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SPECIAL ISSUE

Practical Anatomy and Physiology: The Skeletal Muscle System

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This article is the first in a series that summarizes the essential anatomy and physiology of the body systems that are trained in biofeedback and neurofeedback. This article examines the skeletal muscle system, the types of skeletal muscle fibers, motor units, muscle action potentials, the surface electromyographic signal, muscle contraction, sensory-motor integration, and practical recommendations for beginning biofeedback professionals.

Skeletal Muscle System

The word *muscle* is derived from the Latin *mus*, which means ''little mouse,'' because the rippling that accompanies skeletal muscle contraction resembles mice scampering underneath the skin. Muscle tissue's defining characteristic is its conversion of chemical energy into mechanical energy (Marieb & Hoehn, 2007). Muscles are the largest consumers of energy in the body. In an average individual, muscles typically account for 70% to 85% of gross body weight. An individual's muscles are housed in approximately 600 sacks of connective tissue called fascia. This connective tissue provides boundaries of shape for muscles and acts as glue to hold muscles in place (Marieb & Hoehn, 2007). Tendons are made of dense fascia that connect muscles to other structures, such as bones. Connective tissue contributes to the skeletal muscle system's elasticity, which allows muscle fibers to produce and transmit force (Tortora & Derrickson, 2009).

Most skeletal muscles are attached to and move the bones of the skeleton. They appear striped (striated) due to alternating dark and light bands. They share many of the structures found in other cells, but unlike other cells, they contain more than one nucleus (Fox, 2009).

The skeletal muscle system consists of extrafusal muscle fibers and connective tissue. Extrafusal fibers are enclosed by a plasma membrane called the sarcolemma. Each extrafusal muscle fiber is composed of hundreds to thousands of cylindrical myofibrils that are built from thin and thick filaments. These filaments are shorter than a muscle fiber and are stacked in compartments called sarcomeres that are separated by dense zones called Z discs. Muscle fibers contract and generate force by pulling Z discs together. This action shortens the sarcomeres and produces movement at joints (see Figure 1).

Skeletal muscles are highly adaptable because they can generate a remarkable range of force. The same muscles that can pick up a 1-ounce pencil can also lift a 14-pound textbook (Marieb & Hoehn, 2007).

Types of Skeletal Muscle Fibers

Skeletal muscle fibers vary in structure and function. Two primary fiber categories are usually identified: slow-twitch, or type I fibers, and fast-twitch, or type II fibers. Slow-twitch fibers are often referred to as red muscle. They are designed for posture maintenance and sustained aerobic activity and are generally resistant to fatigue. Fast-twitch fibers are often referred to as white muscle. They are designed for quick responses and heavy lifting, but they fatigue relatively quickly. Nearly all skeletal muscles are composed of some proportion of both of these fibers based on the type of work that they are designed to perform (Saladin, 2007).

Motor Units

Skeletal muscle fibers are organized into motor units that consist of an alpha motor neuron (nerve cell) in the spinal cord, the muscle fibers it controls, and an axon (nerve fiber) that connects the two together. The end of the axon and the muscle fiber are separated by a synapse (small space), called the neuromuscular junction. When the neuron sends an

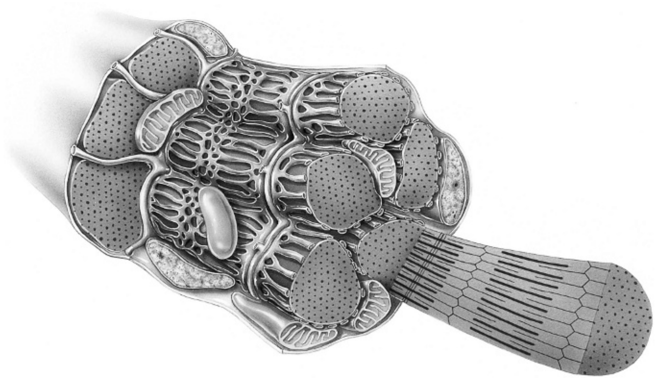

Figure 1. Details of a muscle fiber. From *Principles of Anatomy and Physiology*, 12th edition, by Gerard J. Tortora and Bryan H. Derrickson © 2009 John Wiley & Sons, Inc. Reproduced with permission of John Wiley & Sons, Inc.

electrical signal down the axon, the neurotransmitter acetylcholine is released into the neuromuscular junction, which stimulates the muscle fibers to contract. The motor end plate is the section of the muscle fiber, located on the sarcolemma, which receives chemical messages from the neuron (Saladin, 2007).

The axon of a single alpha motor neuron can be as long as 3 feet and may branch out and communicate with different muscle fibers. Muscle fibers that perform several actions may be innervated by more than one motor neuron. Most axons are covered in myelin. This myelin sheath allows the nerve to conduct electrical impulses rapidly down the nerve. The neurological symptoms (such as muscle weakness) that are seen in multiple sclerosis are due to the loss of myelin that occurs with this disease. Alpha motor neurons are called efferent nerves because they conduct messages from the central nervous system to skeletal muscles (Chandler & Brown, 2008).

Muscle Action Potentials

When an alpha motor neuron transmits instructions down the axon to skeletal muscle fibers to contract, a muscle action potential (MAP) is created. A MAP is a rapid electrical signal that travels along the surface of the motor end plate, resulting in a muscle contraction. Muscle contractions involve ionic depolarization, in which the positively charged ions rush into the cells and negatively charged ions rush out, and vice versa, creating a rapid back-and-forth shift in positive to negative polarization (Saladin, 2007). The process of depolarization begins at the motor end plate and moves sequentially along the length of the muscle. This is why when recording a muscle with surface electromyography (SEMG), it is often recommended that the recording electrodes be placed along the muscle fibers, rather than across them (Sherman, 2003).

Figure 2 shows both the wrong and correct way to record masseter activity. In the left image, the two active electrodes located at the bottom of the MyoScan™ sensor are incorrectly oriented *across* this muscle's vertical fibers. In the right image, the sensor is rotated 90 degrees correctly so that the active sensors can record *along* the masseter's striations.

Electromyography

SEMG measures the electrical activity within a muscle that is generated by MAPs (Tortora & Derrickson, 2009). The amplitude or strength of an SEMG signal reflects the number of active motor units, their firing rate, and resistance from skin and adipose (e.g., fat) tissue. Adipose tissue acts like an electrical insulator between the muscle and the recording electrodes. The thicker the layer of adipose tissue, the smaller the signal that will reach the electrodes (Cram, 1998).

MAPs travel through tissue and interstitial fluid via volume conduction. The body is like a water-filled bag subdivided by tissues and membranes, creating separate electrical zones. The electrical charge that triggers muscle contraction in one zone influences the electrical field in adjacent zones. This means that the SEMG does not exclusively monitor the muscle over which surface electrodes are placed; it also records MAPs generated by underlying muscles and distant muscles (Sherman, 2003). The motor units closest to the electrodes generally contribute more to SEMG signal amplitude than distant motor units because their signals have a shorter path and lose less energy (Stern, Ray, & Quigley, 2001).

The wider an electromyograph's filter bandpass, which is the range of frequencies it analyzes, the more remote the motor units that can be detected. More closely spaced electrodes measure less volume conduction, whereas widely spaced electrodes measure a relatively large amount of volume conduction. When adjacent muscles contract at the same time as the monitored muscle, one cannot accurately distinguish how much of the SEMG signal is coming from each muscle. This phenomenon is often referred to as cross-talk (Sherman, 2003).

When performing general relaxation training, some clinicians prefer to use wider placements, which encourage a significant amount of volume conduction. Wide placements for general relaxation training can involve placing active electrodes across the muscle fibers, rather than along them (such as with a frontalis placement), placing active electrodes on the belly of two separate muscles (such as with a bilateral upper trapezius placement), or even placing the active electrodes on nonspecific sites away from any muscle belly (such as with a wrist-to-wrist placement; Cram, 1998).

Figure 2. Incorrect and correct masseter placements. Photos courtesy of Tim Barcus (photographer) and Peter Schaffner (model), Truman State University.

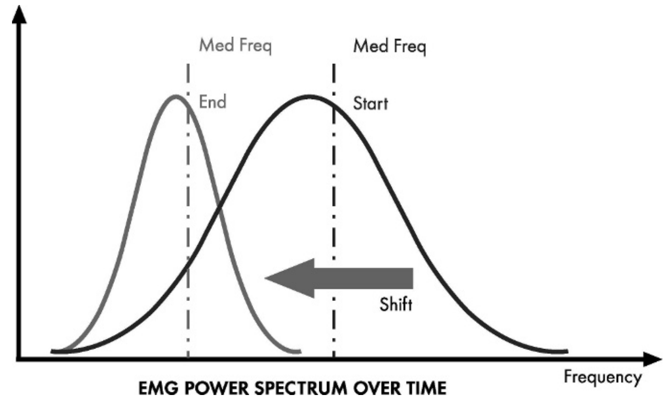

Figure 3. As a muscle fatigues, the power density spectrum and the frequency spectrum shift to the left side of the frequency scale, and consequently, the median and mean frequencies decrease. Note that mean and median frequencies are relevant muscle fatigue indicators only for isometric contractions (sustained contraction with no movement). Graphic courtesy of www.thoughttechnology.com.

Spectral analysis, which is typically performed using a fast Fourier transformation, shows the frequency component of the SEMG signal in hertz (Hz), or cycles per second (Andreassi, 2007). When muscles contract, they produce many different frequencies, and each muscle generates its characteristic pattern of frequencies at different levels of tension (Sherman, 2003). Although each skeletal muscle has its own power spectral curve, the bulk of SEMG signal power for most muscles is estimated to lie between 10 and 150 Hz (Stern et al., 2001) or 20 and 200 Hz (Andreassi, 2007). The upper limit for surface recording is 1,000 Hz, because tissue (skin, subcutaneous fat, muscle, and connective tissue) absorbs higher frequencies (Andreassi, 2007). Muscles measured in research and clinical practice generally produce frequencies between about 8 and 500 Hz (Sherman, 2003).

Strong muscle contraction shifts the distribution of SEMG power upward and toward higher frequencies (Sherman, 2003). If a muscle begins to fatigue following sustained contraction, energy is depleted, metabolites build up in its tissues, and the mean and median frequencies shift downward toward lower frequencies (see Figure 3). This frequency shift only indicates muscle fatigue during isometric contractions (sustained contraction with no movement) (Florimond, 2009).

There are multiple theories to explain the shift in the frequency spectrum with muscle fatigue, including a slowing of the conduction velocities of the muscle fibers, the synchronization of motor unit recruitment patterns, and a shift from fast-twitch to slow-twitch fiber dominance (Cram, 1998).

Use of a wide bandpass is often recommended for SEMG recording and biofeedback training. Because a narrow bandpass eliminates lower frequencies from the recording, one might interpret a muscle as being more relaxed than it really is. Also, when measuring a muscle during sustained or repetitive activity, muscle fatigue may be falsely interpreted as increased muscle relaxation, as the muscle's frequency spectrum shifts downward.

Muscle Contraction

When a motor unit is activated, all of its muscle fibers contract completely. The body adjusts the strength of muscle contraction by varying the number of motor units it activates. The somatic nervous system achieves fine motor control by activating numerous small motor units. For example, the average motor unit of the eye muscles contains 23 muscle fibers. We generate more powerful contractions, at the cost of precise control, by activating large motor units. For example, each motor unit of the gastrocnemius (calf) muscle of the leg, which allows us to walk or run, contains from 100 to 2,000 muscle fibers (Fox, 2009).

Motor units are recruited in order of size. Smaller motor units are recruited first, generating tension in gradual steps to produce smooth movements. These motor units provide the precise motor control required in tasks such as writing. Larger motor units are recruited later as additional force is required, as in performing a bench press. In life-threatening emergencies, both small and large motor units may be recruited at once as part of the fight-or-flight response. During endurance tasks, our body rotates motor unit firing between different muscle fibers to prevent fatigue and produce smooth movement. A muscle's power is determined by the total number of muscle fibers that are available for contraction (Tortora & Derrickson, 2009). Although the muscle fibers comprising an individual motor unit show an all-or-none response, a skeletal muscle can produce graded responses by activating different sets of motor units (Tortora & Derrickson, 2010).

In an isometric contraction, during which the joint doesn't move and the muscle length remains constant, SEMG amplitude is positively correlated with muscle tension. The relationship between isotonic contraction, during which a joint moves as the muscle lengthens or shortens, and SEMG amplitude is complicated by changes in the relationship between muscle length and generated tension and by the movement of the surface electrodes with respect to the motor units they are monitoring. Although the consensus of opinion is that the surface EMG signal is consistently and reliably proportional to the force and contraction intensity for each subject (Sherman, 2003), there is only a direct relationship between SEMG amplitude and muscle tension when a muscle shortens at a constant velocity (Stern et al., 2001).

Sensory-Motor Integration

Proprioception is the ability to perceive the body's movement and position based on internal information (Breedlove, Rosenzweig, & Watson, 2007). For example, when you contract the biceps brachii muscle, your arm flexes. This limb movement activates muscle length and joint receptors that provide the information you need to position your arm. Proprioceptive sensations allow us to determine the weight of an object and the muscular effort necessary to lift it (Tortora & Derrickson, 2009).

There are two primary proprioceptive sensory organs within muscles. A Golgi tendon organ informs the central nervous system about the effort produced by a muscle, which helps us to acquire and refine motor skills. A muscle spindle is a stretch receptor, whose purpose is to regulate muscle length and establish muscle tone (the degree of contraction while the muscle is at rest). Muscle spindles are associated with intrafusal muscle fibers, which run parallel to the larger extrafusal muscle fibers of skeletal muscles. Intrafusal fibers are innervated by the gamma motor system, which is designed to adjust stretch receptor calibration and is associated with balance, coordination, muscle stretch reflex, and posture maintenance (Breedlove et al., 2007; Tortora & Derrickson, 2009).

Sensorimotor control of the skeletal muscle system combines voluntary movement and unconscious motor reflexes. We can consciously use muscles to walk, bend, reach, and lift, but we are often unaware of the rhythmic movement of the diaphragm and the intercostal muscles that allow us to breathe and the muscle tone that maintains our posture and stabilizes our limbs.

Practical SEMG Tips for Beginning Professionals

Beginning biofeedback professionals who wish to use SEMG effectively must become familiar with the muscle anatomy that they intend to monitor and must learn how to properly place electrodes, understand and recognize artifacts, and set up the SEMG recording equipment (Sherman, 2002). To accurately record from a target muscle, it is essential to know the shape of the muscle, where it is attached to the bones in the body, and the location of the muscle belly (central region of the muscle). We recommend that beginners obtain a good muscle chart and/or anatomy text, SEMG placement map, a practical laboratory manual on SEMG such as *Biofeedback Mastery* (Peper, Gibney, Tylova, Harvey, & Combatalade, 2008), and seek guidance from a qualified mentor.

A valid SEMG recording requires a number of steps:

1. Prepare the skin with an alcohol swab or abrasive rub (as recommended by the equipment manufacturer) to reduce skin-electrode impedance to an acceptable level.
2. Ensure that sensors make good contact with the skin, and check sensor contact frequently during the recording session to guarantee that skin-electrode impedance remains stable, especially during dynamic recordings.
3. Select the correct sensor placement for your purpose. If you are up-training a muscle and/or recording a muscle during dynamic movements, use closely-spaced electrodes to help reduce cross-talk. If you are down-training a muscle or muscle group during static postures, such as during general relaxation training, you may prefer wider electrode spacing. Failure to choose the appropriate placement can lead to an invalid recording and/or an incorrect interpretation.
4. When monitoring a muscle during dynamic assessment, its position can dramatically shift underneath the skin as joints flex, extend, and rotate, especially in the limbs. This means that recording electrodes that are properly placed in one body position may completely miss the muscle of interest when the client assumes another position.
5. Choose the proper bandpass for the best SEMG recording. To capture as much SEMG activity as

possible, a wide bandpass is always preferred. A narrow bandpass is recommended only when one is attempting to reduce cardiac, cross-talk, or electrical artifacts from the signal.

6. Be aware of external sources of artifact that might contaminate the recording, such as cell phones or fluorescent lighting. Sometimes computers, monitors, and other electrical equipment, in close proximity to the SEMG leads and sensors, can produce electrical interference. A spectral analysis display can help identify electrical artifact. Make sure that the SEMG instrument has a notch filter to help eliminate 50/60-Hz artifact and that you have chosen the appropriate filter for your region (60 Hz in the United States).
7. Consider the effects of adipose tissue on impedance when interpreting an SEMG recording. Even with a comparable level of muscle contraction, the amplitude of an SEMG signal from a client with very little fat between the skin and the muscle can appear to be much higher than that of a client with a significantly larger fat layer. Variations in subcutaneous fat render SEMG amplitude comparisons between subjects, or even between different muscle placements on the same subject, problematic.

Using standardized SEMG assessment and training procedures can help biofeedback professionals to meaningfully compare repeated measurements over a series of sessions to evaluate client progress. As professionals use standardized protocols over time and gain experience in SEMG interpretation, they will be better able to evaluate and compare SEMG patterns and degrees of SEMG abnormalities between different clients.

To ensure a minimal level of competence in SEMG recording and biofeedback assessment and training procedures, beginning biofeedback professionals should pursue certification by the Biofeedback Certification International Alliance (http://www.bcia.org).

Conclusion

The competent use of the SEMG requires an understanding of skeletal muscle anatomy and physiology. This knowledge allows a clinician to accurately place surface electrodes along the belly of a target muscle and to interpret measurements within the context of electrode placement, filter bandpass, volume conduction, the effects of adipose tissue, and the client's musculoskeletal activity.

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