Skeletal Muscle Contractions & Sliding Filament Theory

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Abstract

The human body is able to move as a result of contractions in skeletal muscle. The basic anatomy of a muscle is a collection of muscle cells made up of strings of contractile units called sarcomeres. The contractions of the sarcomeres determine the contraction of the muscle. The first lesson introduces the mechanisms of contraction in the sarcomeres which are Sliding Filament Theory and Cross Bridge Cycling. The second lesson applies the concepts learned in the first lesson to explain factors that regulate the force produced by a muscle contraction.

Introduction

Muscles have several roles in the human body such as allowing movement, stabilization and generating heat. These functions are essential for living and are made possible by the muscle's ability to contract. Muscles can be classified as one of three types: striated muscle, smooth muscle and cardiac muscle. Striated muscle is the only type that can be contracted voluntarily; the other two types contract involuntarily. Being able to contract voluntarily means that striated muscle can be controlled consciously, allowing it to be used to movement and related functions. These types of muscles that are used specifically for movement are called skeletal muscles.

Skeletal muscles are wrapped in several layers of cartilaginous connective tissue, the outermost layer being epimysium which bundles the entire muscle together. Within the epimysium is the perimysium, which contains groups of muscle cells called fascicles. Fascicles are comprised of muscle cells, also known as muscle fibers, which are rod-shaped structures sizing up to 100 μm in diameter and 30 cm in length [1]. These fibers are composed of smaller units known as myofibrils that run the length of the cell. As shown in Figure 1, myofibrils of a muscle fiber are long chains of contractile units called sarcomeres which are fundamentally what allows the muscle to contract.

Sarcomeres consist of thick and thin filaments called myosin and actin respectively, and are organized into different bands. These filaments are able to pull against each other, which shortens the distance between the bands and contracts the muscle. This concept is known as Sliding Filament Theory. The theory discusses how muscles muscles are able to contract and by applying this theory, the mechanisms of force production in muscles can be interpreted.

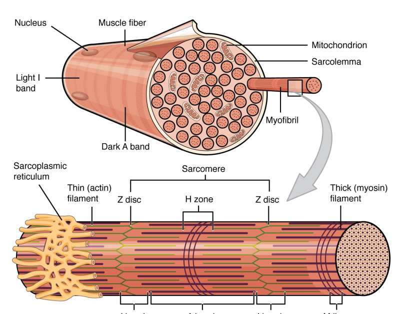

Figure 1: Anatomy of a muscle fiber.

First Lesson

Sliding Filament Theory is a major concept in the physiology of muscular contractions. At its core, the theory describes the molecular interactions between actin and myosin within a sarcomere. The sarcomere can be divided into three sections: the A band, the I band, the H zone and the z band which can be seen in Figure 2. The A band spans the length of the thick myosin filaments and is located in the middle of the sarcomere and remains in this position throughout a contraction. The I band is the remaining space between the A band and the edges of the sacromere, also called the z band. Thin actin filaments extend from the z bands to constitute the I band and continue to overlap with a section on both sides of the A band. The remaining section of the A band not covered by this overlap is known as the H zone [2].
The myosin filaments are able to pull on the actin filaments due to the presence of globular structures referred to as "heads". The "heads" are able to bind to specific sites on the actin and pull them through a process called Cross Bridge Cycling, where a "cross bridge" is the connection created between the actin and myosin filaments by the myosin heads [2]. The process is initiated when an ATP molecule gives energy to the myosin head. After being energized, the myosin head is able to bind to the actin filament with the help of a calcium ion. The energy in the myosin head is then used to pull the actin filament closer to the center of the A band. This pulling motion is known as the "power stroke". After using up all of the energy in the power stroke, the myosin head can no longer remain bound to the actin, and the process can then be repeated again with another ATP molecule.
The pulling that takes place from Cross Bridge Cycling shortens the length of the sarcomere. This process temporarily shortens the lengths of the I band and the H zone. The A band maintains its length since it consists of the myosin that is responsible for pulling the actin. An analogy that can help with visualizing this process is to imagine a person pulling in a rope that is tied to a chair on either side of them. In this analogy, the person is acting as the myosin, the ropes are the actin and the chairs are the z bands. The act of the person pulling on the ropes is similar to the myosin heads pulling on the actin filaments. When this occurs for all of the sarcomeres in a muscle fiber, the entire fiber is shortened, resulting in the contraction of the muscle.

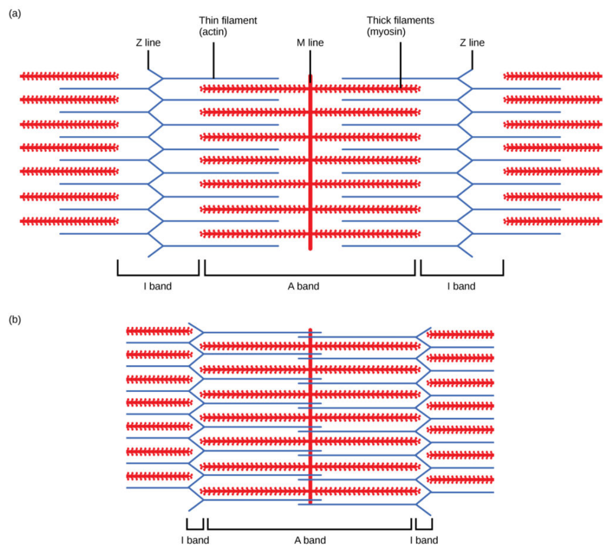

Figure 2: Diagram describing a sarcomere and the regions explained in Sliding Filament Theory.

Second Lesson

To better understand the ideas discussed in the first lesson, applications of these concepts can be explored in the context of force production. The contractions made by skeletal muscles are able to move the body because they produce force. Different amounts of force are required force different actions. Consider the differences when holding a dumbbell and an egg. If you held the egg with the same force as the dumbbell, it is likely that the egg would be crushed. Being able to regulate the amount of force produced by a muscle is important not only in this example, but also when performing other regular actions such as using only enough force to walk without running or typing without destroying your keyboard. There are two factors regulating force production in muscles that can be used as examples to understand the concepts of Sliding Filament Theory and Cross Bridge Cycling, these being the length of the muscle and the types of muscle fibers.

The length of the muscle in terms of force production refers to the muscle's length relative to its size at rest. It concerns whether or not the muscle is stretched or compressed [3]. Consider Figure 3, that shows the percentage of the maximum force of a muscle produced at different lengths. If the muscle is stretched too much, the H zone will be larger, meaning that the actin filaments will have very little overlap with the myosin. Since fewer myosin heads will be able to bind to the actin and pull it, the force produced will be much smaller. Recall the analogy with the chairs and rope. In this situation, the rope would be just far enough that you can only hold it with the tips of your fingers. As you might imagine, it would be much more difficult to pull the chairs towards you from this position. If the muscle is too compressed, the action of the myosin heads pulling on the actin filaments will not have much effect since there is little distance left between the myosin and the z bands. Once again using the analogy from before, in this scenario the chairs would already be right beside you before you start pulling. Pulling on the ropes at this point will not accomplish anything since the chairs cannot move any closer to you. The optimal length for force production is at the muscle's resting length. Here, the actin will fully overlap with all of the myosin heads and have ample room to contract.

The type of muscle fiber that that a muscle is comprised of will also impact the amount of force produced. Muscle fibers are categorized based on whether their contractions are fast or slow. Fast fibers are able to produce greater force, but fatigue rapidly [3]. Slow fibers are the opposite; they produce less force, but are more resistant to fatigue. The speed of a contraction depends on the power stroke. To visualize this, imagine a person rowing a boat. The action of rowing can be seen as very similar to what occurs in the power stroke. When rowing a person first reaches far then puts their oar in the water, just like the myosin head reach and connecting to the actin filament. The rower then pulls very hard to move the boat and takes their paddle out of the water. After the myosin heads binds to the actin, it too pulls very hard to move the actin, then detaches. After the rower pulls, the speed of the boat will depend on how hard they pulled. This same idea is how muscle fibers contract at different speeds.

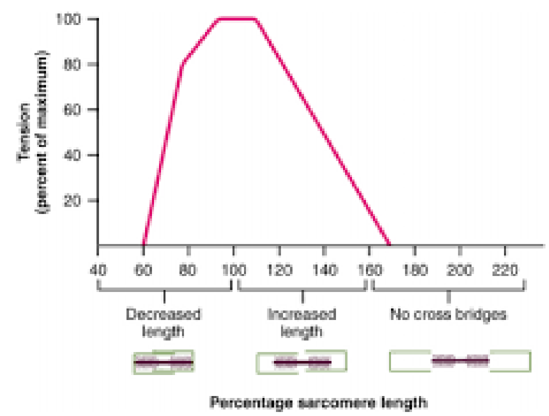

Figure 3: Graph detailing the force produced by a muscle at varying lengths.

Conclusion

In summary, muscles contract as a result of the actions of the sarcomeres within its fibers. Sarcomeres consist of myosin and actin filaments that can pull against each other as described by Sliding Filament Theory. This involves the actin being pulled by the myosin, which in turn moves the z bands. The result is that the I bands and H zone shrink as the overall length of the sarcomere shortens. The process of the myosin pulling the actin filaments is explained through Cross Bridge Cycling, which allows myosin heads to pull the actin in the presence of ATP and calcium ions.

These concepts also aid in explaining how muscles are able to produce force. If a muscle is too stretched or too compressed, it is incapable of producing optimal force since either the myosin heads are unable to bind to the actin or there is no room left to pull. Force production is also dependent on the speed at which a muscle fiber can contract. The speed at which the power stroke occurs will determine the speed of contraction, meaning that a faster power stroke will produce more force.

References

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