Sliding Filament Theory

In this Tough Topics section, we are going to discuss the basis for muscle contraction in the human body. A muscle contracts when sarcomeres shorten. Sarcomeres are the smallest contractile units in the muscle fiber. The mechanism used by sarcomeres to shorten is called the Sliding Filament Theory because protein filaments within your muscle cells must slide past one another to shorten and produce tension. Because this topic is complex, we'll break it into three sections. We will begin with a review of the structure of a muscle cell, to give you a road map to follow as you listen. Then we'll move on to a description of what the sliding filament theory is, including regulatory and contractile proteins, the active site, and cross-bridge formation. Finally, we will take a brief look at how a muscle relaxes.

Let's start off with the structure of a muscle cell down to its functional unit, the sarcomere. As muscle cells develop, they fuse together and become big, multinucleated cells. That means that muscle cells can combine their cellular components to produce stronger contractions. That is exactly what happens when someone lifts weights to “bulk up.” Fused muscle cells are bigger, have more stored energy and a greater blood supply, and are more effective at producing tension than a single, smaller cell would be.

Each muscle cell contains hundreds or even thousands of long, cylindrical structures called myofibrils. Myofibrils extend the length of the muscle cell as long, parallel tubes, like lengths of dried spaghetti inside of a canister. Each myofibril is divided into equal segments along its length called sarcomeres. Each sarcomere is packed full of small, fine protein strands called myofilaments. Myofilaments are the actual proteins involved in muscle contraction. These myofilaments may be either thick filaments, made of protein molecules called myosin, or thin filaments, made of a helix of proteins called actin.

Individual myofilaments of myosin and actin do not extend the length of a muscle cell like the larger myofibrils do. Instead, they are packaged in a precise pattern into sarcomeres. The sarcomeres are arranged end-to-end in single file along the length of the myofibril. So, you can think of sarcomeres as precisely-measured sections of spaghetti cut from the length of the spaghetti strand. There can be up to ten thousand sarcomeres joined together end-to-end to make a single myofibril.

The actin and myosin filaments within a sarcomere are arranged in a very precise order. It is the alternating arrangement of thick and thin filaments that gives each myofibril a banded or striped appearance. The banded myofibrils are also uniformly aligned, which gives muscle fiber a striped or striated appearance.

Let's review what we've discussed so far. A muscle fiber is made up of many long parallel cylindrical tubes called myofibrils. Each myofibril extends the entire length of the muscle fiber and is divided into segments called sarcomeres. The sarcomeres are lined up end-to-end in single file for the length of the myofibril. Each individual sarcomere is packed with contractile proteins called myofilaments that can be either thick or thin.

Sarcomeres shorten during contraction. Each sarcomere contains four different protein components: the thick filaments of myosin, the thin filaments of actin, elastic proteins that hold actin and myosin in

place, and regulatory proteins that control the interactions between myosin and actin within the sarcomere.

Now let's look at the sarcomere at the microscopic level. Tension in a contracting muscle is produced by the shortening of the sarcomeres. Each end of the sarcomere is formed by a dense protein sheet called the Z disc. The Z discs are like caps on the end of a tube. Thus, a myofibril is divided into sarcomeres by the Z discs and each sarcomere extends from one Z disc to the next. Actin filaments on either end of a sarcomere are anchored to the Z discs and project inward like small, thin fingers. In a relaxed sarcomere, the actin filaments from opposite Z discs do not touch. The space between the opposing actin filaments is called the H zone.

You can simulate this basic structure by holding your hands in front of you, about 12 inches apart. Turn your palms toward you and extend your thumbs so they are pointing straight up. Now straighten all of your fingers so they are pointing toward the opposite hand. The fingers of one hand should not touch the fingers of your opposite hand. If they do, spread your hands farther apart. In this position, your palms and extended thumbs represent the Z discs, or ends of the sarcomere. Your fingers represent the actin filaments on either end of the sarcomere. Finally, the space between your fingertips would be the H zone, the space between the opposing actin filaments in a relaxed sarcomere. While in this position, it is also easy to see that we can shorten our sarcomere if we slide the actin filaments closer together until they overlap. In our model, the actin filaments are your fingers, and when your hands slide together your fingers will interlock. Now the Z discs--your thumbs--are much closer together because the sarcomere has shortened. This same concept is used in the Sliding Filament theory, only on a microscopic level.

Within each sarcomere, centrally located myosin or thick filaments are stretched between the opposing fingers or actin filaments extending from each Z disc. There is a varying degree of overlap between the myosin filament and the surrounding actin filaments. The thick filament is composed of hundreds of molecules of myosin and is often compared to a bundle of golf clubs. The shafts of the golf clubs form the major portion of the filament. The heads of the golf clubs extend out from the thick filament on either end of the main shaft, almost touching the actin filaments beside them. There are no myosin heads in the middle of the thick filament.

Using energy from ATP, the myosin heads can swivel back and forth, like swiveling a golf club in your hands and watching the head of the club move up, down, and around. The myosin, or thick filament, is anchored to a center point in the sarcomere called the M line. It is towards this point that the myosin will pull the actin using the simple pivot action powered by ATP.

In addition to actin and myosin, we need to discuss two regulatory proteins that play important roles in muscle contraction. The first one is called tropomyosin. It is an elongated protein that winds along the actin filaments. Its job is to prevent the myosin heads from binding to the active sites on the actin filament and causing contraction without the appropriate nerve signal. Tropomyosin is similar to a plastic child-protective cover on an electrical outlet. Until the cover is removed, you can't plug anything

into the outlet. Similarly, in a muscle fiber, the myosin heads can't bind to the active sites until tropomyosin is removed.

Associated very closely with tropomyosin is a protein called troponin. Troponin is a small protein molecule that binds to tropomyosin to form the troponin-tropomyosin complex. Troponin has the job of moving the tropomyosin off the active sites. In other words, troponin removes the child-protective cover--the tropomyosin--from the outlet--the active site on the actin filament--so that contraction can occur.

Now that we've reviewed the basic components of a muscle fiber, let's turn to the Sliding Filament Theory of muscle contraction. Muscle contraction is literally a shortening of your muscle fibers. This shortening produces tension. When you flex your biceps muscles, they get shorter and thicker and produce tension. This contraction occurs through the interactions of the proteins in the sarcomere with the help of calcium and energy in the form of ATP.

How does this happen? When the active sites on the thin filaments are exposed, the myosin heads can bind to actin and contract the muscle fiber. Whether binding occurs or not depends on the actions of the regulatory proteins, tropomyosin and troponin. As we mentioned, tropomyosin covers the active sites. Troponin can move the tropomyosin off of the active sites if calcium is present. This happens because the binding of troponin by calcium causes a subtle change of shape in the troponin-tropomyosin complex, which moves the tropomyosin off the active sites. In addition to calcium, muscle contraction also requires a considerable amount of energy in the form of ATP. ATP is used to cock the myosin heads back away from the midpoint of the sarcomere in an extended high energy position. Once the active sites on actin are exposed, the myosin heads are already in position to bind to actin at the active sites.

The myosin heads of a muscle fiber are synchronized to move either toward the M line, which is in the center of the sarcomere, or away from it. If we imagine we are looking at a thick filament with the myosin heads extended from either end, the heads on the left will be directed toward the left Z disc and away from the M line when in the high energy position. The myosin heads on the right end of the thick filament will be directed toward the right Z disc, also away from the M line, when in the high energy position.

Let's put this all together and walk through the steps that occur as a sarcomere shortens. As we look around the sarcomere, we see that the myosin heads are already cocked back in an extended position away from the midpoint of the sarcomere. They will hold that position until the active sites on actin become available. Remember, when a muscle is relaxed, tropomyosin is covering the active sites. With an appropriate nerve signal telling the muscle to contract, calcium will be released from the sarcoplasmic reticulum of the muscle fiber. Calcium ions bind to troponin and trigger the tropomyosin complex to shift, exposing the active sites on the actin filaments. The myosin heads are already in the extended position and will immediately bind to the available active sites, forming cross-bridges between the myosin and actin filaments. The myosin heads release the ADP and phosphate from the spent ATP and swivel back to the low energy position, moving toward the midpoint of the sarcomere and pulling

the actin filaments with them. The actin filaments on the left end of the sarcomere are pulled to the right and the actin filaments on the right are pulled to the left. This movement is called the power stroke. The actin filaments slide over the myosin filaments. Because the actin filaments are anchored into the Z discs of the sarcomere, the Z discs are pulled closer together. As the overlap between filaments increases, the H zone gets smaller and the sarcomere shortens. Please note that none of the filaments have actually changed length. The sarcomere shortens because the actin filaments have simply slid closer together, eliminating the gap or H zone in the middle, just as in our exercise earlier when we slid our fingers together. But on a macroscopic level, the muscle shortens.

Once the myosin head returns to the low energy position, a new ATP molecule is required to break the cross-bridge. The ATP molecule is hydrolyzed to ADP and phosphate and the energy released is used to recock the myosin head into the extended, high energy position. This process is called the recovery stroke. As long as calcium is present in the sarcoplasm, the active sites will remain uncovered and the entire process of forming cross-bridges, pulling the actin filaments toward the M line, and then recocking the myosin heads repeats itself approximately 5 times per second.

Now, not all of the actin and myosin are in cross-bridges at the time. As the sarcomere shortens, tension is created in the muscle. If all myosin heads released at the same time the tension would be lost with each cycle. Instead some myosin heads recover, while others are pulling the actin filaments. Like pulling on a rope, it is much more effective to pull hand over hand, so one hand always maintains some tension, rather than pulling and releasing with both hands at the same time and then trying to pull again with both hands. It is also important to remember that each myofibril in a muscle fiber contains thousands of sarcomeres lined up end to end. Shortening one sarcomere will produce only microscopic changes in muscle length, but shortening thousands of sarcomeres in a long chain results in the considerable change in length necessary for powerful muscle contractions.

So how does the muscle relax? Well, when the nerve signal to contract has stopped, calcium is pumped back into the sarcoplasmic reticulum using active transport pumps. The sarcoplasmic reticulum is specialized in muscle cells for storing calcium so that there is plenty available in the cell for contraction. With no free calcium in the sarcoplasm to bind to troponin, the tropomyosin slides back over the active sites on the actin again. With no available binding sites, the myosin heads are unable to form cross-bridges and remain in the extended position, waiting for the next nerve signal to contract, which will uncover the binding sites once again. The sarcomere passively returns to its original length and the muscle relaxes. When a muscle is fully contracted, it has shortened by about 30% of its resting length. Once contraction has ended, the muscle will go back to its full resting length. Resting length is restored passively using other elastic proteins in the sarcomere that act like rubber bands and help the actin to recoil or through contraction of an antagonistic muscle.

We've now discussed the major components of the sliding filament theory of contraction. We began by reviewing muscle structure. Then we described sliding filament theory in detail. We talked about the importance of the regulatory and contractile proteins, the active site, and cross-bridge formation. We also described how the length of a muscle changes with contraction and relaxation.