section, and the rate at which the motor unit discharges the impulse. The force generated by a muscle is also determined by the number of motor units actively stimulated at the same time. Muscle recruitment is the mechanism of muscle force production and involves the order pattern in which pools of motor units are sequentially activated [48].

2.8.5 Motor Learning

There are two major types of motor abilities that are critical for our day-to-day activities—postural equilibrium control and voluntary motor control involving a particular movement

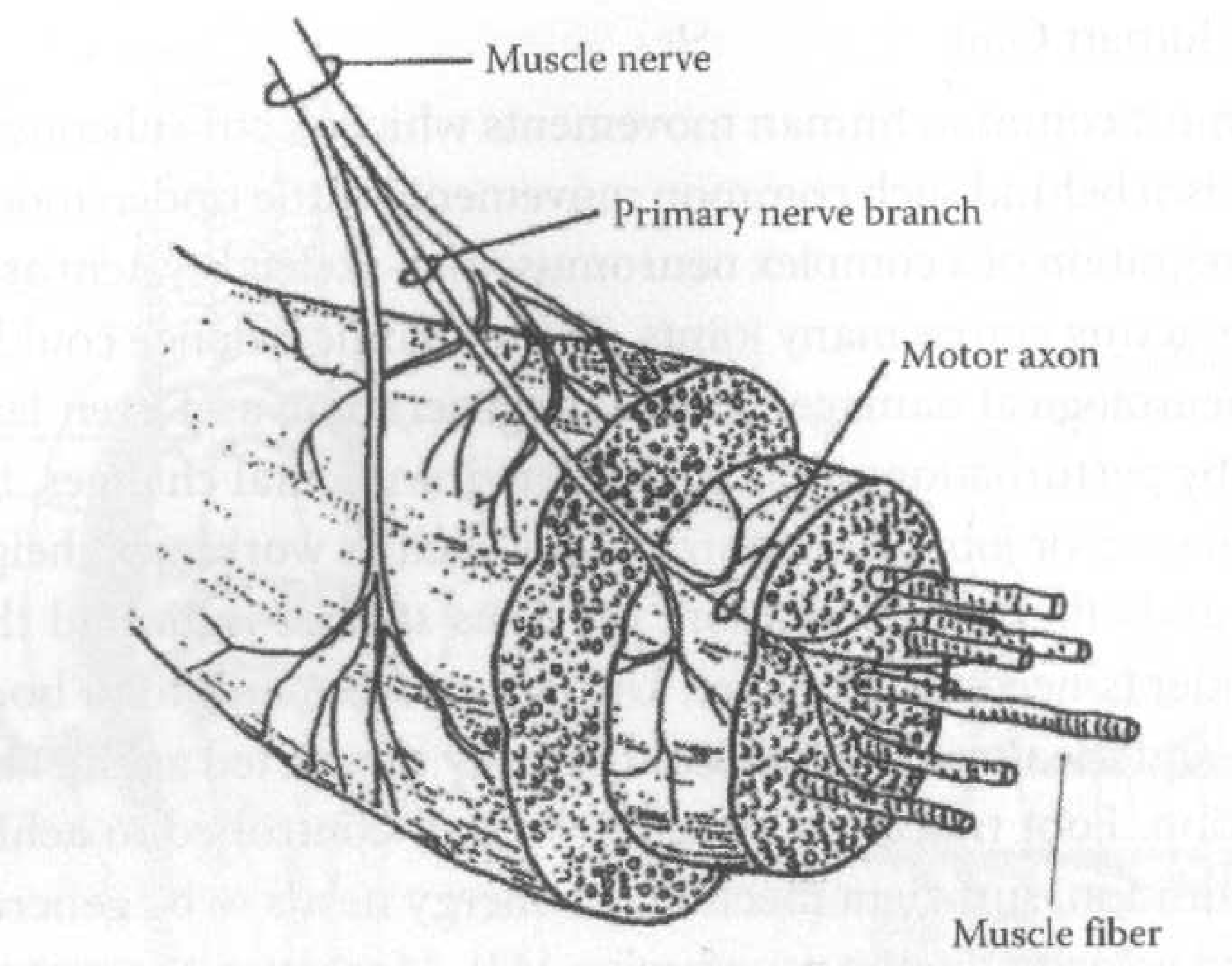


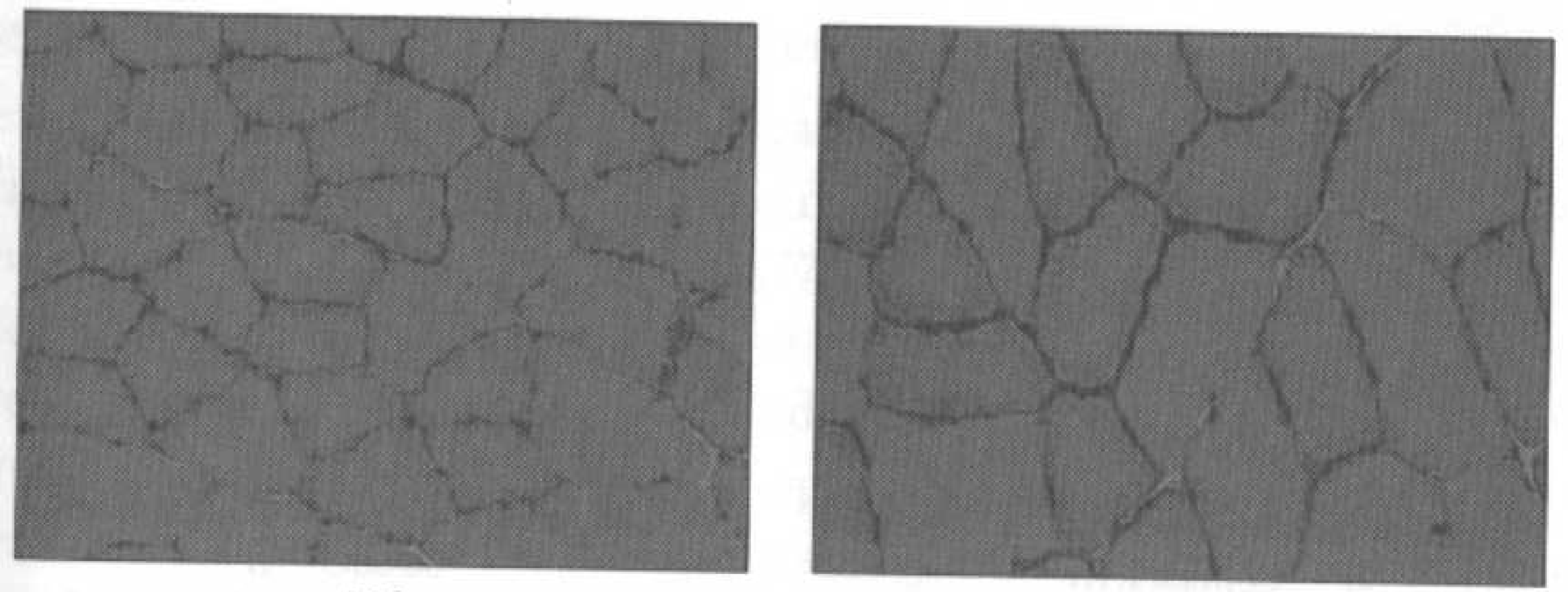
FIGURE 2.15 The muscle nerve, motor axons, and muscle fibers.

goal [49]. The latter is the basis for learning complex motor skills, such as sports routines and job tasks requiring specific motor skills. Motor learning is one of the most complex human behaviors, and enables the human body to adapt and learn in a continuously changing environment. The body relies on a series of sensory impulses followed by motor commands from the brain to accomplish a skilled task with efficiency and precision.

The initial stage of learning relies greatly on visual feedback and the requirement that the movements must be performed consciously. Eye–hand coordination is essential during this stage as many occupational tasks, such as reaching or lifting an object, are guided by visual input and feedback. During the second stage of learning, proprioceptive cues provide feedback to integrate the techniques [50]. When the third stage is reached, a stable movement pattern is formed. New pathways and junctions are established in the brain and the control of movements gradually becomes autonomous, unlike the conscious control needed in the early stage [51]. Muscle firing patterns used for the control of movement is sophisticated and is dependent on a number of variables. As one becomes more accomplished in a task, such as in martial arts training, ballet dancing, basketball, or manual materials handling, those firing patterns become more optimized for the task demands. However, muscle injury can occur when tasks demands exceed the tolerance of skeletal muscle, and those demands can comprise muscle forces, strain rates, repetitions, or work-rest cycles. While evidence indicates that more accomplished firing patterns can reduce muscle injury susceptibility, we must be cognizant of what factors contribute to muscle injury, and the mitigating factors as a foundation to design effective intervention strategies.

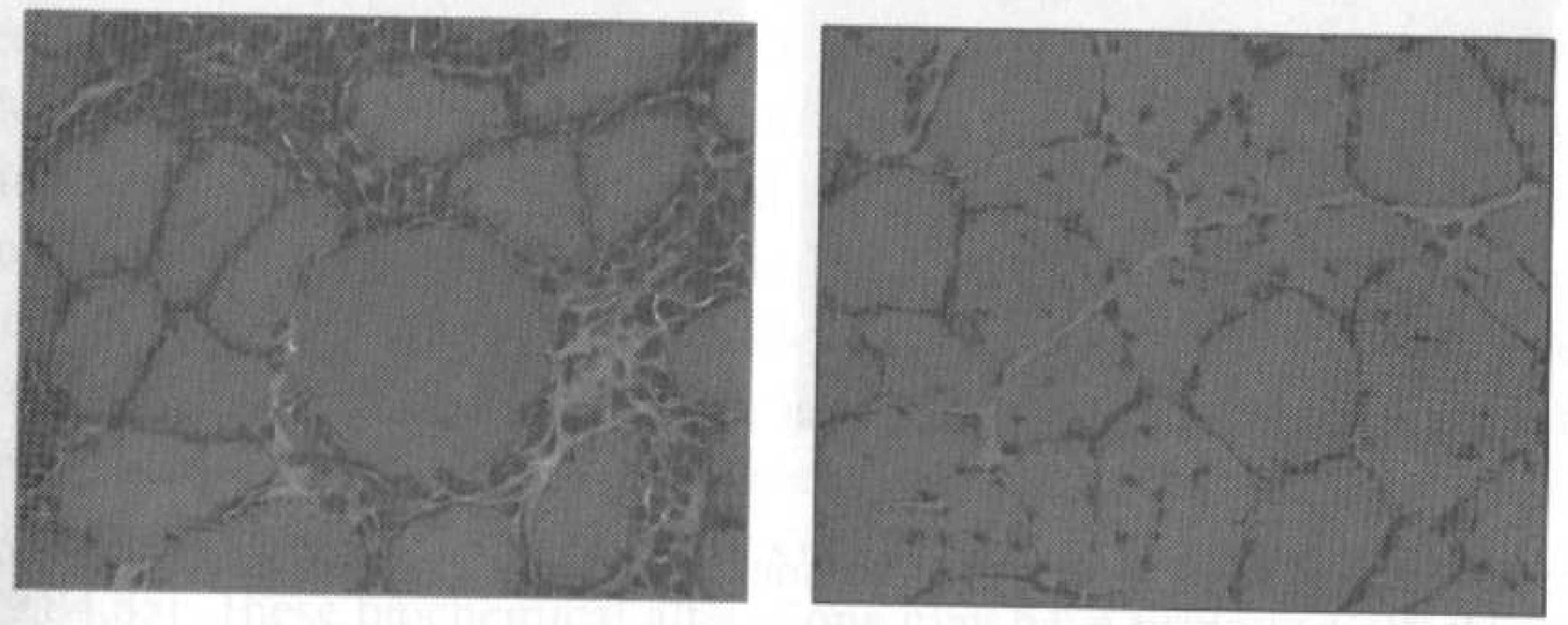
2.9 INJURY MECHANICS

We know that eccentric muscle actions are known to cause a greater amount of muscle damage than concentric or isometric contractions (Figure 2.16). This suggests that high load tensions in fibers may be more important than physiologic considerations in the etiology of the injury process [52–54]. For decades, it has been hypothesized that high mechanical forces produced during eccentric muscle actions have been causal in the underlying etiology of muscle strain injuries [15,55]. This was thought to be due to high fiber stresses in the contractile apparatus due to high forces transmitted axially to the actin and myosin contractile proteins. Additionally, high mechanical forces produced during muscular contractions, particularly in eccentric exercise, where forces are distributed over relatively small cross sectional areas of muscles, cause disruption of contractile and intermediate filament proteins in skeletal muscle fibers and connective tissues [56,57]. A single exposure to damaging eccentric muscle actions results in loss of performance immediately after exposure and can last for up to 30 days [58]. Past investigations of eccentric contraction-induced muscle injury have indicated that mechanical factors such as peak force and average force [59], work during stretch [60], fiber length [59,60], strain [61], range of motion [62], number of repetitions [63] (Figure 2.17), and work-rest cycles [64] influence the amount of muscle damage. Change in maximum isometric force after injurious exposure has been shown to be the best indicator of the degree of muscle damage [65]. Interestingly, exposure to concentric (shortening) or isometric muscle actions does not normally produce muscle injury [15,66–68]. Recently, the ability to rapidly quantify both skeletal muscle degeneration and inflammation following an injurious exposure in the same tissue using a novel stereological technique has been shown to reveal further insight into the injury and repair process of skeletal muscle [63,67,69,70].



72 h 240 h

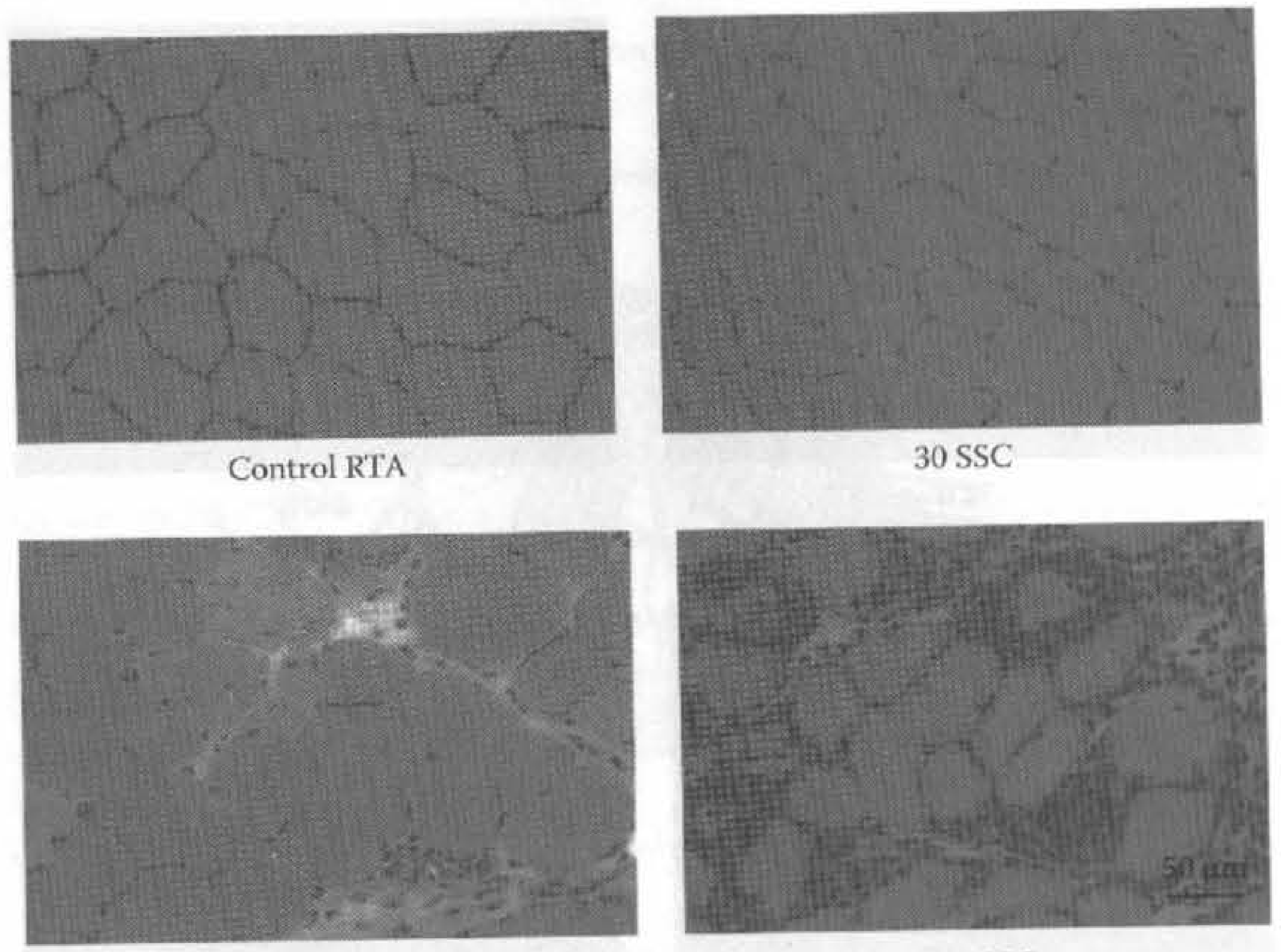
Isometric exposure



72 h 240 h

Stretch-shortening contraction exposure

FIGURE 2.16 Histographs of tibialis anterior muscle sections exposed to isometric contractions and injurious SSCs 72 and 240 h after exposure.



Control RTA

30 SSC

70 SSC

150 SSC

FIGURE 2.17 Histographs of tibialis anterior muscle sections exposed to either none, 30 SSCs, 70 SSCs, or 150 SSCs 72 h after exposure.

Fortunately, our understanding of the cellular and molecular mechanisms involved in mediating muscle damage and repair after strain, or low force, repetitive motion induced injuries is rapidly increasing [2,71,72]. Understanding how muscle tissue responds to these various stressors, and the time course of those responses, is necessary for defining approaches that can be taken to reduce the chances of obtaining an injury, or approaches to enhance the rate of recovery once an injury occurs. The cellular changes that occur as a result of acute muscle strain and repetitive motion are different. Strain injuries are associated with structural damage to myofibers, blood vessels and nerves, and cause edema and inflammation [73,74]. Repetitive motion damage can be associated with muscle ischemia, pain and mitochondrial dysfunction [75,76]. Details regarding the cellular responses to repetitive use and strain injuries are discussed hereafter.

2.9.1 Strain Injuries and Skeletal Muscle

Strain injuries are the result of three basic processes: (1) Initially, excessive forces coupled with lengthening result in structural damage to muscle cells (myofibers), including tearing of the cell membrane (i.e., the sarcolemma). (2) Structural damage to the sarcolemma results in an increase in intracellular calcium levels, modifications of myofiber proteins and lipids and the activation of intracellular pathways that regulate the injured muscle's response to damage. (3) Pro- and anti-inflammatory factors (i.e., cytokines and chemokines) are released by local tissues and infiltrating immune cells. Cytokines and chemokines cause inflammation and stimulate cellular pathways mediating muscle regeneration and repair. These three processes are involved in mediating the extent of physical damage, functional changes of the muscle, pain, and repair.

2.9.2 Muscle Injuries Associated with Repetitive Tasks

Repetitive tasks involve movements that typically require little force generation by a muscle. Instead, the muscle action may need to be maintained over long periods of time, or repeated over and over again during a work cycle [76,77]. Injuries caused by these types of activities are not usually associated with inflammation or large areas of myofiber degeneration, but instead are characterized by muscle pain and/or rapid fatigability of the muscle [78–82]. Repetitive task injuries are prevalent in people working with computers and other less physically demanding tasks. With the decrease in jobs that require high levels of physical exertion, understanding the mechanisms underlying this type of damage is crucial.

Injury due to overuse has been studied in people with trapezius myalgia. This disorder is often seen in workers whose job requires them to maintain stable upper body postures for extended periods of time such as computer and clerical work [78,80]. Trapezius mylagia is associated with the appearance of ragged Type I muscle fibers and with a decrease in muscle blood flow to the injured region. This ragged appearance of myofibers is an indicator of mitochondrial dysfunction in the cell [75,82,83]. The dysfunction and pain associated with trapezius myalgia and with other overuse injuries have been linked to changes in calcium regulation in the damaged area, changes in the pH of the intra extracellular fluid, and changes in the local concentrations of specific ions involved in mediating muscle activity [79,84,85]. These biochemical alterations may have profound effects on myofiber metabolism and on the activity of sensory pathways carrying pain information (reviewed in [76]). Early onset overuse related MSDs have been shown to have an inflammatory component, with increased levels of CRP, TNF-α, IL-1β, and IL-6 in serum [86]. Mechanical tissue injury that is localized from repetitive tasks can result in both local and systemic inflammation followed by structural changes in the tissue [2]. Barbe and Barr developed an animal model of repetitive upper limb tasks to model repetitive use injuries [87]. Based on their results, they argue that inflammation reduces soft tissue tolerance to continued repetitive loading, and is related to pain and movement dysfunction [88]. Also, they established a causal relationship between repetitive tasks and the development of carpal tunnel syndrome with all the associated physiological changes such as reduced conduction velocity, motor function deficits, and sensory changes [89]. As the upper limb task demands increase, serum and tissue levels of cytokines and chemokines increase, along with deleterious changes in grip strength [90]. This is an important finding because it demonstrates a causal link between the task demand, changes in inflammatory mediator levels in the tissue and blood, and motor performance and strength. High force, moderate repetitive tasks of the upper extremities also change central nervous system sensitization by increasing levels of substance P and neurokinin at the dorsal horn of the spinal cord that resulted in reduced motor function, neuropathic pain, mechanical allodynia, and widespread inflammation [91].

2.9.3 Physical Damage to Tissue

Strain injuries are caused by exposure of muscle and other soft tissues, including vasculature, nerves and tendons to excessive strain or lengthening [92–94] Studies performed in both humans [73,95–98], and animals [55,99,100] have demonstrated that exposure to lengthening contractions results in physical damage to muscle tissue that can include shearing of myofibers, the loss of intermediate filaments and mitochondria, damage to the extracellular membrane, and disruptions in Z-line alignment (i.e., Z-line streaming). Immunostaining for structural proteins that maintain the integrity of the myofiber, such as desmin, titin, and fibronectin, have demonstrated that there are disruptions of the exo- and endosarcomeric membranes [66,94,101], and of the extracellular matrix [100,101] in strain-injured muscle tissue. In lengthening contraction-induced injuries, damage within the muscle is most often seen at the myotendinous junction and at specific sarcomeres [102–105]. In fact, it has been hypothesized that there is a population of sarcomeres that are weaker, and tear more easily under lengthening conditions [94,106,107]. The stretch-induced damage to the extracellular matrix, sarcomeres, and critical cell organelles are associated with reduced isometric muscle force [62,65,108,109], but not with pain. It has been hypothesized that these initial structural changes initiate a chain of events that may maintain an injury-induced force deficit, result in inflammation and pain, and stimulate pathways important for regulating muscle repair and regeneration.

2.9.4 Muscle Inflammation

The physical disruptions of muscle fibers along with increases in intracellular calcium are the initial effects of muscle injury. However, force deficits, muscle swelling, and soreness occur 1–7 days after the initial injury, and are associated with muscle inflammation [55,63,93,101,110]. Neutrophils, the first immune cells to enter damaged tissue, actually infiltrate muscle within 2 h of the initial injury [111,112]. We are only beginning to understand the complex roles that various immune cell types play in the damage and repair processes. However, it has been demonstrated that neutrophils phagocytize degenerating fibers and debris produced by injury. In addition, neutrophils can participate in the production and release of free radicals from damaged tissue, which can exacerbate the damage [113]. Neutrophils can also produce proteases and a number of cytokines, including tumor necrosis factor-α (TNF-α; [114]) and IL1-β [115]. These cytokines might increase muscle catabolism and degradation and act to attract monocytes to the site of the injury [116–118].

Monocytes/macrophages, the other inflammatory cells commonly seen in injured muscle, can be found between 12 h and 14 days after the initial muscle injury [119,120]. In rats, macrophages expressing specific cell-surface molecules, including ED1 and ED2, have been identified in damaged muscle tissues [120–122]. ED1 expressing macrophages infiltrate damaged and necrotic tissue and remove debris. These macrophages also express pro-inflammatory cytokines including TNF-α [123,124]. Aside from increasing muscle catabolism and promoting protease activity, TNF-α also activates the transcription factor, nuclear factor κB (NF-κB), to stimulate transcription of genes encoding for proteins that are part of the ubiquitin proteolytic pathway [125,126]. TNF-α may also stimulate the transcription of other pro-inflammatory cytokines including IL-1β and IL-6 and the chemokine monocyte chemoattractant protein (MCP-1; [127,128]). The increased production of cytokines and chemokines by inflammatory cells in damaged tissue enhance local pathways mediating tissue inflammation and may act to exacerbate damage during the first 5 days after muscle injury.

2.9.5 Muscle Regeneration and Repair

The infiltration of immune cells along with the release of pro-inflammatory cytokines appears to enhance muscle damage. During the acute phase of the injury, both pain and force deficits appear to be reduced by treating animals with nonsteroidal anti-inflammatory drugs (NSAIDs). For example, rabbits which were exposed to a session of repeated eccentric contractions and treated with the NSAID flurbiprofen, showed improved functional recovery during the first week after injury as compared to controls [129]. However, 4 weeks after the injury, the NSAID treated animals demonstrated reduced force generation. The authors hypothesized that treatment with NSAIDs may have interfered with or delayed the recovery process in these animals [129]. This finding was supported in more recent work by LaPointe and colleagues [121,122]. In humans with muscle damage caused by downhill walking, treatment with over the counter doses of acetaminophen or ibuprofen results in a decrease in pain, but these anti-inflammatory agents also decrease protein synthesis which may be needed for muscle repair [130–132]. These findings suggest that inhibition of the inflammatory response interferes with normal recovery of muscle after a strain-induced injury.

Inflammatory cells, particularly macrophages, may stimulate myofiber regeneration through a number of different mechanisms. ED2 expressing macrophages, also referred to as resident macrophages, are thought to play a role in muscle repair and myofiber regeneration [120–122,133]. These macrophages may stimulate growth and repair by releasing a number of factors that could stimulate the division, migration, and differentiation of muscle precursor cells. These factors include, fibroblast growth factor-2 (FGF-2; [134,135]), insulin-like growth factor-1 (IGF-1; [136–138] and hepatocyte growth factor (HGF; [134,139]). In addition, ED2 expressing macrophages may also release the anti-inflammatory cytokines IL-6 [140,141] and IL-15 [142–144]. Although inflammation causes pain and appears to exacerbate myofiber damage, the inflammatory process also appears to be necessary for complete repair of tissue and recovery of muscle function [145].

2.10 FUTURE DIRECTIONS

In this chapter, basic aspects of skeletal muscle physiology, motor control and learning, and more advanced concepts of muscle injury were discussed. The control mechanism for postural balance and human gait was also reviewed. There are many directions in which research on the mechanisms of motor control described in the chapter could be extended. Besides locomotion, other motor behaviors that are commonly seen in occupational settings could be further researched. For example, the control of reaching movement using different arm postures, body movement strategies during obstacle crossing, postural control strategies after slips and falls, and so forth. The contribution of these postures and strategies to common injury risks for overexertion, traumatic injuries, and musculoskeletal disorders, for example, is intuitively apparent, but not substantiated by sufficient research efforts. Further in-depth understanding in these areas will provide insights to improve job performance and to prevent such common occupational injuries as slips- and falls-related trauma. In addition, skeletal muscle injury mechanics is important to the field of ergonomics and the mitigation of occupational musculoskeletal disorders [146]. Recent work in muscle pathomechanics have allowed better understanding of the response of tissues to repeated mechanical exposures [70]. Efforts to incorporate epidemiological, biomechanical loading, soft tissue tolerance, and psychosocial findings into a systems-engineering approach should be pursued to establish a better understanding of the pathways of musculoskeletal injury and the resultant preventive strategies. Although we are beginning to understand how the major risk factors influence the load-tolerance relationship of human tissue, the mechanism of interaction of these risk factors in producing tissue damage is virtually unexplored [147]. Further work is needed to clarify the response of tissue to acute and repetitive loading and the pain pathways associated with these physiological responses. Much of our knowledge about tissue tolerance, especially that related to repetitive loading, has been gained from cadaver studies. Such data do not reflect the biological system's ability to physiologically adapt to exposures that occur during actual working conditions. Future research efforts should examine the in vivo tissue tolerance of healthy populations as well as compromised populations that are reflective of workplace populations [147]. Additionally, research involving the risk of further injury associated with return-to-work is sparse. Integration of epidemiological data, biomechanical exposures, soft tissue pathomechanics, and psychosocial data are needed to determine how the risk of injury is affected when an individual is working while recovering from a musculoskeletal disorder [147]. The findings from research on the pathomechanics of skeletal muscle injury are beneficial for incorporation into modern biomechanical and psychosocial models. In addition, biomarkers that are identified from pathomechanics studies could be beneficial for use in field studies to help determine jobs and populations at risk.

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