# **Lab 6: Muscle Physiology**

## **Pre-Lab Reading**

Skeletal muscle can be directly stimulated to contract through the skin using an electrical stimulus. Certain sensitive spots that elicit a very strong response are known as **motor points**. Motor points are usually found on the belly of the muscle where the nerve enters.

The muscles you will be stimulating include the **abductor digiti minimi** (innervated by the **ulnar nerve**) and the **flexor digitorum superficialis** (innervated by the **median nerve**). The abductor digiti minimi is located on the medial surface of the palm while the flexor digitorum superficialis is located on the anterior surface of the forearm. The function of the abductor digiti minimi is to abduct the little finger. The flexor digitorum superficialis flexes first the middle phalanges and then with continued action, the proximal phalanges and wrist. This muscle is involved only in rapid, forceful flexion of the digits in grasping movements. The motor point (median nerve) for the flexor digitorum superficialis is found on the lateral side of the anterior forearm. The motor point for the abductor digiti minimi is found on the medial side of the hand, just distal to the wrist. You will begin with the abductor digiti minimi motor point; however, if you have difficulty finding this motor point, you can attempt to find the motor point for the flexor digitorum superficialis.

**Single Muscle Twitch**

A skeletal muscle is made up of many **muscle fibers** (muscle cells) that run the length of the muscle. Each muscle fiber contains many **myofibrils**, which are “bundles” of many contractile proteins arranged into functional contractile units called **sarcomeres**. Among these contractile proteins are **actin** (a major constituent of the thin filaments) and **myosin** (thick filaments). When the muscle fiber is stimulated to contract by a **somatic motor neuron**, an action potential is generated in the **sarcolemma** (the muscle fiber’s plasma membrane). The action potential is conducted over the sarcolemma and deep into the muscle fiber by **transverse tubules** or **T tubules**, which are tubular extensions of the sarcolemma. As the action potential travels down the T tubules, it triggers the release of calcium ions from the **sarcoplasmic reticulum** (smooth ER) into the **sarcoplasm** (cytoplasm).

The calcium ions bind to troponin complex, which moves tropomyosin away from where it was blocking the myosin binding site on actin, thus allowing the myosin heads (crossbridges) to bind to the actin. Using the energy of ATP, the myosin crossbridges pivot (power stroke) and pull the actin filaments toward the center of the sarcomere. The sarcomeres shorten and pull on the tendons, which then pull on the bone. The muscle fiber relaxes when the calcium ions are pumped back into the sarcoplasmic reticulum via primary active transport. The myosin crossbridges can no longer bind to the actin, and the actin filaments slide back, returning the sarcomere to its original length.

A **muscle twitch** is the mechanical response of a muscle cell or whole muscle to a single stimulus. If you look closely at a single muscle twitch, you will see that the **contraction phase** occurs faster than the **relaxation phase**. Also note the **latent period**, which is the period of time it takes the muscle to start generating tension after it has been stimulated to contract. The latent period exists because the events that result in a contraction take time. These events include (1) depolarization of the sarcolemma and the T tubules, (2) release of calcium ions into the sarcoplasm from the sarcoplasmic reticulum, (3) attachment of myosin crossbridges to actin, and (4) tightening of elastic elements within the muscle cell.

There are two kinds of muscle twitches: **isometric twitches** and **isotonic twitches**. These two types of twitches differ based on whether the muscle shortens in length or not. In an isometric contraction, tension develops, but the muscle is not able to overcome the **load** (force opposing the contraction) and does not shorten. An example of an isometric contraction would be trying to lift a two-ton boulder. When a muscle contracts isotonically, the muscle generates enough tension to overcome the load, and thus the muscle shortens and lifts the load. An important point to remember is that all isotonic twitches start out as an isometric twitch. When a muscle first starts to contract, it does not shorten because it has not generated enough force to move the load (isometric contraction). With continued contraction, the muscle will produce enough tension to overcome the load and shorten (isotonic contraction).

**Threshold Stimulus and Motor Unit Recruitment: The Effect of Stimulus Strength on Tension Development (Twitch Amplitude)**

Skeletal muscles contain functional units called **motor units**. Each motor unit consists of a single **somatic motor neuron** that branches to innervate one or more muscle fibers. When a motor unit is stimulated, all of the muscle cells within that motor unit will contract with all of the force they can develop. In order to maintain smooth contraction of the whole muscle and to decrease fatigue of the individual motor units, the motor units are activated asynchronously. All the motor units of the muscle do not contract at the same time – while some motor units are contracting, others are relaxing.

In a given muscle (for example, the abductor digiti minimi), there are many motor units which differ in their size and ease of stimulation. Small motor units, which consist of a small motor neuron which innervates a small number of thinner diameter muscle fibers, respond to weaker stimuli and contract first, while large motor units, which consist of a larger motor neuron which innervates a larger number of thicker diameter muscle fibers, are harder to stimulate and require a much stronger stimulus. The overall contraction strength of a muscle is the summation of the pull of all of the motor units operating at any one time. As the stimulus strength increases, more motor units are stimulated to contract, generating a stronger force of contraction. This process of increasing the number of motor units that are active is known as **recruitment**. Besides recruitment, another way to increase muscle contraction strength is **summation**. Summation is when stimulus is applied to the muscle fiber before it has completely relaxed from a preceding twitch. In summation, the force produced by an individual muscle fiber increases when it is stimulated to contract more frequently, which causes the twitches to add together, generating more force.

The muscle fibers found in most mammalian skeletal muscles are either **fast-twitch fibers** or **slow-twitch fibers**. Each type has a unique form of myosin, which differs in the rates of ATPase activity and crossbridge cycling and, thus, results in differing contraction speeds. Within the group of fast-twitch fibers, **fast glycolytic fibers** use mainly fermentation (glycolysis) to produce ATP, while **fast oxidative fibers** generate ATP mainly by cellular (aerobic) respiration. The fast-glycolytic fibers have the largest diameter and generate the strongest force of contraction, while fast oxidative fibers are intermediate in diameter and are hence intermediate in contraction strength. Fast glycolytic fibers are the quickest to fatigue because they break down glucose very inefficiently. A burst of contractile activity diminishes glucose levels and causes lactic acid to accumulate, which both lead to fatigue. The least powerful (due to their smallest diameter) but least likely to fatigue fiber types are the **slow oxidative fibers**, which rely almost entirely on cellular respiration for their energy source.

Skeletal muscles contain all three types of these fibers intermixed with each other. Typically, a given motor unit, however, only contains one fiber type, and thus, the stimulation of a particular motor neuron will cause contraction of only one type of muscle fiber. When muscle tension is required, the brain will recruit the small motor units containing slow oxidative fibers first. Increased signals will stimulate the fast-oxidative fibers in the intermediate motor units to contract next to generate more force if needed. The fast-glycolytic fibers in the large motor units are recruited last when a large amount of force is required, such as in high-intensity exercise like weight lifting. To summarize, as muscle tension requirements increase, the order of recruitment for these fibers is slow oxidative fibers first, fast oxidative fibers next, and fast glycolytic fibers last.

**Effect of Load on Isotonic Contractions**

When a muscle is stimulated to lift a weight, it first develops tension without shortening (isometric contraction). If the muscle is able to create enough tension to overcome the load, the muscle shortens, and the load is lifted (isotonic contraction). The time between when the muscle is stimulated, and the beginning of shortening is called the **latent period**. The size of the load affects isotonic contractions in several ways. As the load becomes heavier, (1) the latent period becomes longer (it takes more time to start lifting the load); (2) the duration of muscle shortening decreases (the load cannot be lifted as long); (3) the velocity of shortening is slower (the load is not lifted as quickly); and (4) the distance shortened decreases (the load is not lifted as far).

The size of the load affects the amount of work that a muscle can perform. By definition, work is the product of a force being moved and the distance through which that force is moved. The equation for work is written as WORK = Force x distance. Based on this definition, a muscle does no work when it does a completely isometric contraction because nothing is being moved through a distance. In this lab, you will measure work as the mass of a weight being moved by your finger times the amplitude of the muscle twitch that occurs in your finger.

**Summation and Tetanus**

Remember that there are two factors that determine the amount of force generated by a muscle: (1) the number of muscle fibers contracting (recruitment) and (2) the amount of force produced by the individual muscle fibers (summation).

When an individual muscle fiber is stimulated before it has completed its current muscle twitch, the next twitch will add to the previous twitch in a process called **summation.** When the stimuli arrive close together in this fashion, each individual muscle fiber contracts more powerfully than it did in response to a single stimulus. This increased contraction strength is caused by the increased amount of calcium ions present in the sarcoplasm. The calcium ions released from the sarcoplasmic reticulum in response to the first action potential have not all been pumped back into the sarcoplasmic reticulum when the next action potential arrives. This higher level of calcium ions in the sarcoplasm causes the exposure of more myosin-binding sites on the actin, allowing more myosin crossbridges to bind and greater tension to be produced. One way to think of this is to imagine a tug of war with a rope. If you can add more people to your end of the rope, your team will be able to pull more strongly.

As the frequency of stimulation increases further, the muscle fiber has even less time to relax and summation leads to **incomplete tetanus**. Incomplete tetanus is characterized by a higher average tension than that generated by a single muscle twitch; however, the individual twitches are still observable. When the stimulus frequency is increased even further, summation produces a plateau called **complete tetanus**. During complete tetanus, no relaxation occurs between stimulations and thus a sustained, maximum amount of tension is developed. Once the frequency for a tetanic contraction has been reached, increasing the stimulus rate any further will not increase the force of the contraction. The rate of muscle relaxation is much slower after tetanus than after a single muscle twitch because it takes more time to pump the excess calcium back into the sarcoplasmic reticulum.

Under normal conditions, motor units are not activated by single stimulus but instead by many stimuli in rapid succession. Thus, tetanic contractions are produced by each motor unit. The muscle as a whole is able to produce a smooth, sustained contraction because of asynchronous firing of the many motor units within that muscle.

**Muscle Fatigue**

When a muscle fiber is frequently stimulated to contract, the tension produced eventually decreases. This decline in muscle tension due to repetitive stimulation is called **muscle fatigue**. Muscle fatigue is influenced by many factors including the type of exercise, that is, the rate and force of contraction, and by the quantity and quality of the blood supply to the muscle. In high-intensity exercise, such as weight lifting or sprinting, fast glycolytic fibers are recruited, and they use fermentation (glycolysis) to produce ATP, resulting in the buildup of lactic acid. The change in pH alters the shape and activity of the contractile proteins and sarcoplasmic reticulum calcium pumps. Very high-intensity exercise can also cause neuromuscular fatigue, where the somatic motor neurons run out of neurotransmitter from being stimulated so frequently. In low-intensity, long-duration exercise where mostly slow oxidative and fast oxidative fibers are used, the depletion of fuel sources, such as glycogen, to run cellular respiration is an important cause of muscle fatigue.

While it may be obvious that energy is needed for muscle contraction, energy is also required for muscle relaxation. For relaxation to occur, the calcium ions must be pumped back into the sarcoplasmic reticulum from the cytoplasm, a process that takes about 0.033 seconds. In the absence of ATP the calcium remains in the cytoplasm longer and the actin and myosin will continue to interact with each other. Also, in the absence of ATP, the myosin head cannot become uncoupled from the actin active site; thus, the muscle will not be able to relax