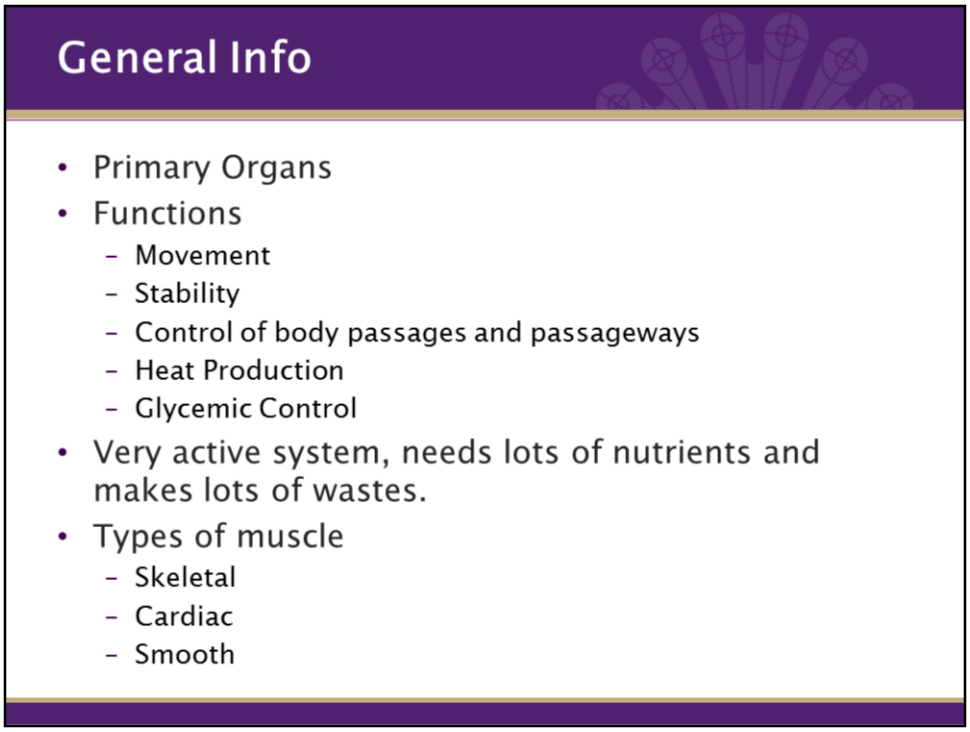
ST. CATHERINE UNIVERSITY

Muscular System



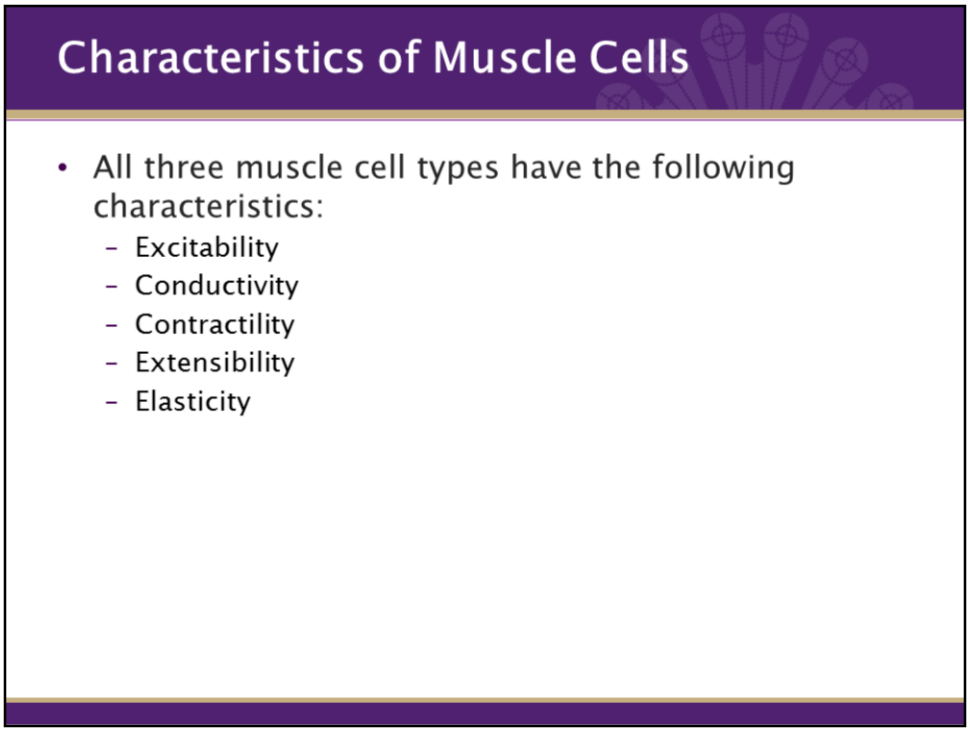
Muscles themselves are considered the primary organ is this system. Each muscle is considered a separate organ. The functions of muscle are movement, stability (our posture and tone to stay upright), control of body openings and passageways, heat production through shivering, and glycemic control (or the control of glucose levels in the blood). As you may determine from the list of functions, the muscular system is a very active system, therefore it needs a lot of nutrients and produces a lot of wastes, so it is very vascular. As a system, it is highly regulated by the nervous system. The system needs nervous signals to tell muscles to contract.

As we have mentioned previously, there are 3 types of muscles. To refresh,

Skeletal: most common, voluntary, striated, multinucleated, acts on bones

Cardiac: only found in heart, very active, striated, involuntary, intercalated discs

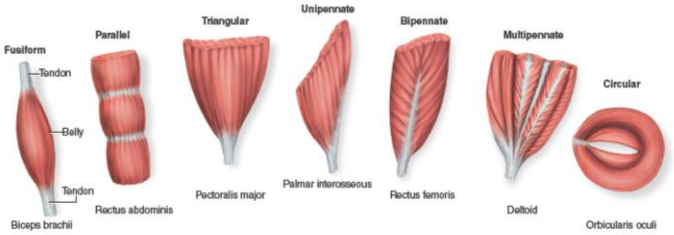
Smooth: involuntary, not striated, found in systems such as the digestive and respiratory systems.



All three muscle types have the following CHARACTERISTICS:
1. Excitablity: responds to an electrical or chemical stimulus.
2. Conductivity: carries electrical signals.
3. Contractility: ability to shorten which pulls on bones and results in movement.
4. Extensibility: ability to stretch.
5. Elasticity: ability to return to its original shape.

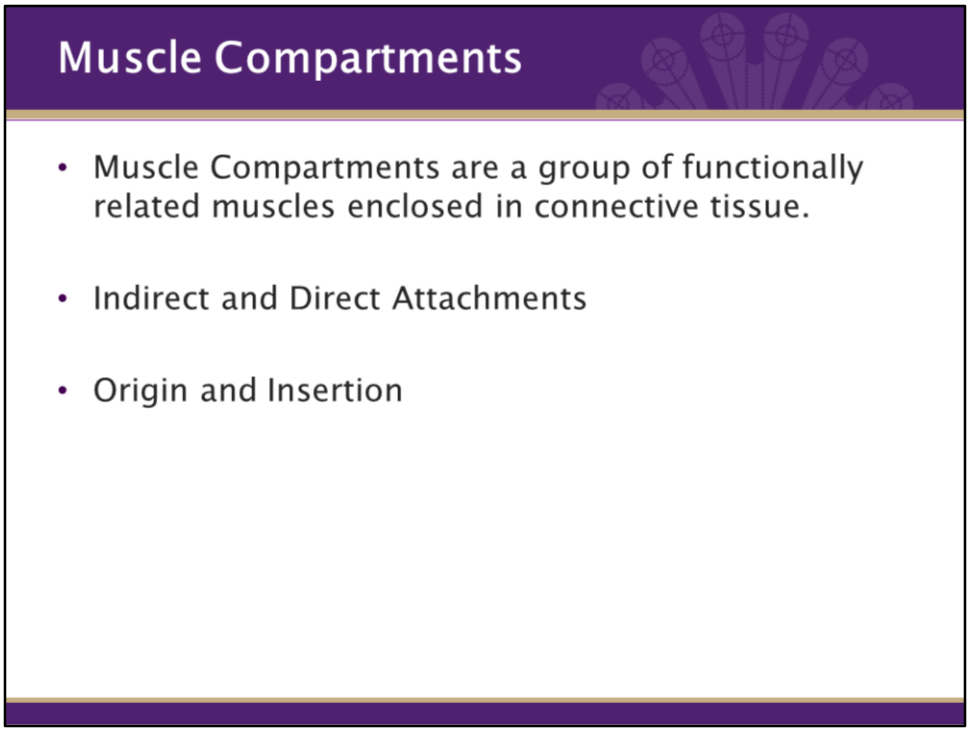
Skeletal Muscle Shapes

- Skeletal Muscle Shapes:
  - Fusiform
  - Parallel
  - Triangular
  - Pennate
  - Circular



For now, we are going to focus on skeletal muscle. Skeletal muscle comes in a few different shapes. Muscle strength is determined by their shape and the direction they pull. Shape is determined by the orientation of the muscle cells.

1. Fusiform are wide in the middle and tapered ends.
2. Parallel are uniform in width and parallel cells, they are elongated straps, can span long distances, shorten more than other types and produce less forces due to fewer cells.
3. Triangular are fan-shaped, broad at one end and narrow at the other, and are relatively strong due to a large number of cells
4. Pennate are feather shaped and generate the most force
5. Circular are round and usually sphincters



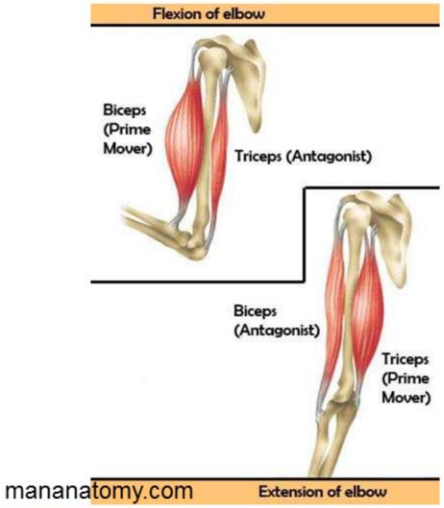
Muscle Compartments are a group of functionally related muscles enclosed in connective tissue.

Muscles and Muscle Compartments attach to bone indirectly and directly. In an indirect attachment, it looks like the muscle stops before it reaches the bone. The gap between the muscle and bone is spanned by tendons. So, in indirect attachments, tendons act as a connector between the structures. In direct attachments, the gap between the muscle and bone is so small that it looks like the muscle attaches directly to the bone. In actuality, the muscle is attached to the bone via collagen fibers.

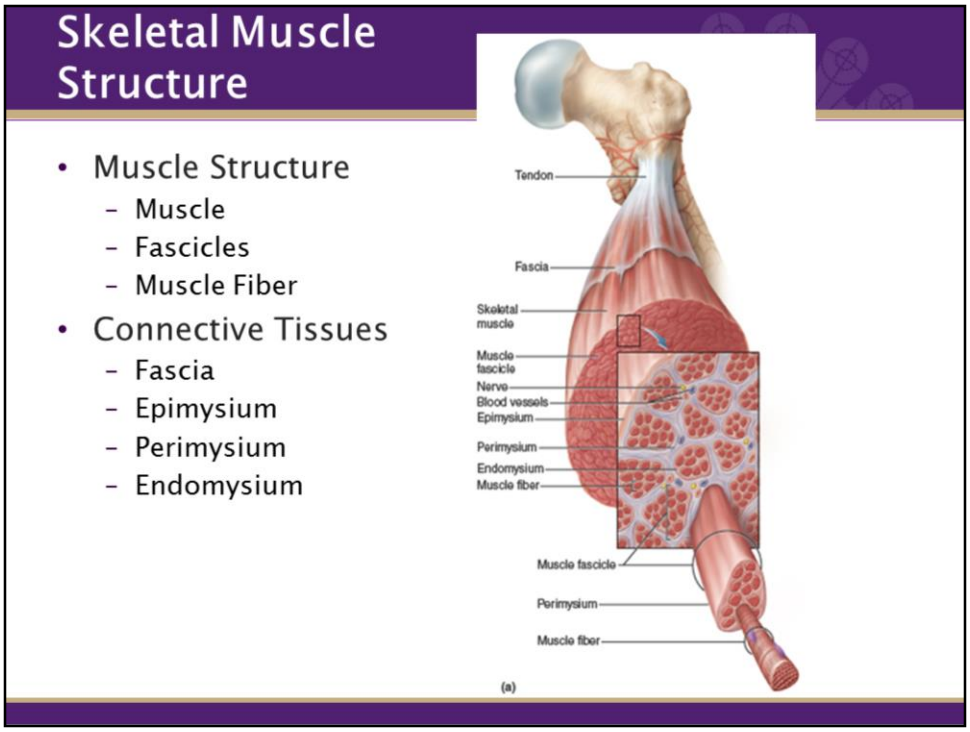
Muscle work on bone the same way we use levers to lift things. With levers, one end of the lever needs to be stationary while the other will do the moving. For muscles, one will attach to a bone that will remain stationary while the other end will attach to the bone that will do the work or move. The end that attaches to the stationary bone is referred to as the origin. The end of the muscle that attaches to the mobile one is referred to as the insertion. For instance, your textbook gives the example of the biceps brachii. The origin for the biceps brachii is on the scapula and the insertion is on the radius. When the muscle contracts, it acts on the radius and allows flexion of the elbow.

Muscle Actions

- A muscle action is the effect produced by the muscle itself.
- Prime Mover
- Synergist
- Antagonist
- Fixator



A muscle action is the effect produced by muscle. Muscles do not work in isolation. When we have an action, there is a prime mover, a synergist, an antagonist, and a fixator. The prime mover produces the primary force for the action. The Synergists aids the primer and the fixator holds the bone in place and steady. When we have an action, we always need a counter action to limit excessive movement and speed. The antagonist provides this counter action and opposes the prime mover. In other words, antagonists work as a check and balance for the prime movers. The antagonist keep the prime mover from moving to far and fast to cause injury and they help stabilize the joint.



The STRUCTURAL FEATURES of skeletal muscle are as follows, starting with big and working small.

1. A muscle is composed of a bundle of fascicles
2. Fascicle are a bundle of muscle fibers
3. Muscle Fibers (muscle cells) are long fiber like cells.

Each structural feature is surrounded by connective tissue. These connective tissues are as follows, starting big and working small:

1.Fascia is connective tissue that separates muscles from other muscles or muscles from skin.

2. Epimysium is the connective tissue that surrounds entire muscle.

3. Perimysium is the connective tissue that surrounds and separates fascicles.

4. Endomysium surrounds and separates muscle fibers

So, the endomysium surrounds and separates each muscle fiber. Muscle fibers are grouped together and bound by perimysium, this is then called a fascicle. Multiple fascicles bound together by epimysium are then a muscle. Fascia helps to keep the muscles separate.

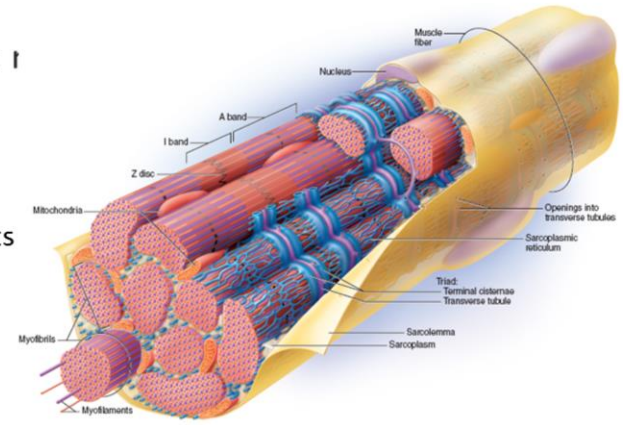
One thing to note is the prefixes epi-, peri-, endo. When you see these, epi always

means outer or surface and endo- always inner and peri- around. The suffix –mysium refers to muscle. This is how the connective tissues get their names, the prefixes telling you which layer and the suffix telling you it is associated with muscle. You will probably see theses again in another system.

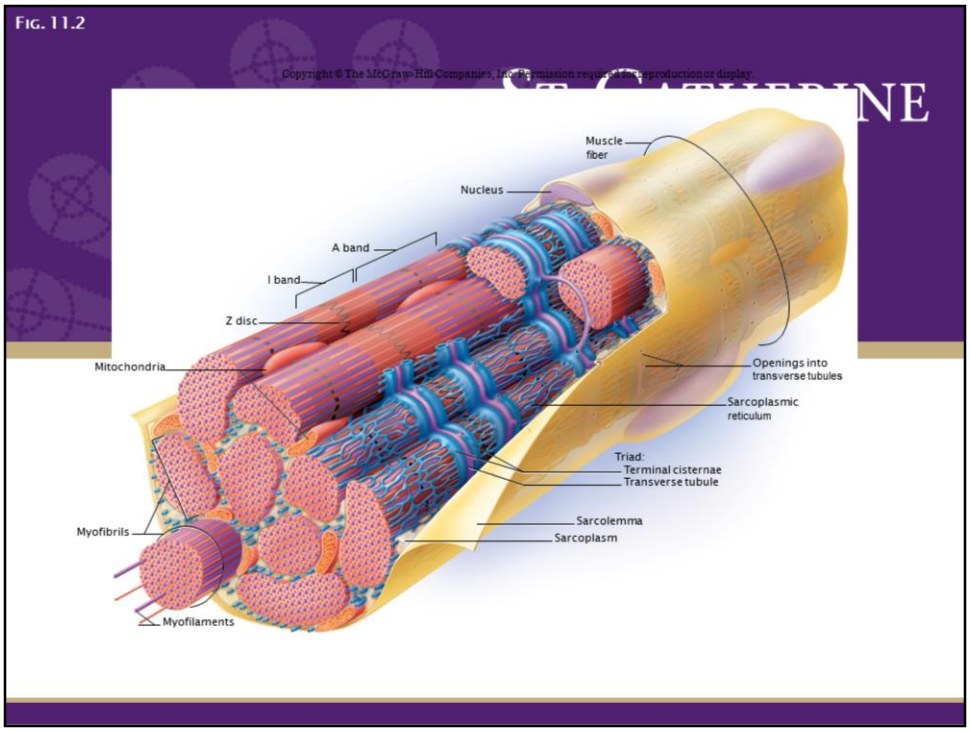
Can we have animation that highlights the terms as they are being narrated?

Muscle Fibers

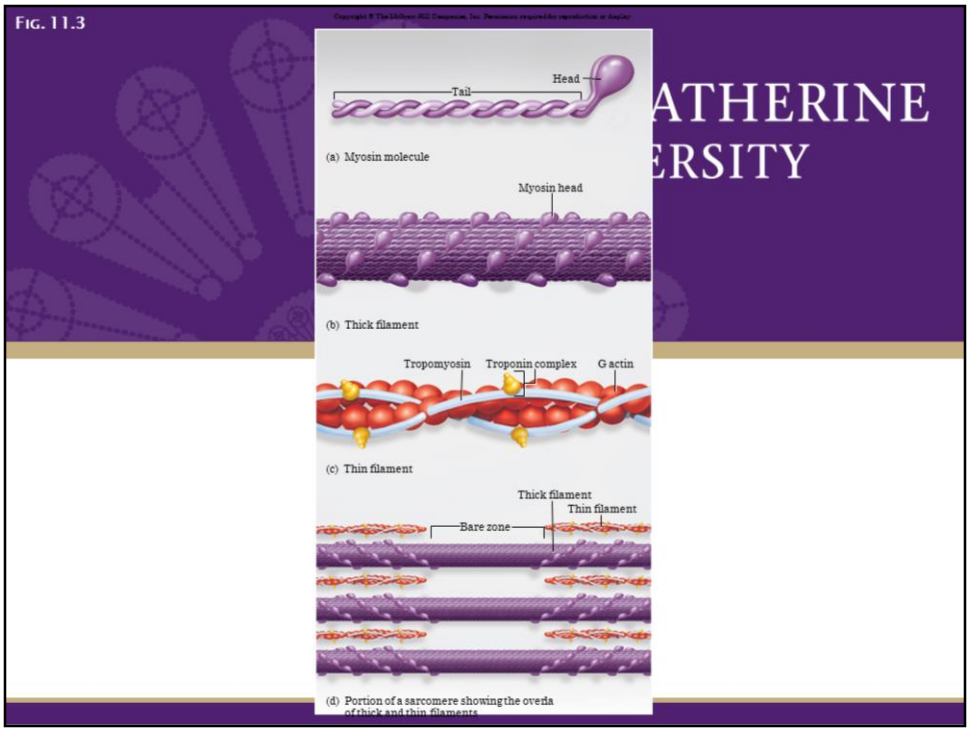
- Sarcoplasm
- Transverse Tubules (t-tubules)
- Sarcolemma
- Sarcoplasmic r
- Myoglobin
- Glycogen
- Myofibrils
  - Myofilaments



MUSCLE FIBERS contain the same organelles as other cells, but because of their functions, we give them specialized names.
Sarcolemma is the cell membrane.
Transverse Tubules, or t-tubules, are unique to muscle cells. They are inward folds of the sarcoplasm that run across the cell.
Sarcoplasm is the Cytoplasm of a muscle fiber.
Sarcoplasmic Reticulum is the smooth ER of a muscle fiber.
In muscles we also find a red pigment call myoglobin. If functions to store oxygen.
Muscles require a large amount of ATP in order to fulfill their functions. To produce ATP more efficiently, they are constantly using a large amount of oxygen, so we need to store as much as possible.
Muscle fibers also require a large supply of glucose to produce ATP. So they usually have a great deal of Glycogen, a polysaccharide made of many glucose molecules, that stores energy.
We will discuss the production of ATP further in following slides
Finally, we find Myofibrils which are long bundles of protein microfilaments. There are about 11 per myofibrils per muscle fiber.
Each myofibril is made of 3 types of myofilaments. More about the myofilaments in the following slides.



Review of the structures once again.



Myofilaments are a thread like complex of several hundred protein molecules. The three types are:

1. Thick filaments also called myosin. They are made of a protein called myosin that has a golf club shaped head. The myosin heads face outwards from the bundle.

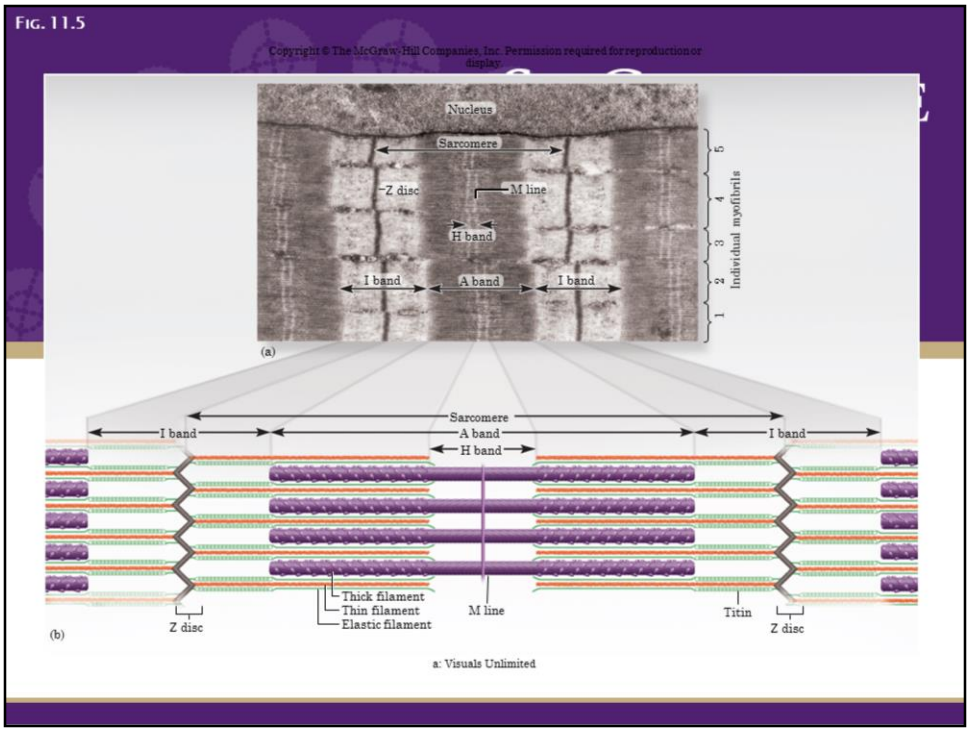
2. Thin filaments also called actin. They are made of actin and is what myosin tries to bind to during muscle contraction.

Also found on actin is Tropomyosin, a protein ribbon that wraps around actin and blocks the binding sites on actin, preventing myosin from attaching to it. Another protein called troponin binds to tropomyosin and is able to bind with calcium. Together, troponin and tropomyosin cover the binding sites on actin. When calcium binds to troponin it causes tropomyosin to be pulled away from the actin and exposes the binding sites. I think the picture of troponin in the book looks like little snowmen sitting on the actin binding sites.

3. Elastin filaments are made of titin, a springy protein that helps anchor myosin and stabilizes it and prevents over stretching.

On the top of this diagram is a single myosin molecule. Several hundred of these combine to form the thick filament (often just referred to as myosin). The next molecule, with the red beads, is actin (thin filament). The white ribbon protein that

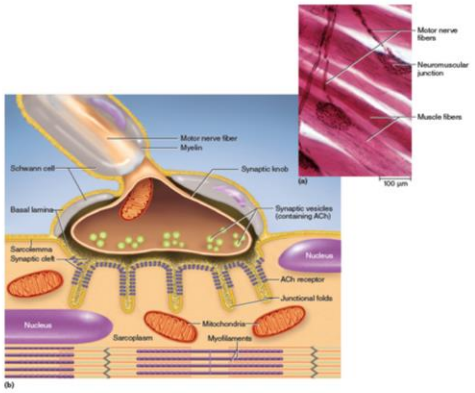
wraps around it is called tropomyosin. Attached to the tropomyosin is a molecule called troponin complex. This complex blocks the binding sites on actin, so that myosin can not bind to it. The bottom of the diagram shows how the thin and thick filaments overlap each other.



As you work down a myofibril the myofilaments are aligned in a unique pattern. A Z-disc (or Z-line) breaks up the myofibril and provides a place for the elastin and actin filaments to bind. Each end of a myosin is anchored to an elastin filament and over laps an actin. This overlapping shows up as a dark band (called an A band), this the striations you see when you look at the tissue slides of muscles. This organization of myofilaments from z-disc to z-disc is called a sarcomere. They are the contractile unit of a muscle cell, in other words, they are the working unit that allows for movement. Numerous sarcomeres line up along a myofibril.

Neuromuscular Junction

- Motor Unit
- Synapse
- Neuromuscular junction



A Motor Unit is 1 neuron (nervous fiber) and all the muscle fibers stimulated by it.
A synapse is the functional connection between a nerve and its innervated cell, in this case a muscle fiber. This is where signals are transferred from the nerve to the muscle fiber.
The specific synapse between a nerve and a muscle fiber is called a Neuromuscular Junction. The point of connection on the muscle fiber is specifically referred to the motor end plate

The following structures are part of the neuromuscular junction:

Nerve Fiber

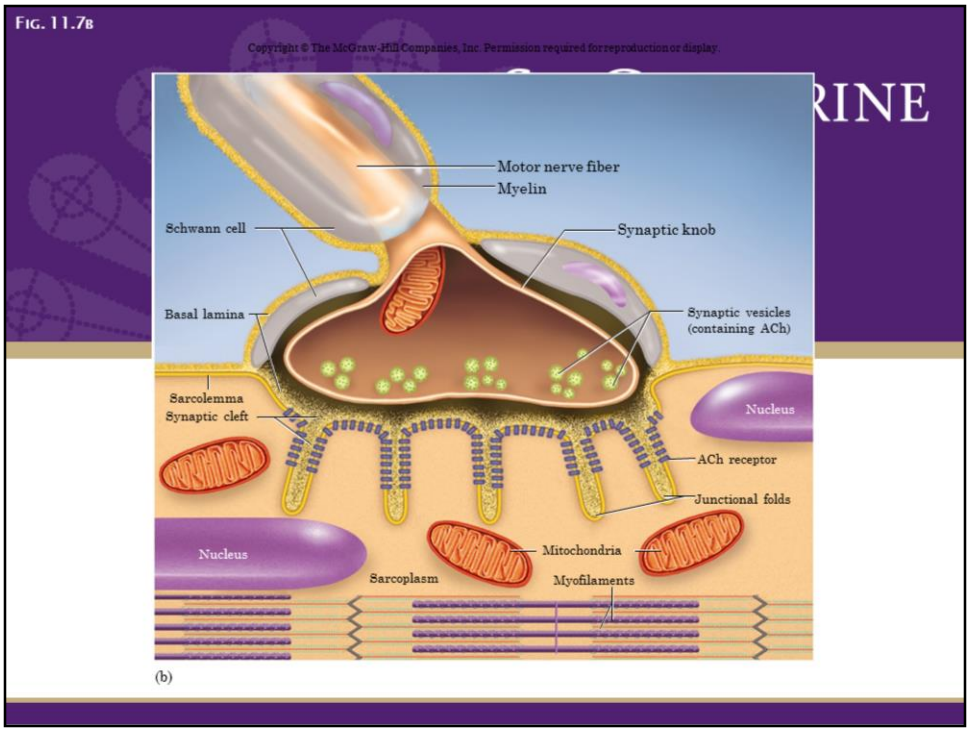
Synaptic Knob – the end of a neuron (nervous cell) that stimulates the next cell

Synaptic Vesicles – little bubble like storage units for a neurotransmitter (chemical messenger) called Acetylcholine (Ach)

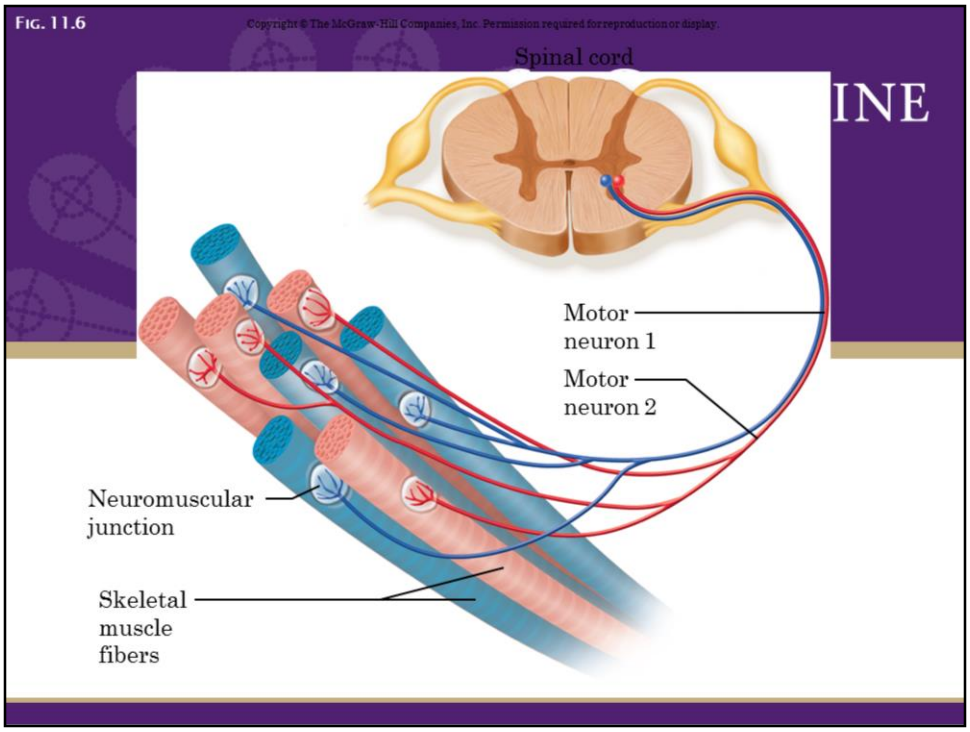
Synaptic cleft – the synaptic knob does not physically touch the muscle cell, so there is this small space between the two cells

Ach Receptors - the receptors for Ach on the motor end plate

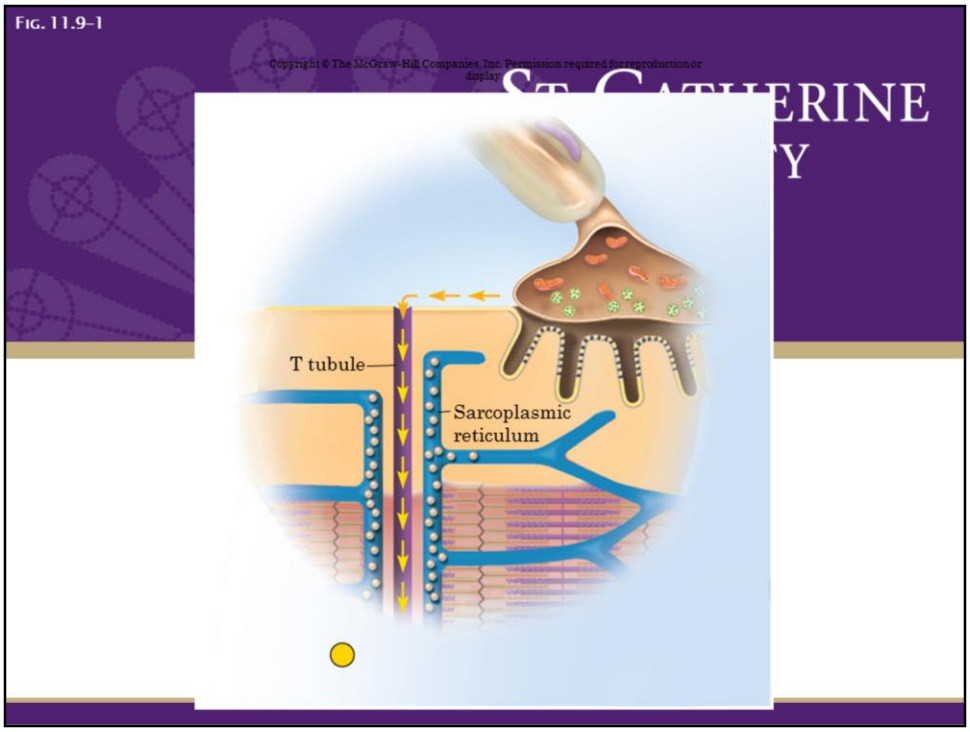
Acetylcholinesterase – this enzyme will break down Ach after it has been used to stimulate the muscle fiber.



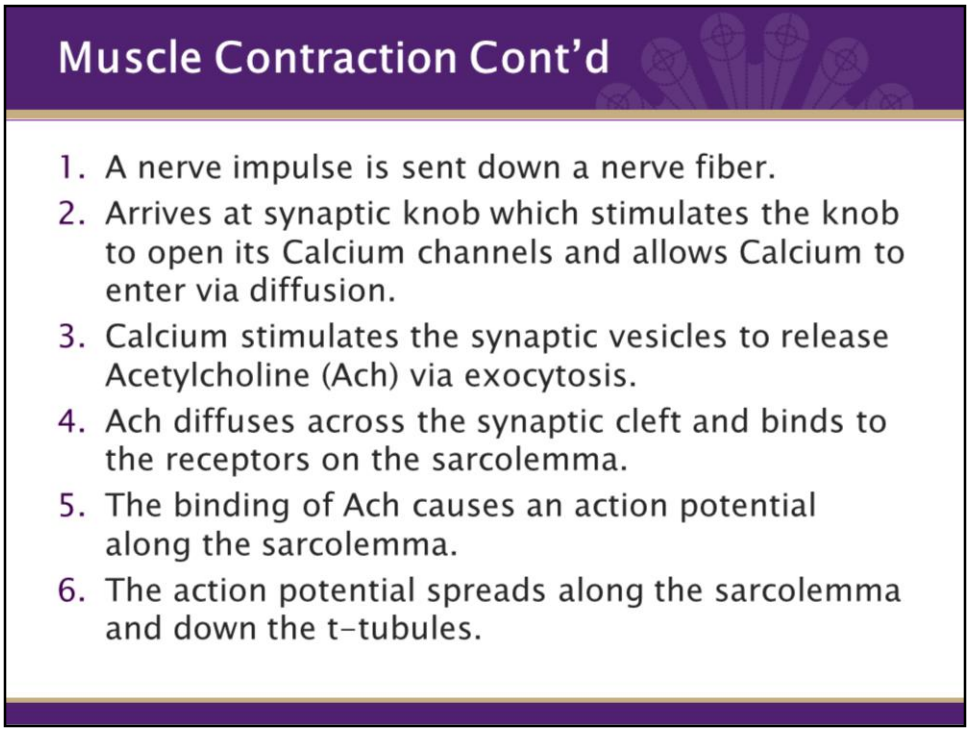
Here is our neuromuscular junction. **Review of the structures once again.**



In this picture, two motor units are shown (blue and red). Remember that a motor unit is one neuron and all the muscle fibers it stimulates. One neuron branches multiple times to stimulate more than one muscle fiber at a time. Muscle fibers are able to contract as 1 unit because the nerve branches stimulate each fiber simultaneously.



This one shows the neuromuscular junction in relation to the t-tubules and sarcoplasmic reticulum of the muscle fiber.



So, now for the actual steps in a muscle contraction.

1. A nerve impulse is sent down a nerve fiber.
2. The impulse arrives at the synaptic knob which stimulates the knob to open its Ca+ channels and allows Ca to enter via diffusion.
3. Ca+ stimulates the vesicles to release Ach via exocytosis.
4. Ach leaves the synaptic knob and diffuses across the synaptic cleft and binds to the receptors on the sarcolemma of the muscle fiber.
5. The binding of Ach causes an action potential (that change in voltage in the plasma membrane).
6. The action potential spreads in a wave like motion along the sarcolemma and through the t-tubules.

****Note that calcium has been used twice so far. It is a really popular element in this process.*****

Muscle Contraction Cont'd

7. The action potential stimulates the sarcoplasmic reticulum to release calcium.
8. Calcium binds to the troponin which causes the tropomyosin to shift and exposes binding sites on the actin.
9. ATP is broken into ADP and P to provide the energy for the myosin to cock its head, with the help of myosin adenosinetriphosphotase. The myosin binds to the actin to form a cross-bridge.
10. Once the cross-bridge is formed the myosin can then shift its head and pull the actin forward. This is referred to as a power stroke.
11. After the power stroke, myosin binds to another ATP and starts the process over again.

Continuing from the slide before…
7. The action potential in the t-tubules stimulates the sarcoplasmic reticulum to release Ca++ and it diffuses into the sarcoplasm.

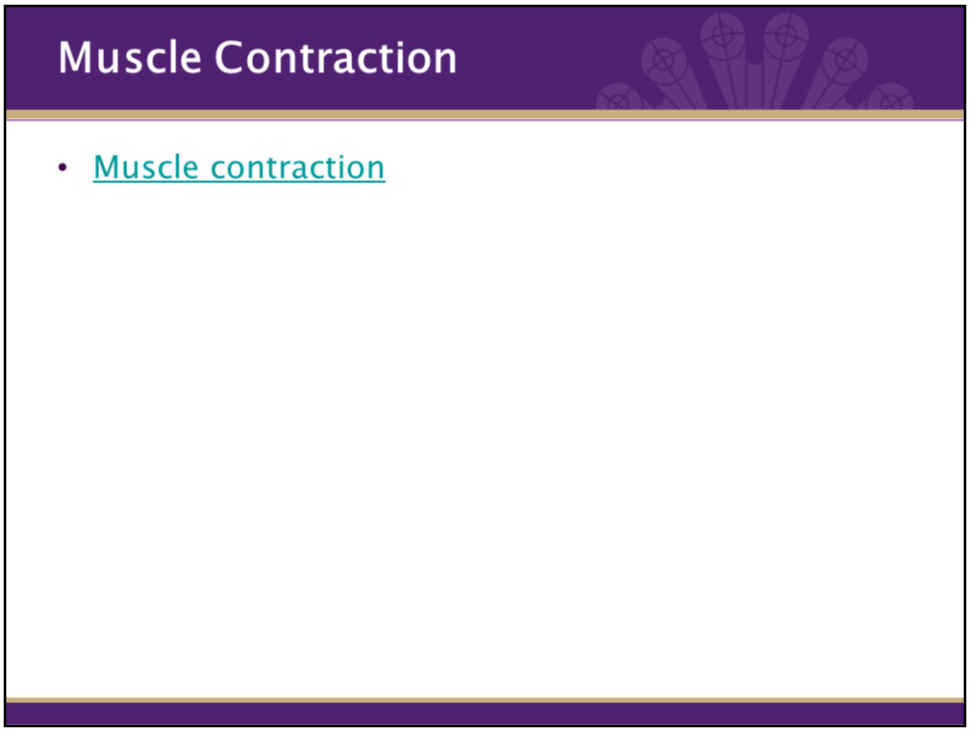
Now, for the filaments and the actual work. The previous steps set up the filaments to start the process. This portion of the process, with the filaments, is specifically called the SLIDING FILAMENT THEORY.

8. Ca+ binds to the troponin which causes the tropomyosin to shift and expose the binding sites.
9.ATP is broken down into ADP and Phosphate to provide the energy for the myosin to cock its head. This is done with the aid of an enzyme called myosin adenosinetriphosphotase. The myosin binds to the actin to form a cross-bridge, or connection between the myosin head and the actin.

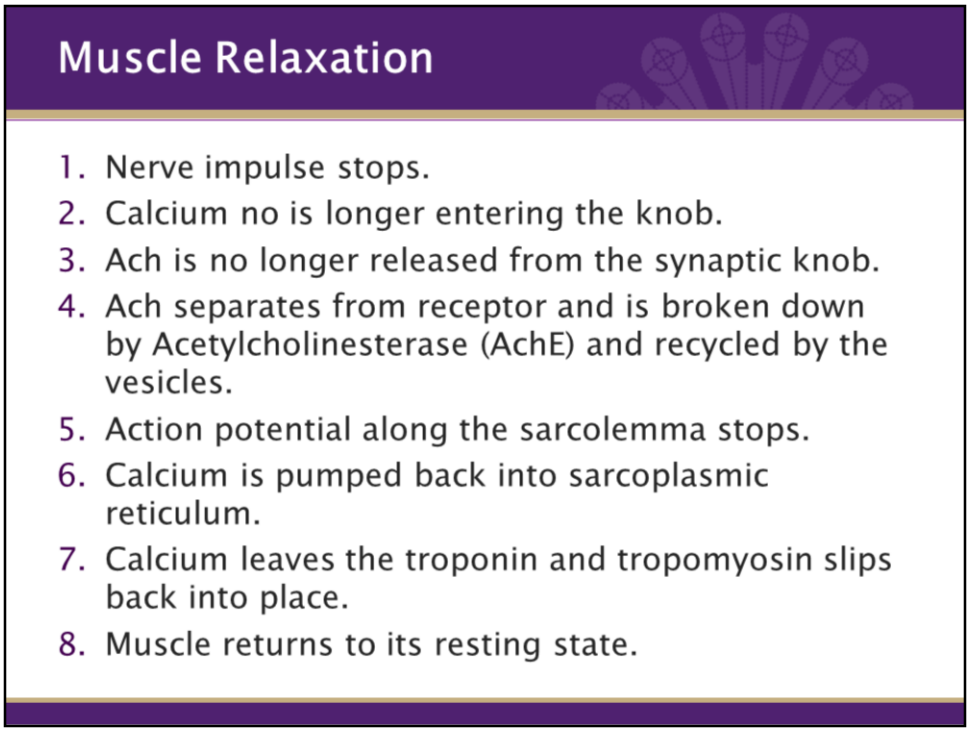
10. Once the cross-bridge is formed the myosin can then shift its head and pull the actin forward. This is referred to as a power stroke.

11. After the power stroke, myosin binds to another ATP and starts the cross-bridge/power stroke process over again.

When myosin releases to form another cross-bridge, actin does not slide back because to its original location because there are numerous myosin heads at different stages of the process. So while some are releasing and re-shifting, others are in the cross-bridge position. When you pull on a rope, one hand moves at a time, it is a similar situation.



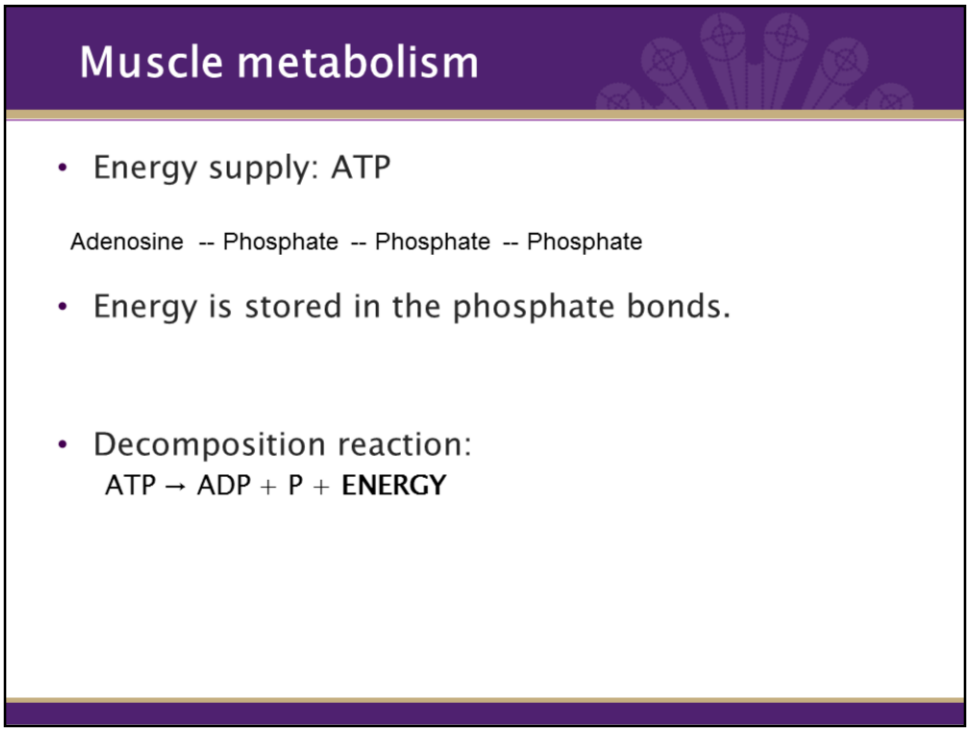
I know this is complicated and it will take a few times going over the steps to let them sink in. One of the ways to learn them is to write them over and over again. If you click on this link it will take you to an animation of the sliding filament theory. Also, pages 409-411 in your text book do a good job of linking the steps with pictures.



If there is contraction, we must have relaxation so the muscles can go back to their resting state.

The steps for RELAXATION:

1. The nerve impulse stops.
2. Calcium is no longer entering the knob.
3. Ach is no longer released from the synaptic knob.
4. Ach separates from its receptor and is broken down by AchE and recycled by the vesicles.
5. Action potential along the sarcolemma stops
6. When the action potential stops, the Ca++ that is not bound is pumped back into the sarcoplasmic reticulum (ATP is needed to do so).
7. The bond Ca++ can then leave troponin which tropomyosin slips back into place.
8. The filaments slide back and the muscle returns to its resting state.



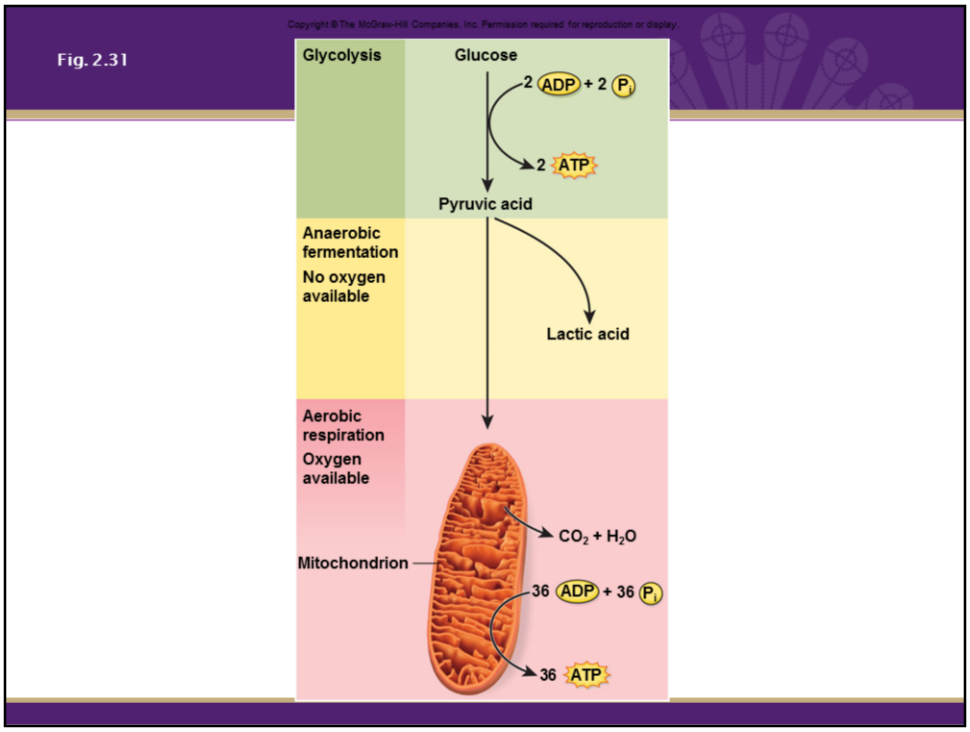
When we discuss muscle metabolism, we are talking about the chemical reactions needed to produce energy. Energy is supplied from ATP, think back to our chemistry section. Adenosine triphosphate (ATP) stores energy in its phosphate bonds. So the molecule looks like: an Adenosine molecule with 3 PO4 attached. Energy is released through a decomposition reaction: ATP → ADP + P + ENERGY.

Muscle Metabolism Cont'd

- Source of energy
- Anaerobic vs aerobic

We primarily use glucose as a means to synthesize ATP. We can do this either in the presence or absence of oxygen.

If oxygen is present, we refer to this as cellular respiration or aerobic respiration. If oxygen is absent, we refer to this process as anaerobic fermentation. Both processes start out with glycolysis. This is a mechanism for converting glucose to pyruvic acid.



This picture shows Glycolysis and both anaerobic fermentation and aerobic respiration.
Glycolysis is the first step to producing ATP. What happens, as shown in the green of the diagram, is that Glucose is used by the cell to add 2 phosphates to 2 ADP (each ADP receives a phosphate). As a result, glucose is converted to pyruvic acid.

If oxygen is not present, we will continue in anaerobic fermentation. In this phase, pyruvic acid is converted to Lactic Acid. Lactic Acid is what makes you feel sore after your work your muscles hard and can also cause them to cramp. Since two ATP were produced during the initial stages of glycolysis, we say that anaerobic fermentation results in ATP.

If oxygen is present, a slightly different path is taken in aerobic respiration. Aerobic Respiration occurs in the mitochondria requires a molecule of 2 oxygen atoms and sends the pyruvic acid into a series of chemical reactions to produce a large amount of ATP. Water, heat, and carbon dioxide are by products of this system.

Both systems utilize glucose, but whereas anaerobic fermentation produces 2 ATP for every 1 glucose, aerobic respiration produces 36 ATP for every one glucose. This sounds great right, so why doesn't our body use it all the time? Well, this system takes time to get going, it kicks in after 40 seconds. But, it can go for quite awhile. In exercise over 10 minutes, 90% of ATP comes from this system. Also, the more you

rely on this system, the more efficient it becomes. If it is used extensively, a small amount of lactic acid can accumulate. It also requires a good supply of glucose, H2O, and minerals to function.

So, to summarize. Pyruvic acid is produced at the end of glycolysis. I oxygen is not available, pyruvic acid is converted to lactic acid with a net gain of 2 ATP. If oxygen is present, it continues onto the mitochondria and used to produce 36 ATP.

Muscle Metabolism Cont'd

- Types of Energy usage
- Immediate
  - Use what is present
  - Phosphagen system
- Short term
  - "Buying Time"
  - Glycogen–Lactic Acid System
- Long term
  - Aerobic respiration

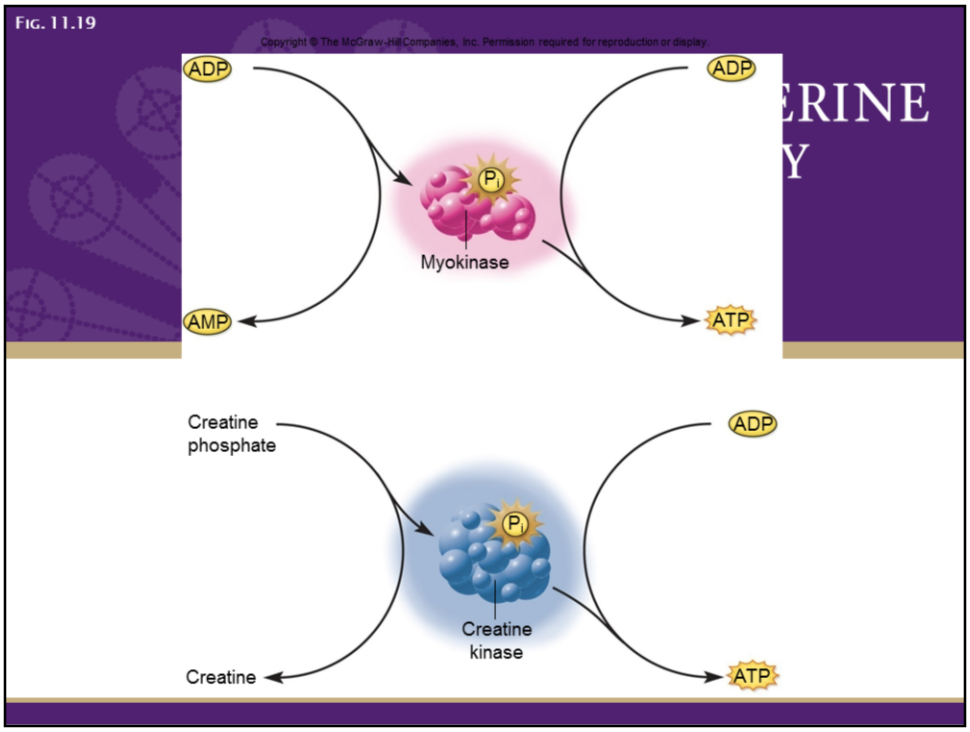
Our muscles will use whatever is present for our immediate energy needs. This is why we have a lot of glycogen and myoglobin in our muscles cells, so we have a ready supply of glucose and oxygen to replenish our ATP supply.

There are a few types of energy usage: immediate, short term, and long term.

Immediate usage utilizes what is currently available in the muscle fiber. One system in particular, the phosphagen system, is essential for providing the immediate supply of ATP. This system is explained on the next slide.

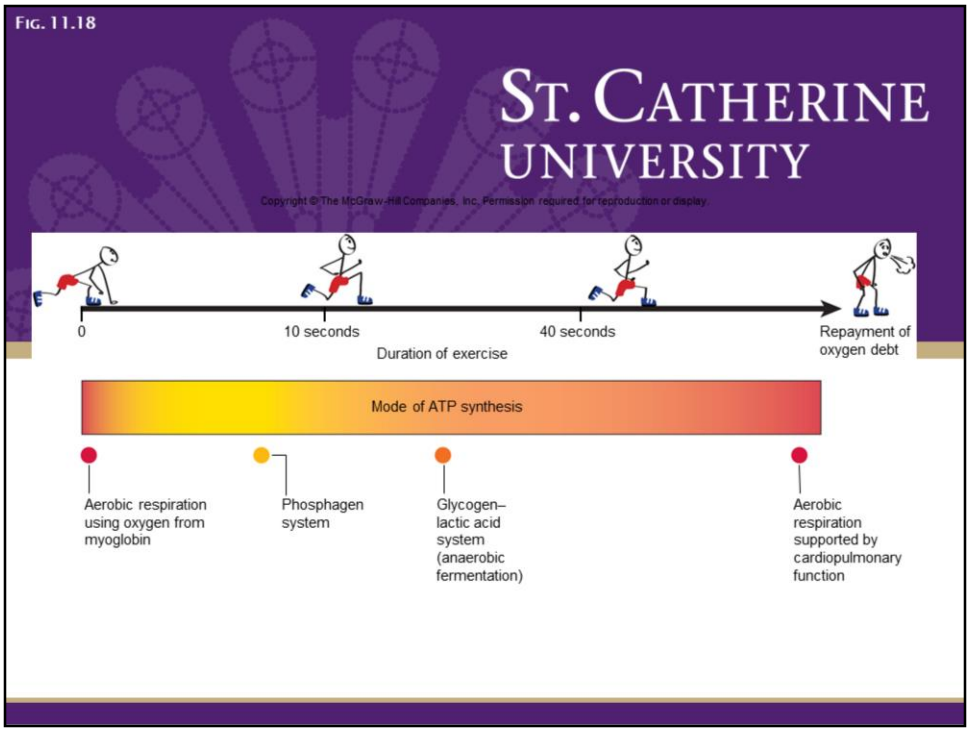
Shorter term use allows us to produce and use ATP while waiting for the respiratory rates to increase and provide an adequate supply of oxygen. This system is our Glycogen-Lactic Acid system. We saw how this system synthesizes ATP in the previously slides when we talked about anaerobic fermentation.

Long term ATP usage is when our respiratory has caught up and is delivering oxygen at the rate that is required for the work that our muscles are doing. In this stage of work, we are primarily using aerobic respiration as the source of ATP

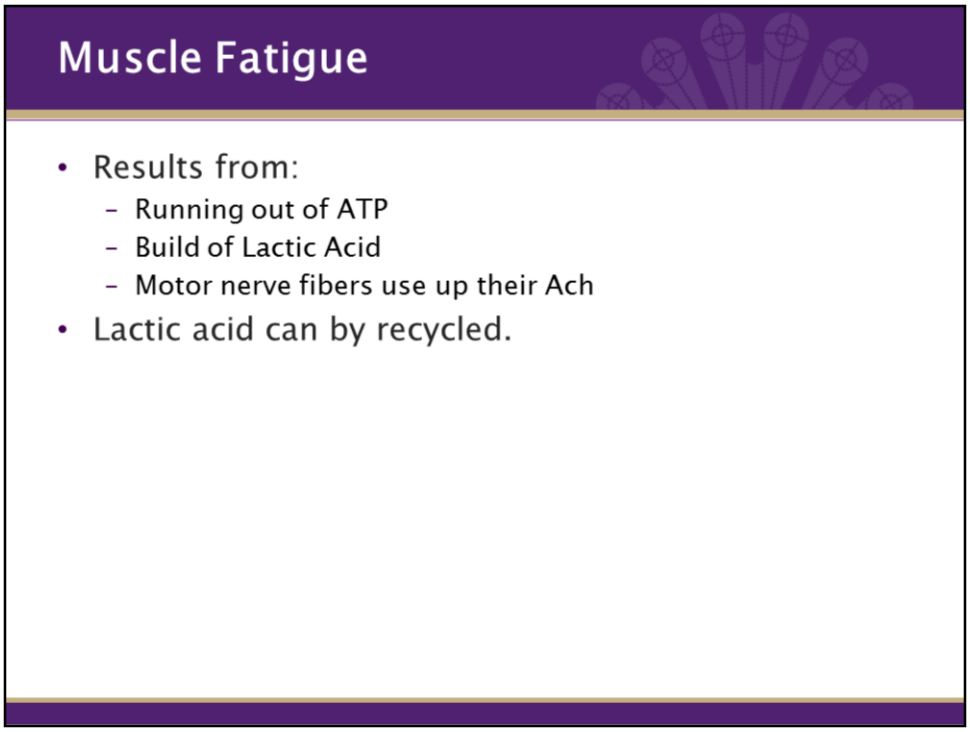


The Phosphagen System is Anaerobic, so no oxygen is present. It provides max strength and speed and only lasts 6-10 seconds. This is our "life saving", last second need of ATP. For instances, if you needed to jump out of the way of an out of control bus. This system is also used in social/athletic activities like the 100 m dash and swinging a bat. This is why sprinters do not even look winded when they finish a 100 meter dash, their body hasn't needed that increase of oxygen to supply energy to the muscles. As mentioned, this is short lived and has a lag time to replenish.

In the top portion of this diagram, myokinase is an enzyme that is transferring one phosphate from an ADP to another. In the bottom portion, creatine kinase is an enzyme that acts as a transfer molecule and helps a phosphate from one molecule (our creatine phosphate) to another, ADP. Both enzymes are like the postal service, you drop the letter in the mail, the postal service delivers it to its intended recipient.

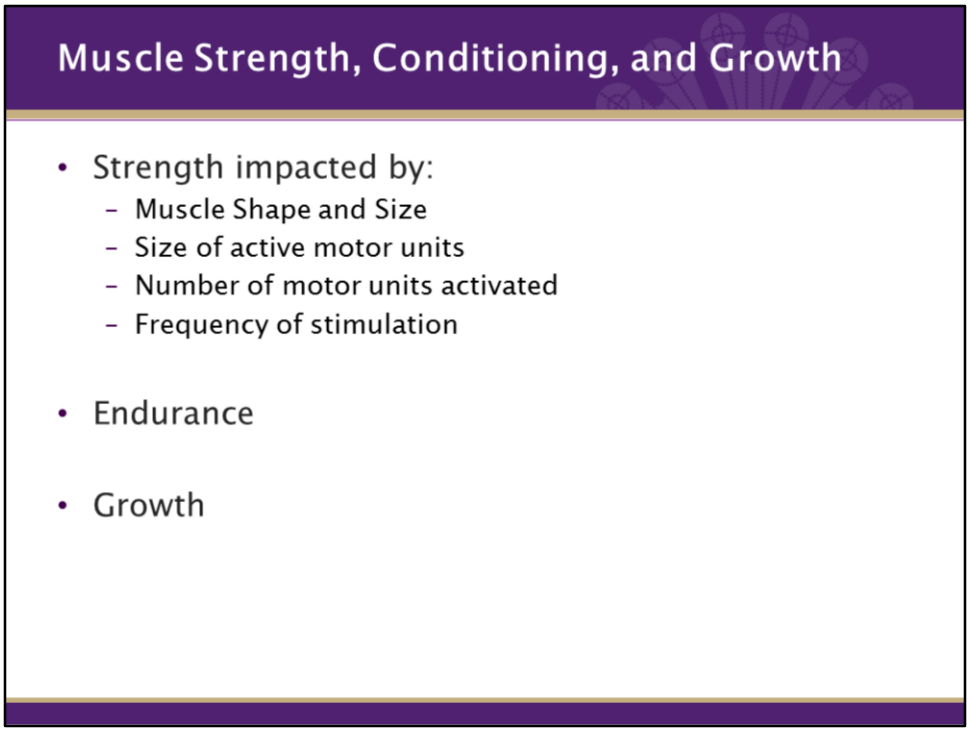


Our little stick figure guy is demonstrating how the different systems grade into one another. If you use aerobic respiration long enough, you will give the phosphagen system time to recover and have a quick supply of ATP handy. This why long distance runners can have that sprint at the end of the race, their phosphagen system has kicked in.



But, we can push or muscles too far, especially if they have not been trained to do the work we are asking them to do. Muscle fatigue results from running out of necessary electrolytes or energy supplies and molecules or the build up of lactic acid. If we do not have the proper molecules to contract, obviously our muscles are not going to work. When lactic acid builds up it lowers pH of muscles and makes the work less efficient (inhibits enzymes needed for contraction). Another way that muscle fatigue can occur is when the motor nerve fibers use up all their Ach and can no longer provide stimulation.

A note about lactic acid, it can be recycled. If it is released from the muscle fibers, it is sent to liver and turned back into glucose. So, if you work the sore or fatigued muscles by easy exercise, massage, or stretching, it will increase blood flow and allows lactic acid to be recycled quicker.

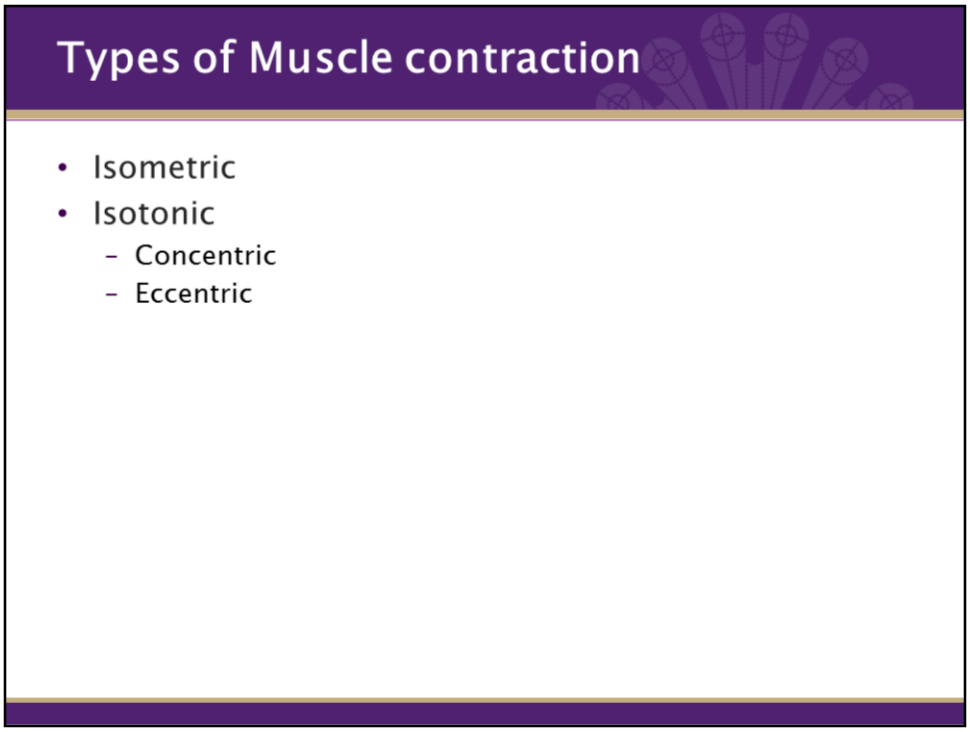


The strength of a muscle is impacted by a number of factors. First, the shape of the muscle impacts of strongly it can contract. For instance, pennate muscles are stronger the parallel muscles. This is due to the how the fascicles are arranged within that particular muscle. Also, thicker muscles will have a stronger contraction than thinner muscles due to the presence of more actin-myosin cross bridges. The size and number of active motor units also impacts how strong a muscle contraction will be. The larger the motor unit, the stronger the contraction. Also, the more motor units that are activated and able to provide a stimulation, the stronger the contraction will be. The strength is also influenced by how frequently the stimulus is sent. The quicker and more often a stimulus comes, the stronger the contraction. As mentioned in earlier, fatigue can also play a role in strength of contraction.

Muscle can gain endurance and limit fatigue through aerobic exercise. Exercises like jogging and swimming, train your muscles to become more efficient at using oxygen and increases the maximum oxygen uptake, we increase the number of myoglobin and mitochondria in the muscle cell. These types of exercises also improve how your cardiac, respiratory, and nervous system work with muscles by enhancing how oxygen is delivered.

When we see our muscle develop due to work, we do not actually have growth in the

sense of developing new muscles. When we work our muscles, we are actually stimulating cellular enlargement not cell division. When we enlarge our muscles, we are increasing the number of myofilaments and myofibrils within the cell.



Muscles do not contract the same way every time. There are a few different ways a muscle can contract.

1. Isometric contraction is contraction without change in length. There is no movement, but there is an increase in tension. For instance, when grabbing a heavy box. Your muscle tense before they move the box.

2. Isotonic contraction is change in muscle length without change in tension. If we stick with our box example, it is when we start to lift the box. The box itself is moving, but we are not changing the amount of tension we are applying to the box. There are two forms of isotonic contraction.

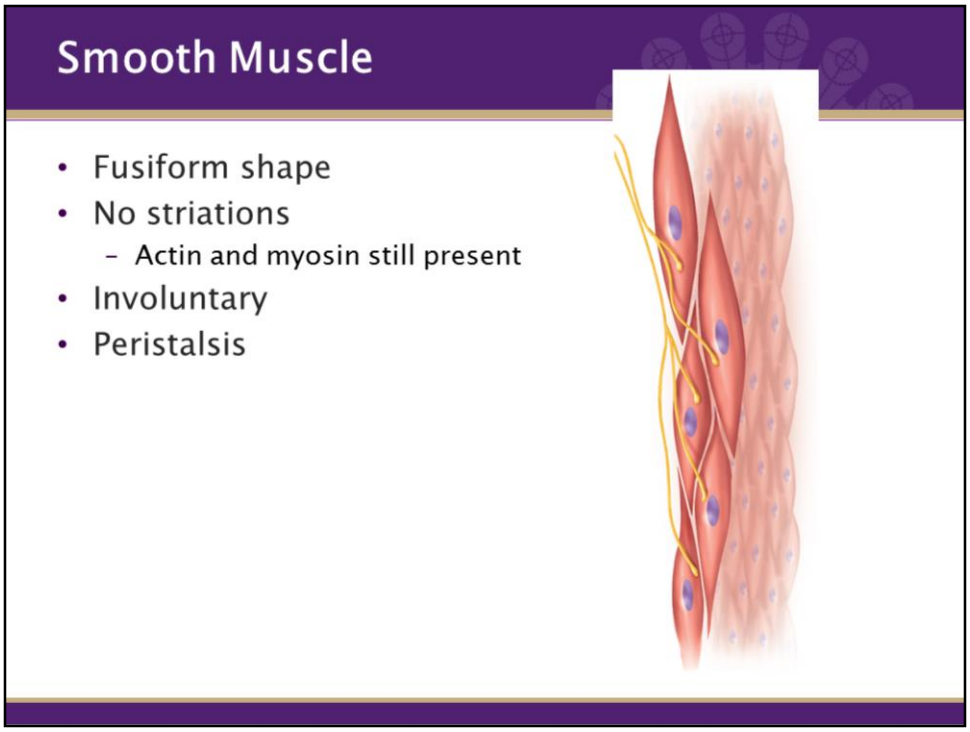
a. Concentric contraction is when the muscle shortens, or flexes, like lifting the box up.

b. Eccentric contraction is when the muscle lengthens and provides control as your muscle extends. This acts like a brake when returning the box to floor.

Cardiac Muscle

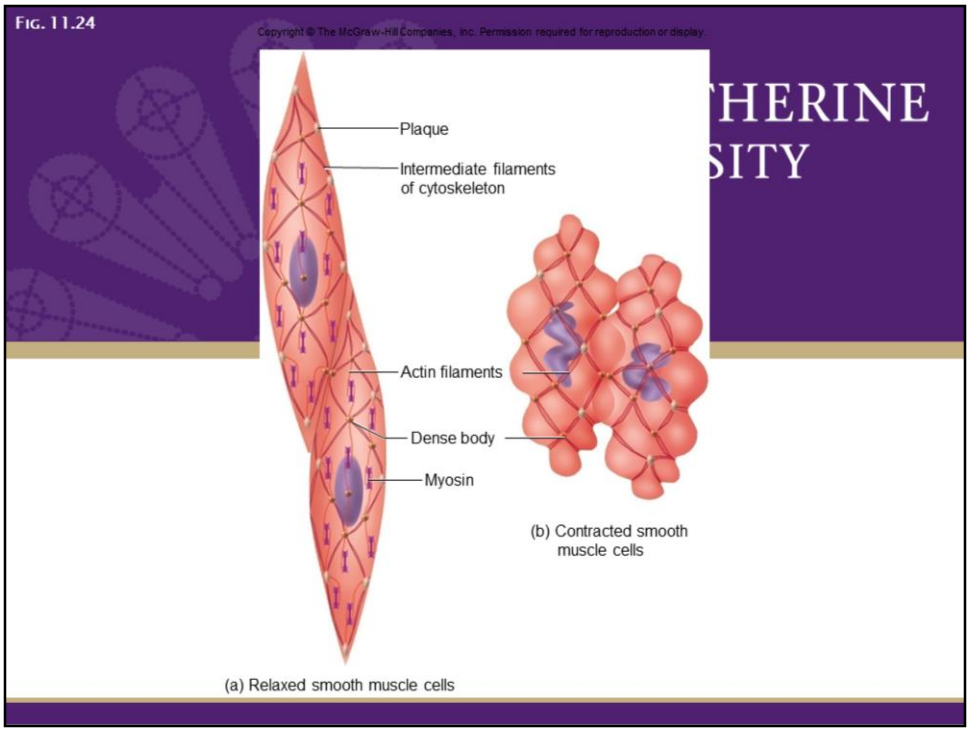
- Striated
- Intercalated discs
  - Gap junctions
- Involuntary
- Doesn't need a nerve supply
- Autorhythmicity
- Almost exclusively aerobic
- Large Mitochondria
- Lots of myoglobin and glycogen

To review CARDIAC MUSCLE, it is striated has intercalated discs and gap junctions so the cells can communicate directly with each other. It also doesn't need nervous stimulation, it can stimulate itself. This is called autorhythmicity. It uses aerobic respiration almost exclusively and has large mitochondria and lots of myoglobin and glycogen. It is also involuntary. Again, it will come back up when we do the cardiac system.



SMOOTH MUSCLES

We have talked a little bit about this muscle type in tissues, but to provide a little bit more information and to review. They are fusiform shape, have no striations, and our involuntary. Even though they do not have striations, actin and myosin are still present. They are just not in the alignment that is seen in skeletal muscles, so no striations. They are found in found in the digestive system, some arteries, and pulmonary air passages. The contract in a wave like contraction that moves contents called Peristalsis.



This picture shows smooth muscle with its actin and myosin filaments.