OVERVIEW of WEEK 8
~ PRINCIPLES OF BIOMECHANICS HK*2270 ~

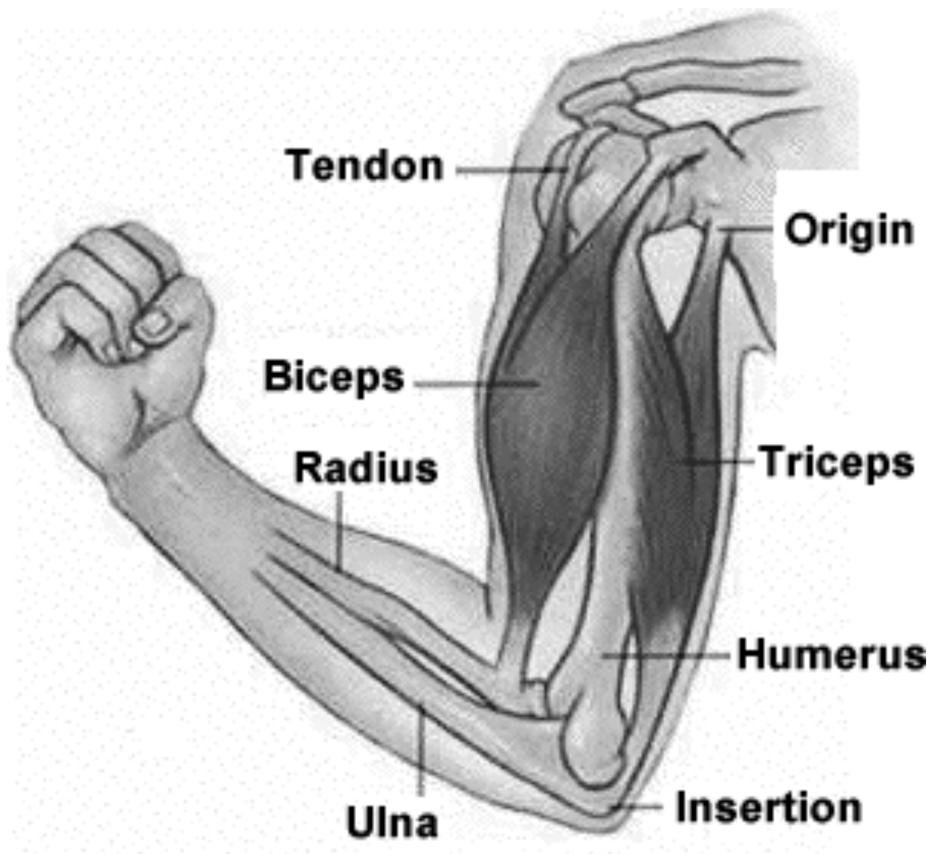
Lori Ann Vallis, FALL 2016

Problem set 6 will be on the quiz for sure, plus some content from this lecture.

Concepts

- **Muscle Mechanics**
- **Sliding filament theory**
- ***Neurophysiology of muscle contractions***
- ***Force – Length curves***
- ***Force – Velocity curves***

MUSCLE MECHANICS!



Anatomy of skeletal muscle

SKELETAL MUSCLE:

Epimysium surrounds

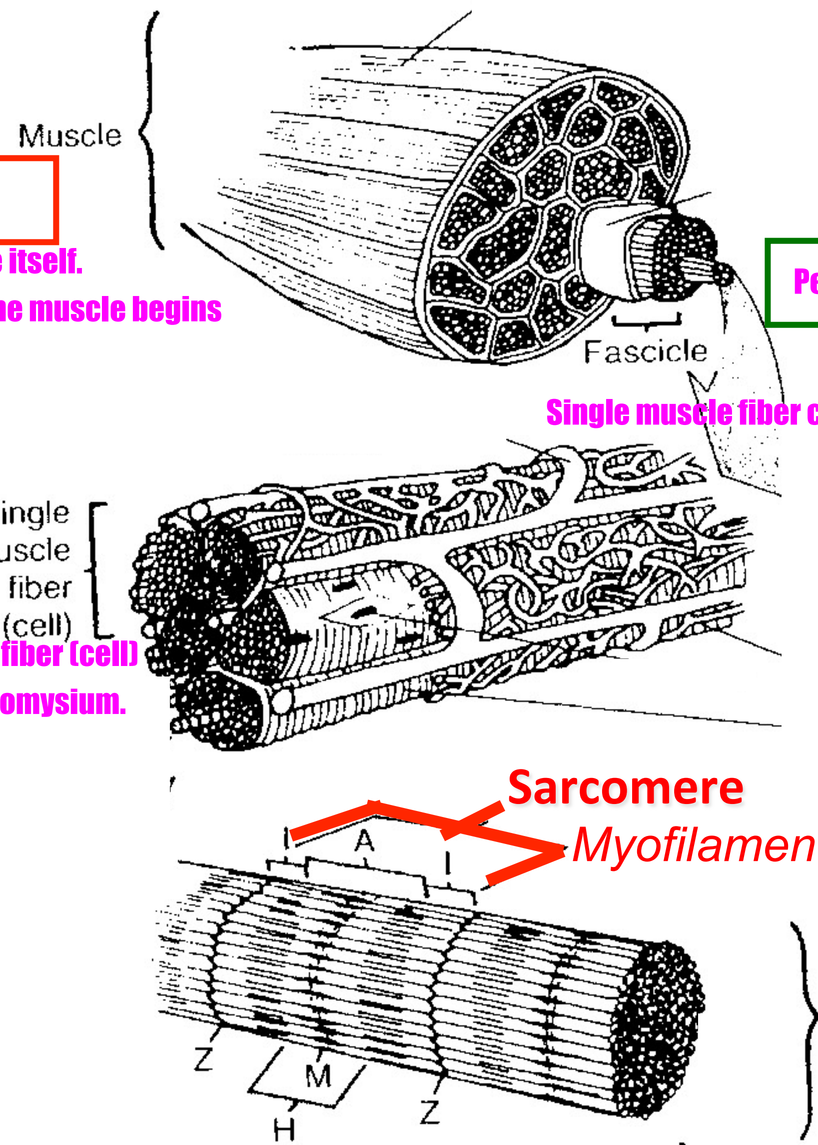
Surrounds the muscle tissue itself.
When you cut through this, the muscle begins to fall apart.

Perimysium surrounds

Single muscle fiber cell, have myofibrils inside

Endomysium

Surrounds the single muscle fiber (cell)
What makes beef juicy is endomysium.



Sarcomere

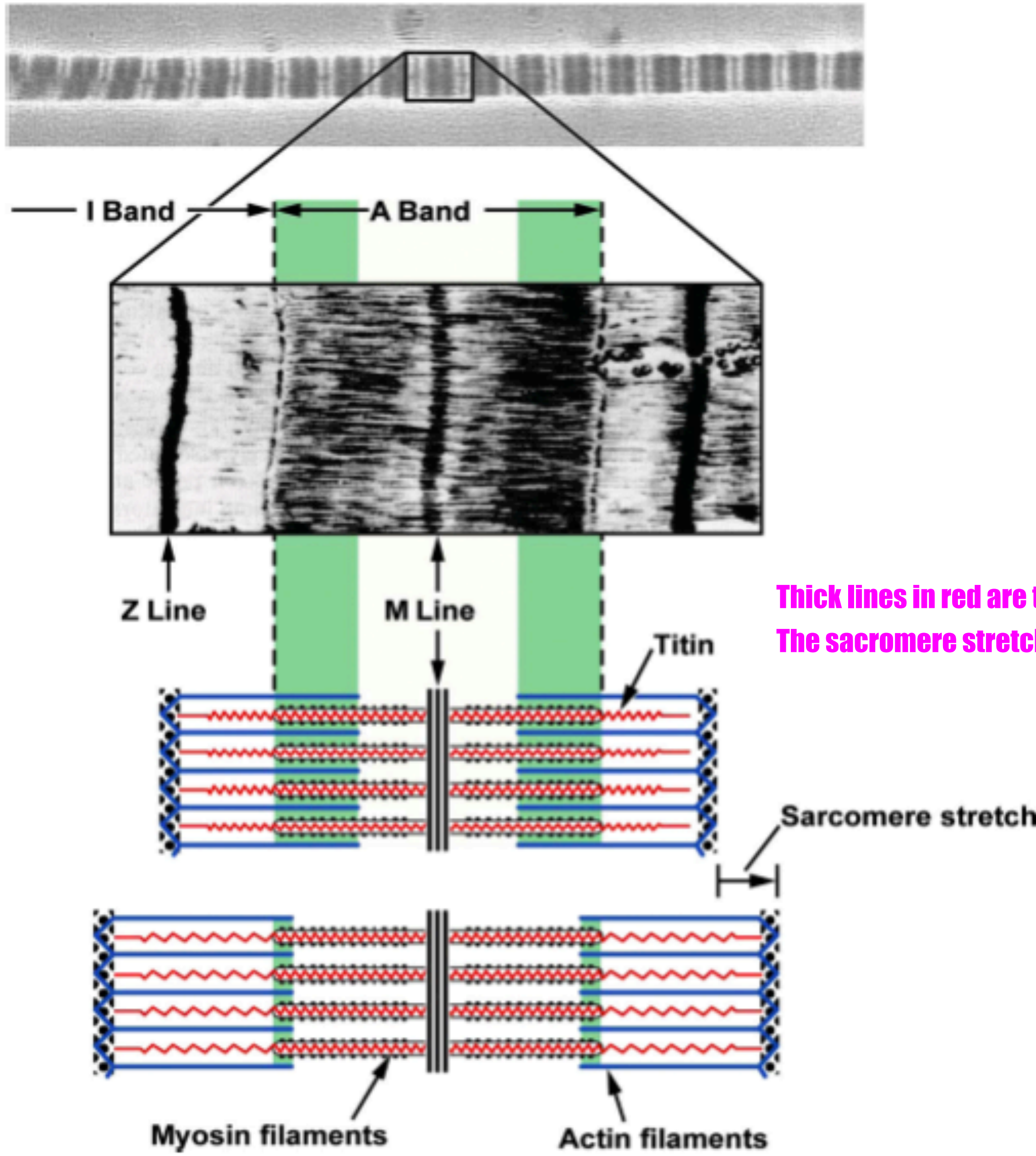
Myofilaments

contains the two myofilaments; can measure the level of forces produced by these two

Myofibril

Anatomy of skeletal muscle

This is the sacromere.

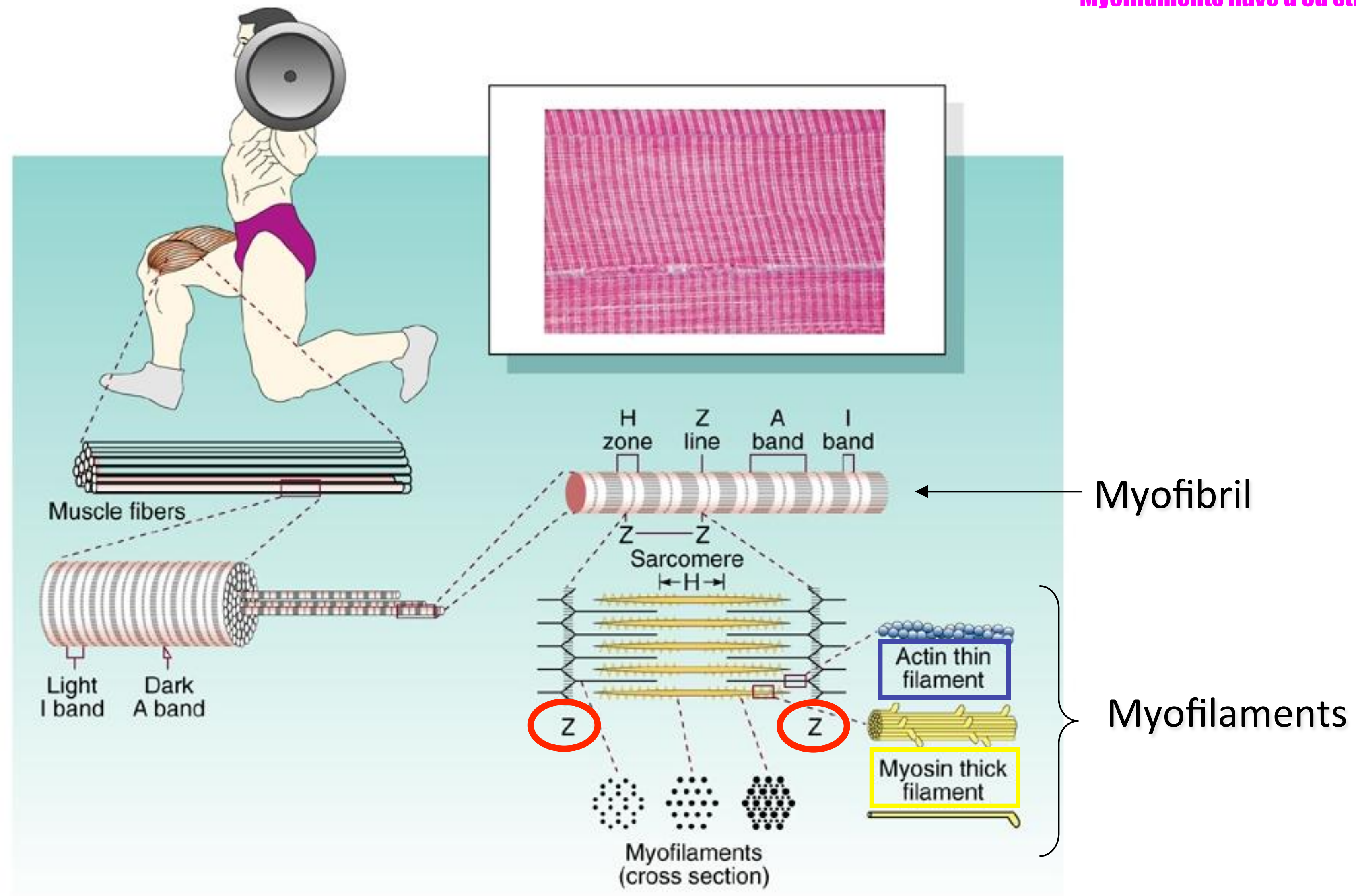


Thick lines in red are the myosin.

The sacromere stretches.

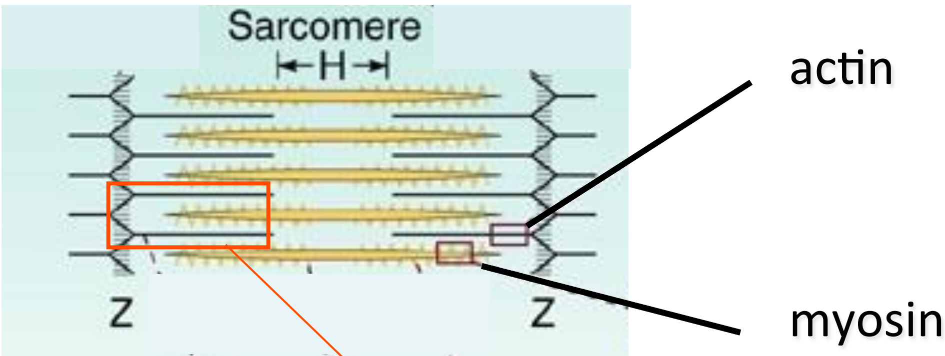
Contractile Mechanism

Myofilaments have a 3d structure.

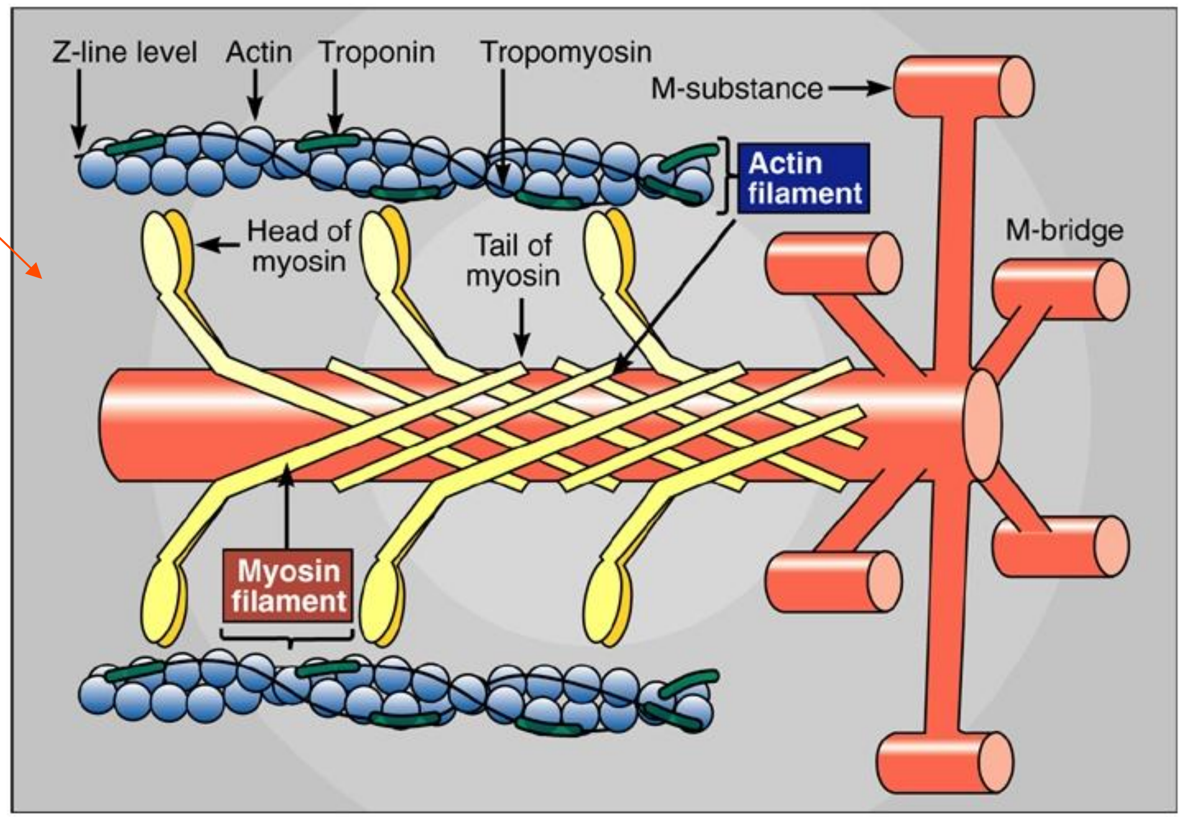


How does a muscle contract?

Contractile Mechanism



6 prong fibers on myosin (in red here). The actin surrounds it (in yellow), looks like an oar going into water.



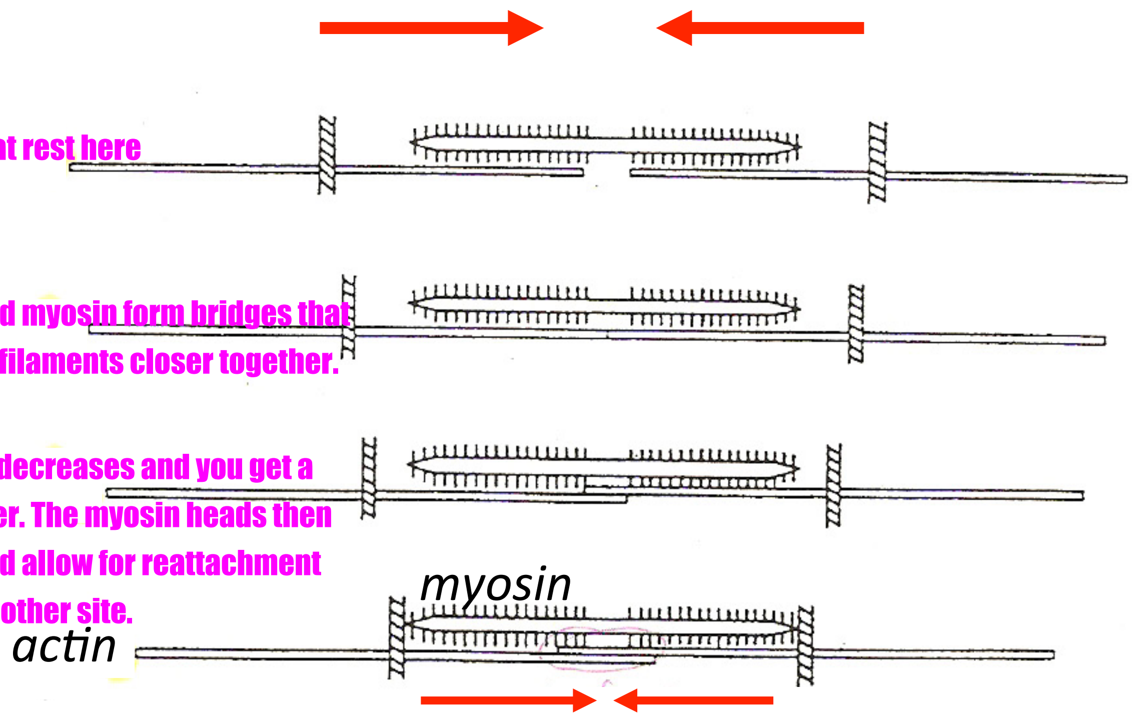
Contractile Mechanism

Sliding filament theory

Muscle at rest here

Actin and myosin form bridges that pull the filaments closer together.

The gap decreases and you get a crossover. The myosin heads then let go and allow for reattachment along another site.



- Actin and myosin form crossbridges
- Myosin heads ‘pull’ the actin filaments closer together
- Myosin lets go and re-attaches at another site further along the actin filament

Result? Z-discs move closer together = sacromere shortens.

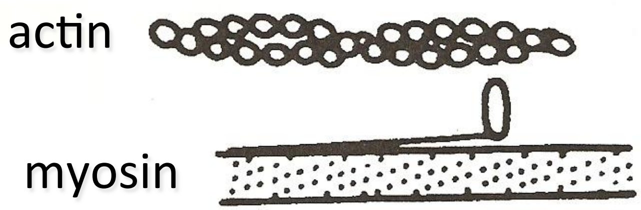
Muscular Contraction and Sliding Filament Theory

http://www.youtube.com/watch?v=EdHzKYDxrKc

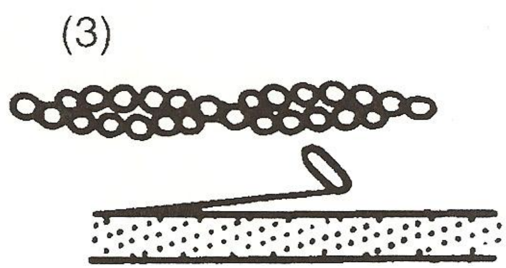
Contractile Mechanism

Cross-bridge cycle

4. Myosin head in high energy position

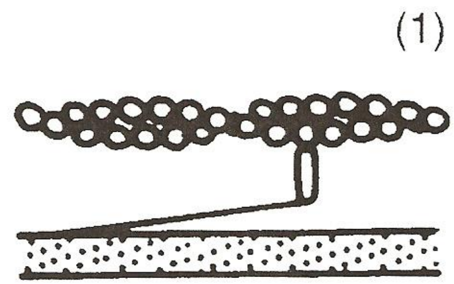


Myosin protein head detaches from actin. Then have an resting state.



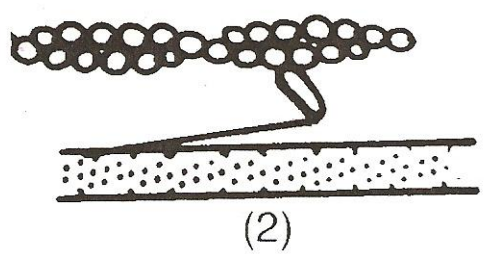
3. Cross-bridge detachment

Chemical that causes this



1. Cross-bridge attachment

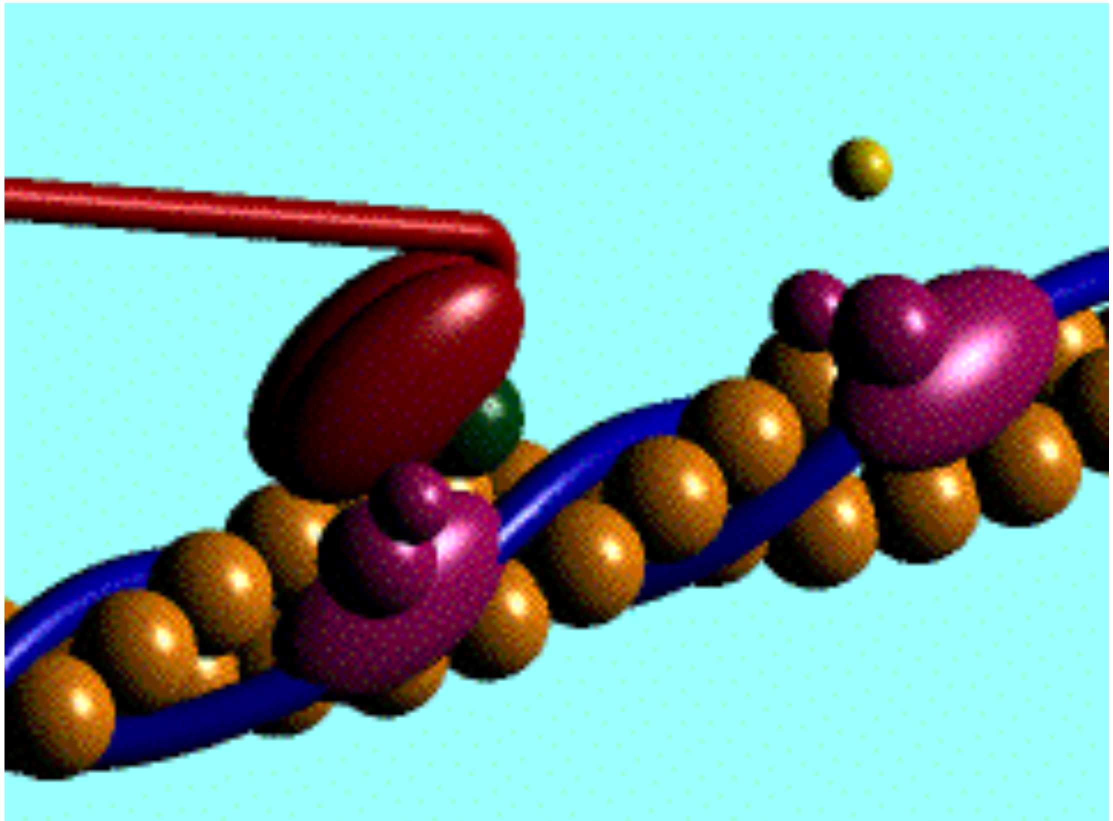
Got myosin head connecting to actin fibers.



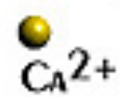
2. Power Stroke

Literally where you got the connection and it starts to slide (myosin and actin slide on top of each other)

Contractile Mechanism



Important players:



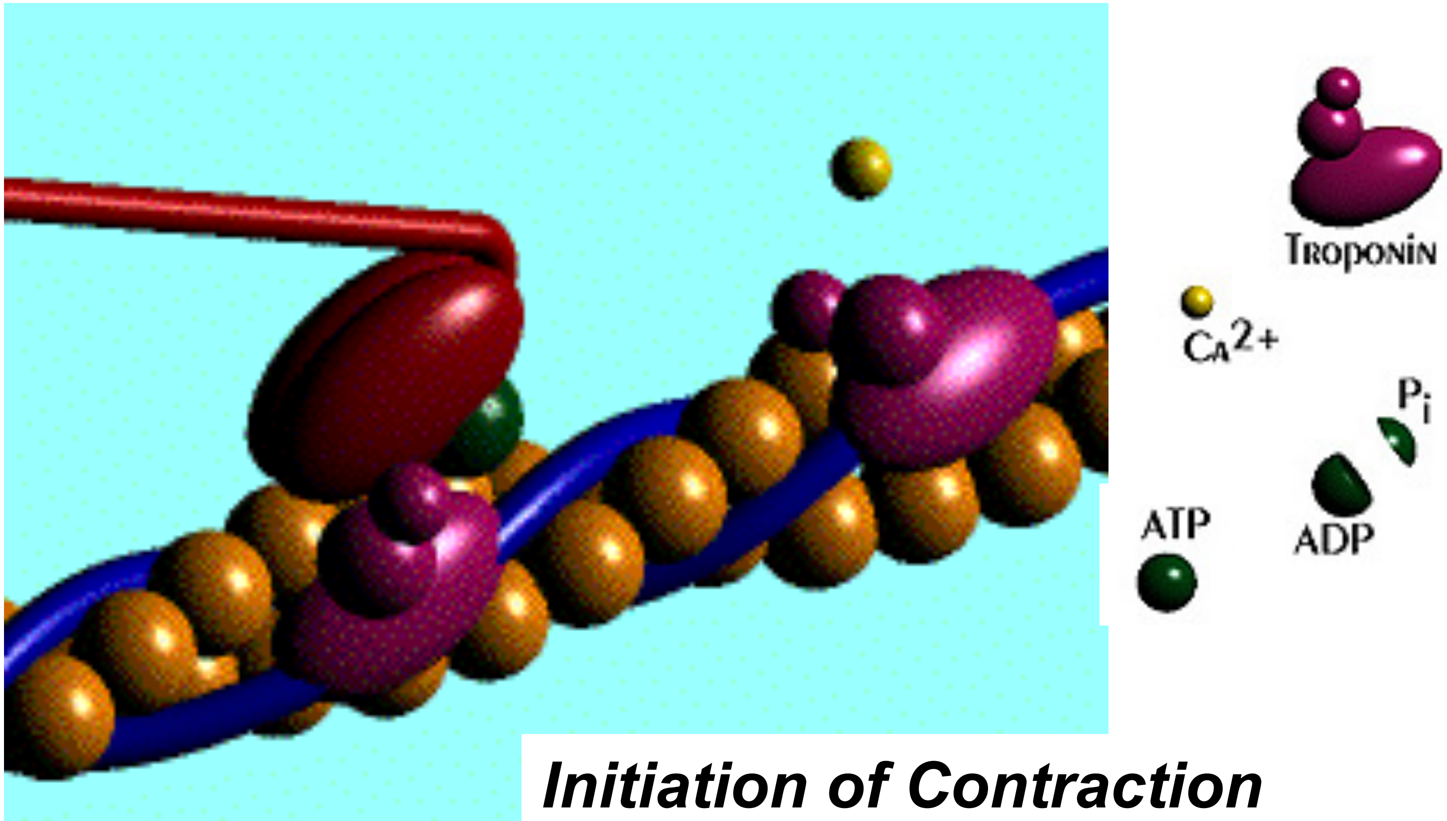
Ca2+ : opens up the myosin-binding sites on the actin filament

ATP : (1) hydrolysis of ATP into ADP + Pi

(2)causes myosin to become unbound from actin

Called the detachment phase

Contractile Mechanism



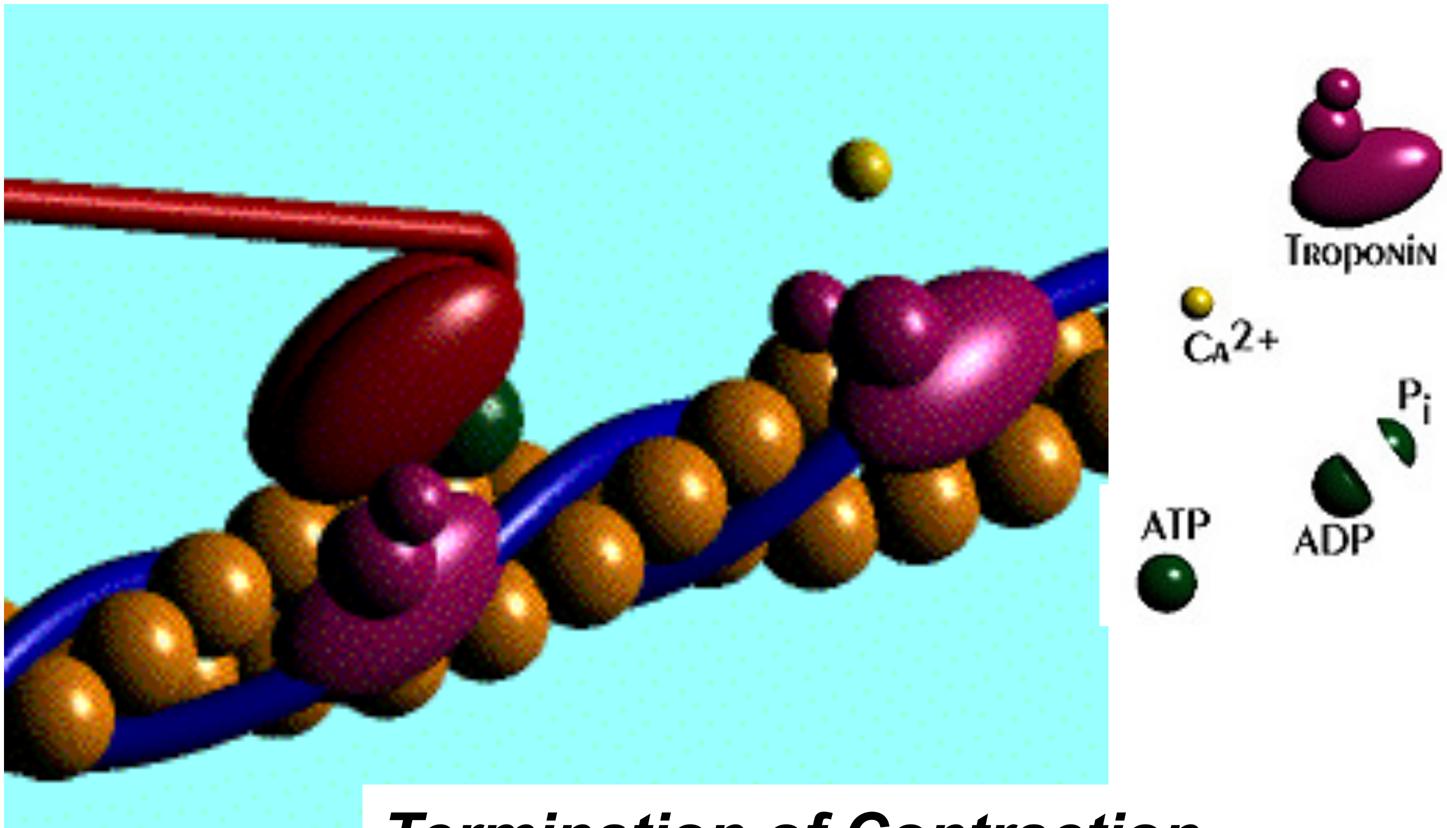
Initiation of Contraction

Breaks down of ACh within the structure of the cell (this is how a structure is terminated)

1. *Acetylcholine (ACh) released, binding to receptors*
2. *Action Potential reaches T-tubule* neural control (coming from the brain), reaches the T-tubule; releases calcium.
3. *Sarcoplasmic recticulum releases* Ca^{2+}
4. *Active site exposure: cross-bridge binding* causes cross bridge binding between myosin and actin.
5. *Contraction begins* Powerstroke happens and shortening slide bone theory happens.

Have to have the right chemicals in the right place and the neural contribution. Can be from different input sources (thinking of something then doing it vs reflexes)

Contractile Mechanism



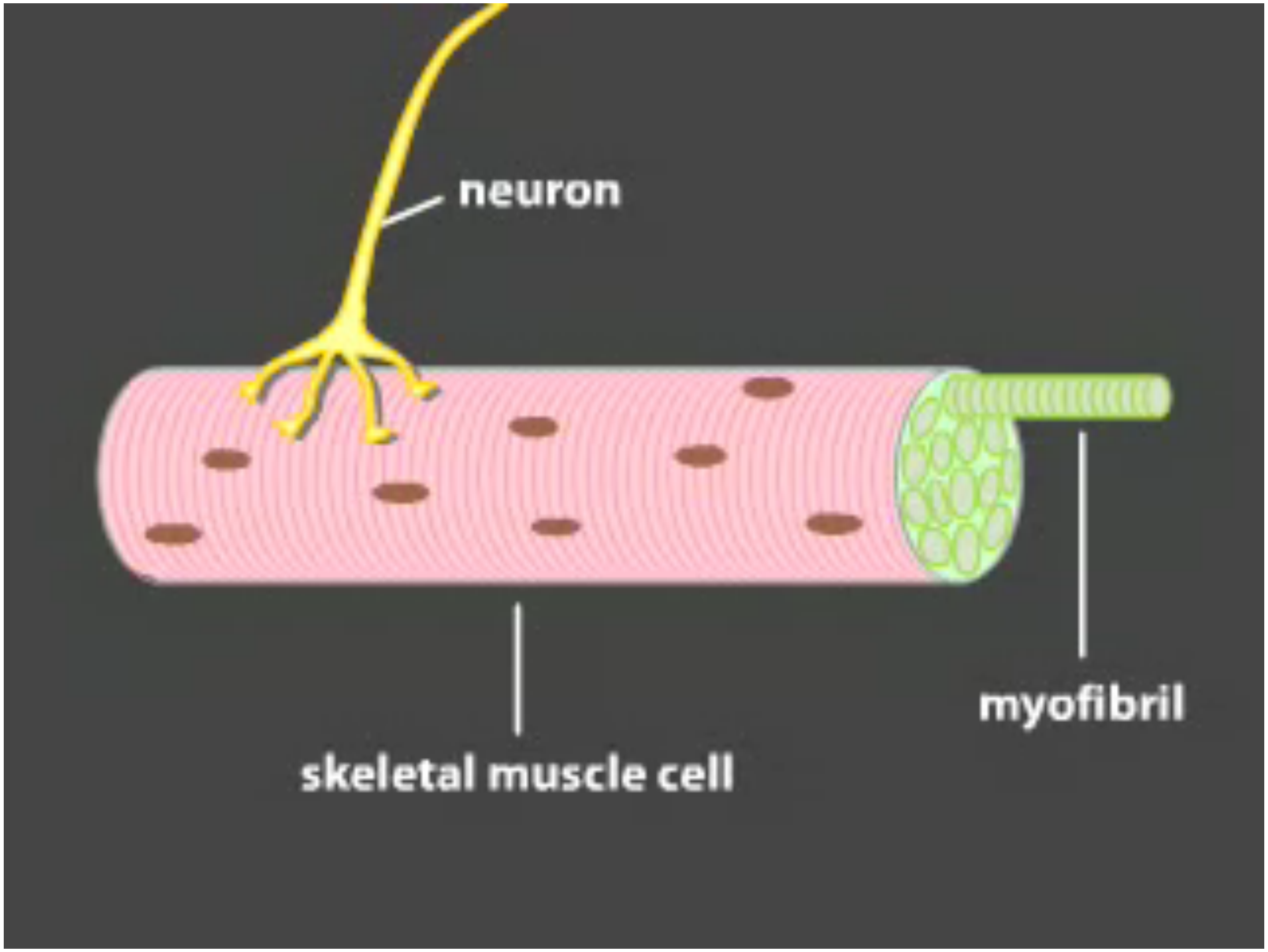
Termination of Contraction

1. *ACh removed by acetylcholinesterase (AChE)*
2. *Sarcoplasmic recticulum recaptures Ca^{2+}*
3. *Active sites covered, no cross bridge formation*
4. *Contraction ends*

How does cross bridge formation happen?

Sliding Filament Theory: Depolarization & Release of Ca+

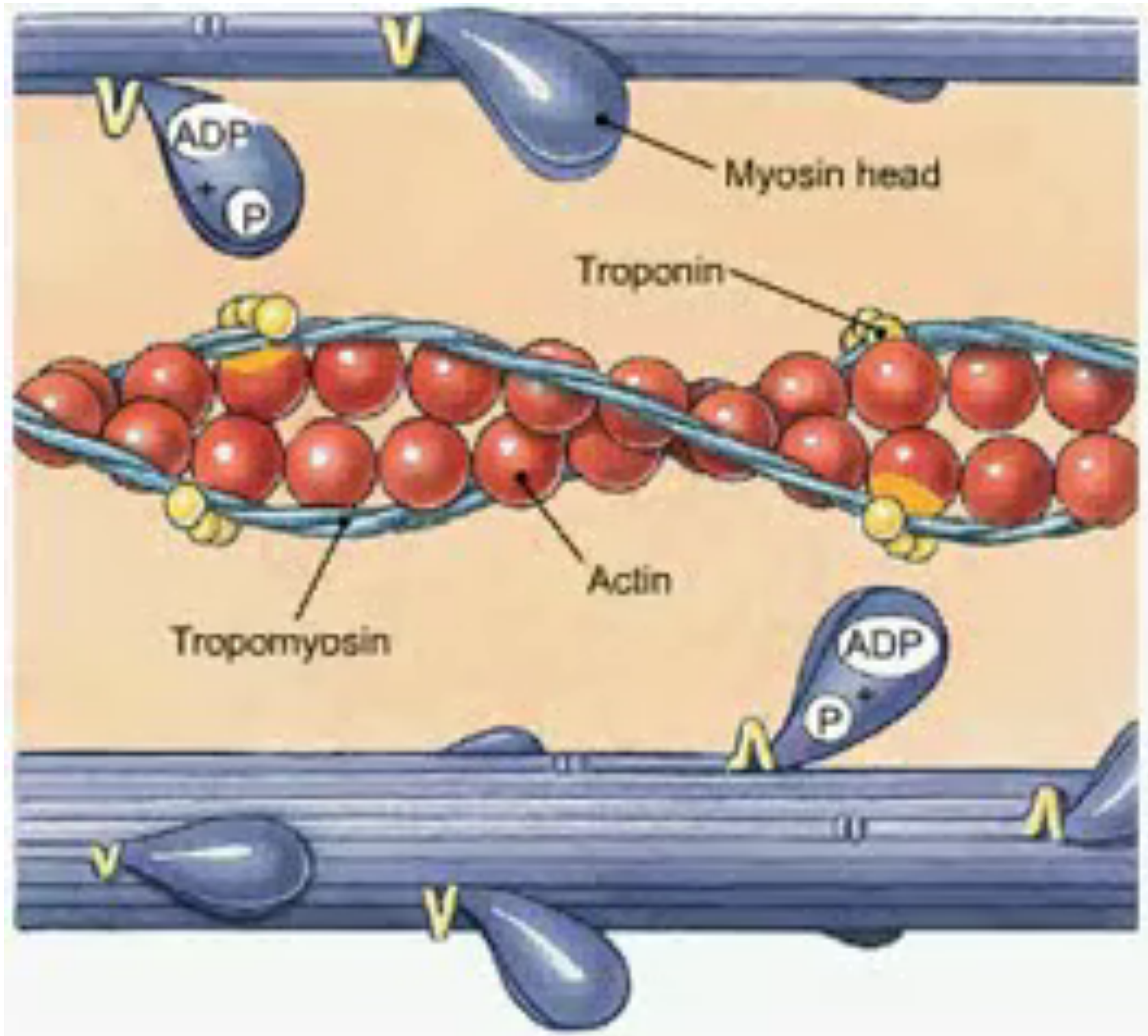
http://www.youtube.com/watch?v=CepeYFvqmk4



Impulse from neuron that comes down to the skeletal muscle cell. Watch the video and make notes!

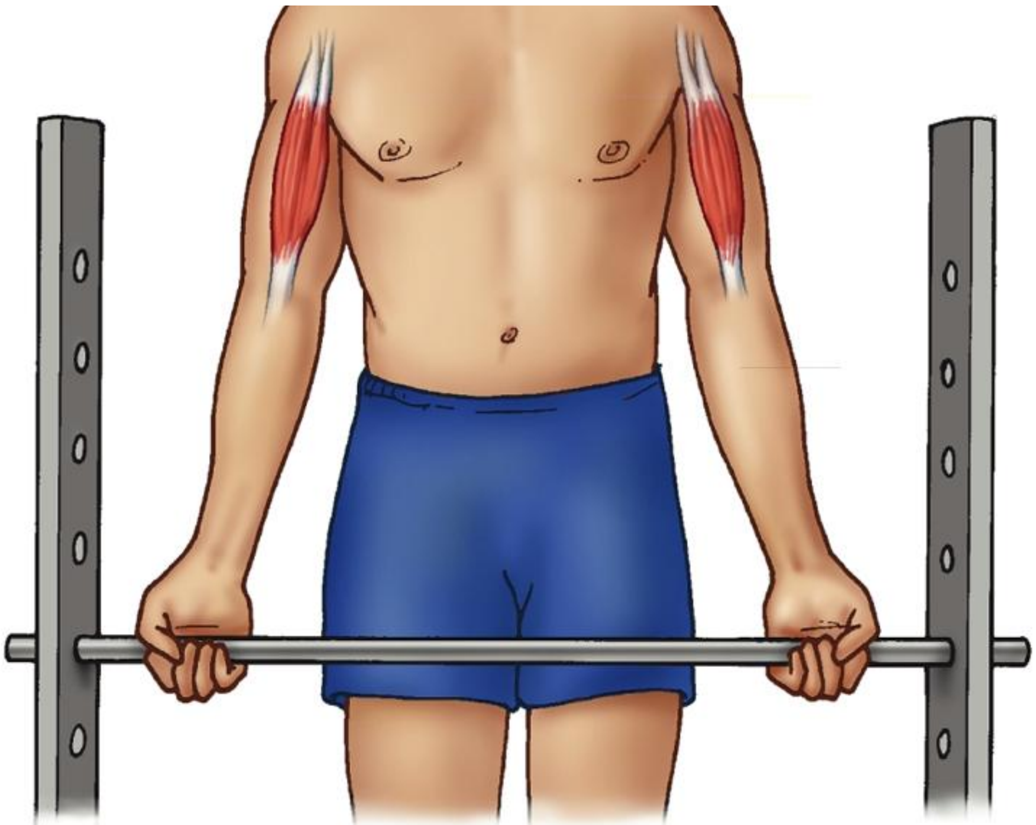
Sliding Filament Theory: Calcium, ATP/ADP +Pi

http://www.youtube.com/watch?v=mWPmUqRZYls



Contraction Types

No movement at all is isometric contractions. It means that the muscle fibers generation tension but there is no change in length. An example would be trying to move a fridge and it doesn't budge because it is so big. There is still tension just no shortening of those fibers.



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Movement: No movement

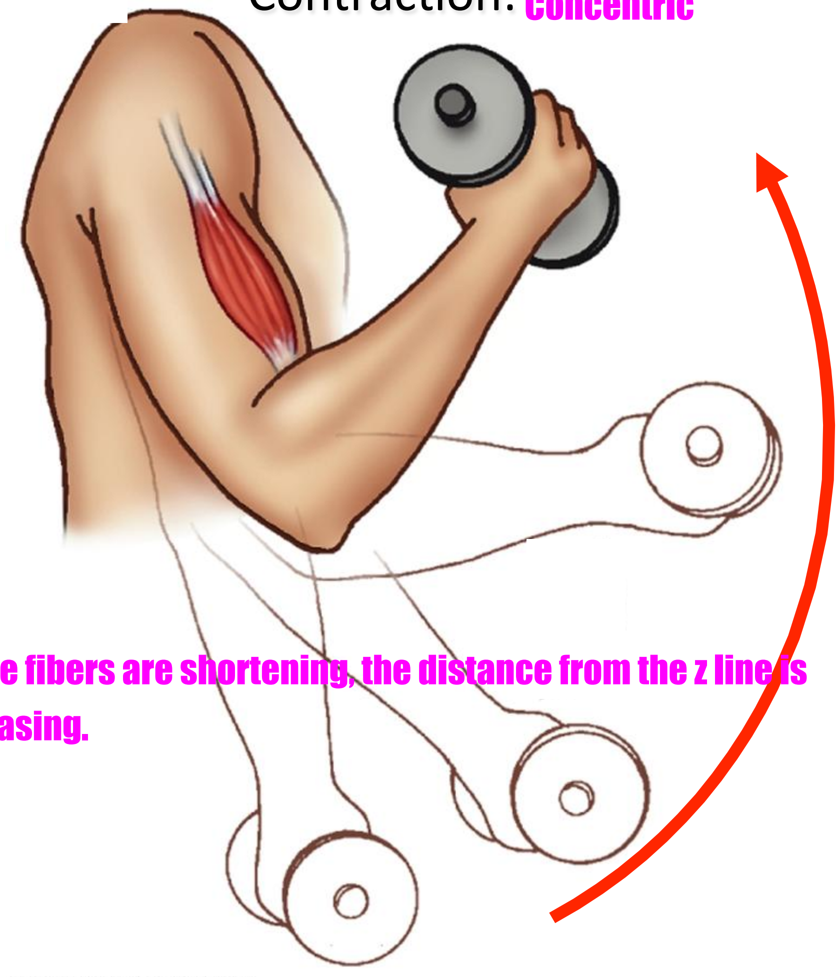
Contraction: Isometric

Isometric_______ contraction: when muscle fibers generate tension but there is no change in length

Contraction Types

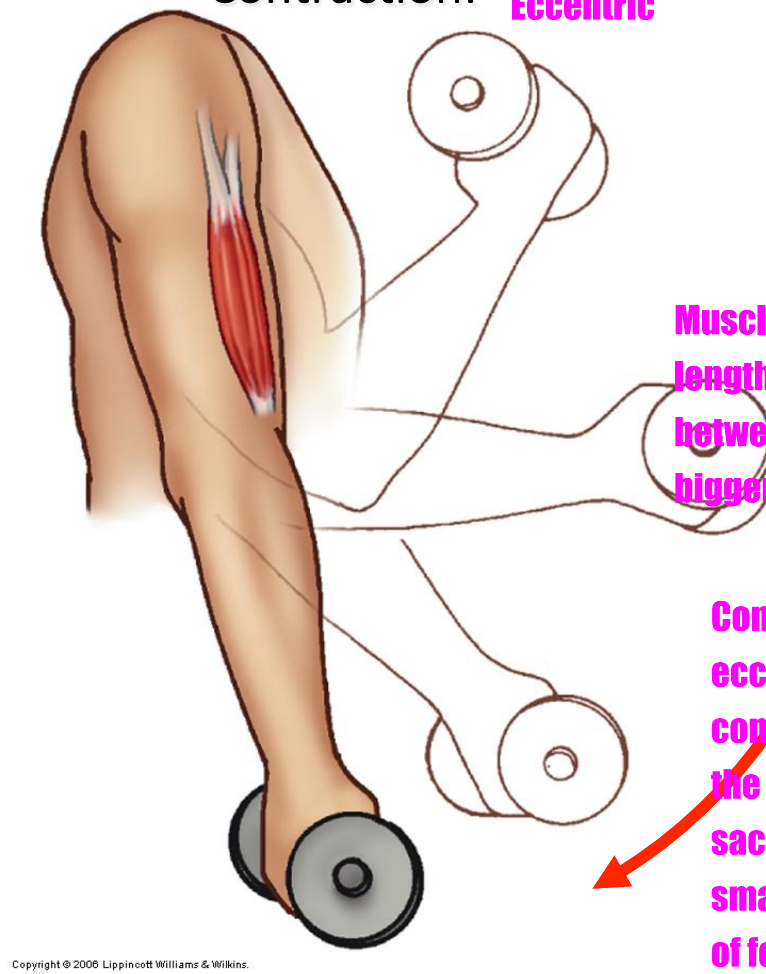
Bicep curl

Movement: Flexion	Movement: Extension
Contraction: Concentric	Contraction: Eccentric



Muscle fibers are shortening, the distance from the z line is decreasing.

Concentric contraction: muscle fiber SHORTENS while generating tension



Muscle itself is lengthening; distance between z lines is getting bigger.

Eccentric contraction: muscle fiber LENGTHENS while generating tension

Concentric and eccentric contractions are at the level of the sacromeres, seem small but there is a lot of force if you look at the whole muscle (all those sacromeres acting together to get the muscle to contract)

Muscles are ALWAYS contracting!

Types of Muscular contraction: At any given instant in time

Note: M_m =Moment generated by Muscle AND M_R=Net Joint Moment

Now must think of not only the direction of the movement, but also the magnitude of the two muscle components.

Isometric

Static sol.

MR = Mm

Concentric

Dynamic now

Actually doing a flexion moment, in this situation, when there is motion and a change in acceleration, then:

MR < Mm

Eccentric

Eccentric actions of muscles are used as brakes! They make sure that this woman doesn't go into hyperextension. Eccentric are critical to prevent going past safe range.

Dynamic movements

Muscles could still be contracting this way but motion is in the opposite direction so:

Mr > Mm

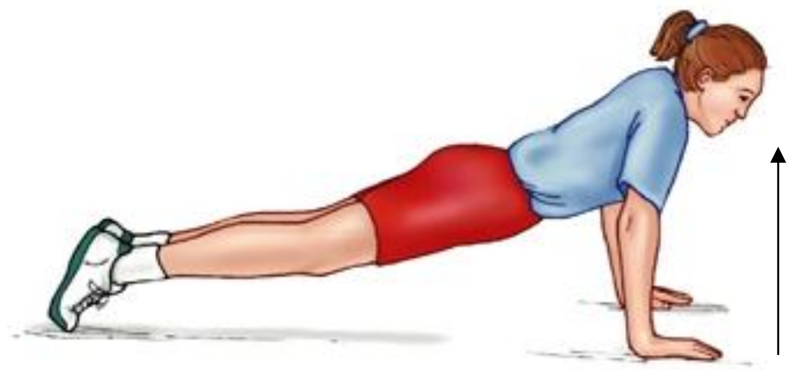
Coming back into an extended position.

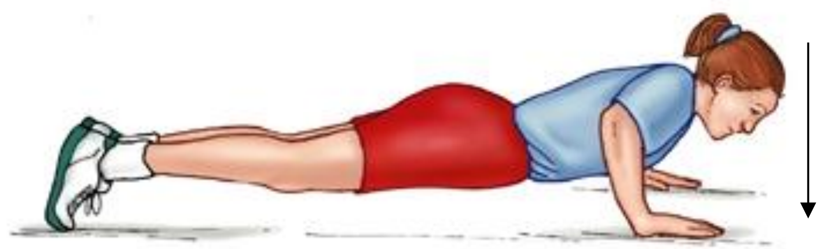
Contraction Types

PUSH – UPS:

Triceps – elbow extensors

Tricep muscles - they are shortening.





Concentric - lengthening here.
When one muscle group shortens, the other lengthens for a controlled action.

Eccentric - harder to do at the gym!
Tricep muscle EXTENDS the elbow!

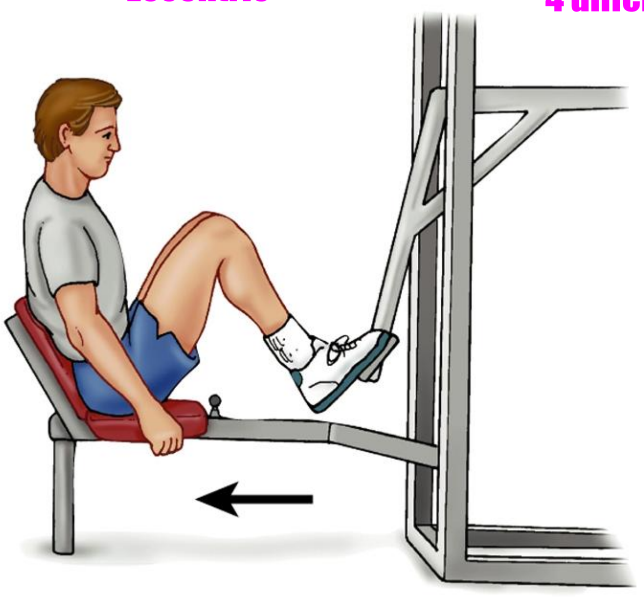
Contraction Types

LEG PRESS:

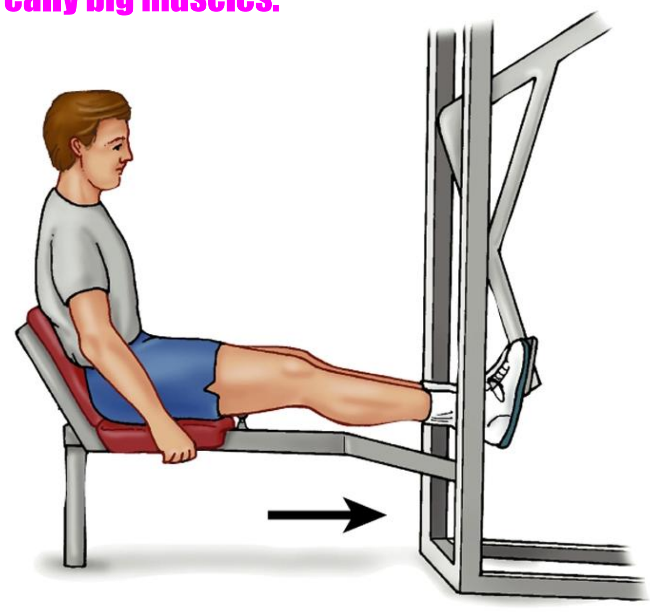
Quadriceps – leg extensors

4 different muscles, really big muscles.

Eccentric



Concentric



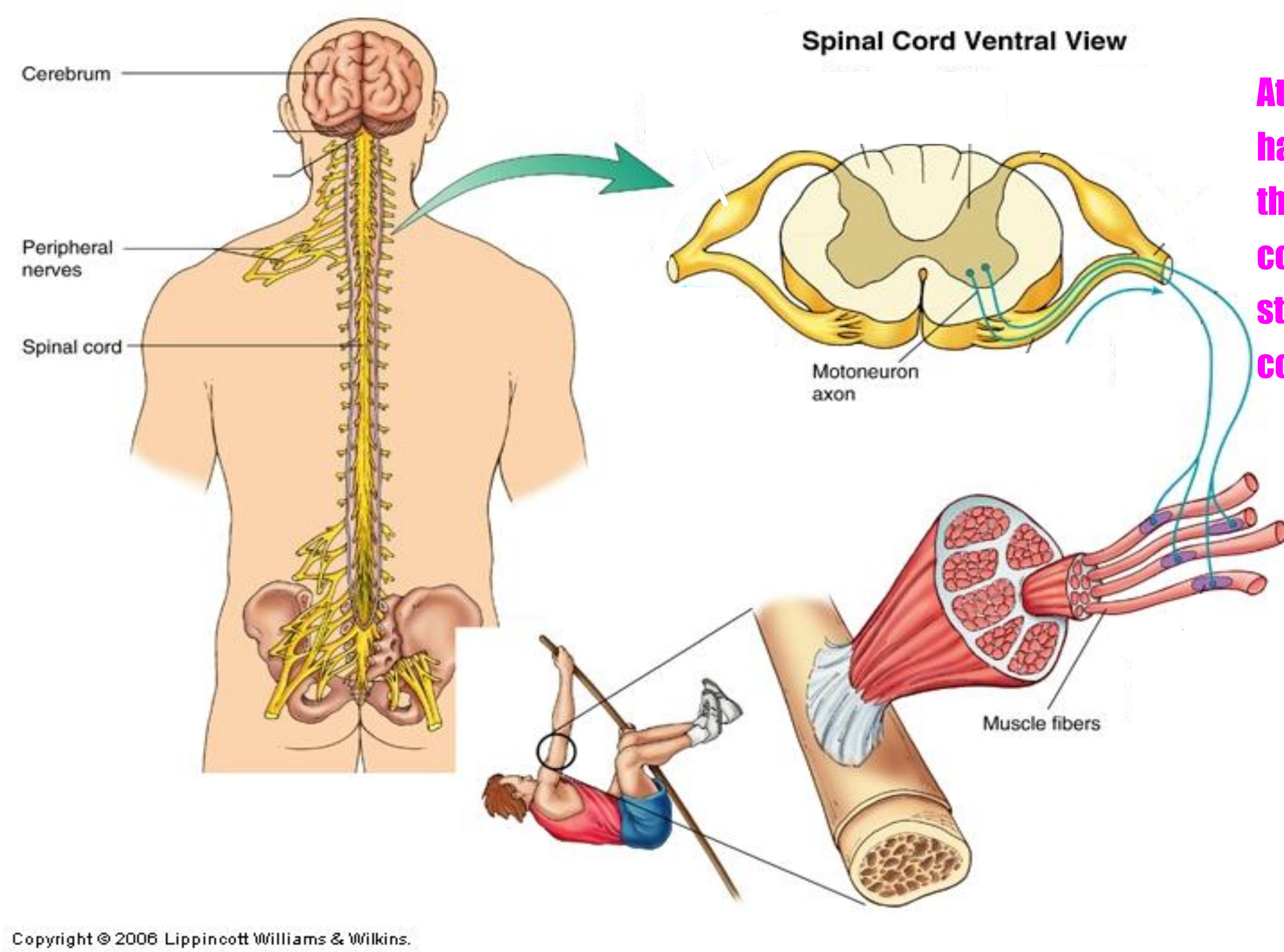
As you push, the reactive force is underneath feet and it is pushing back.

To determine if concentric or eccentric, look at whether the muscle is shortening or lengthening.

Neurophysiology of Muscle Contraction

How do we initiate a muscle contraction?

With a neural signal: **Action potential**



At the spinal cord level, you have motor neurons within the dark matter of the spinal cord. Action potentials that stimulate muscle contractions occurs here.

Neurophysiology of Muscle Contraction

Initiation of a muscle contraction

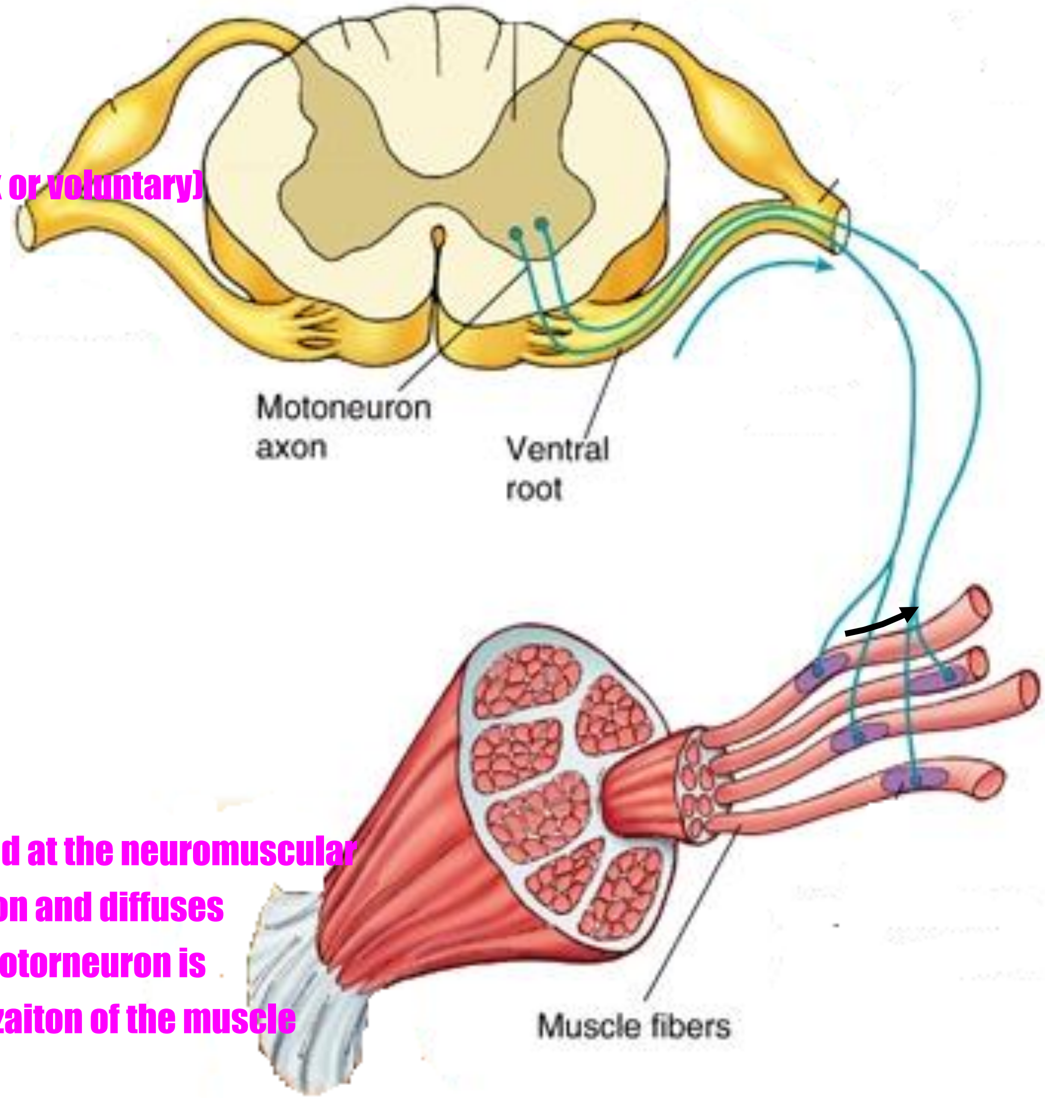
1. CNS initiates depolarization of motor neuron **Have to have some type of input from the brain (reflex or voluntary)**

2. Depolarization is conducted along the motor neuron axon to the muscle fibers

3. At the neuromuscular junction acetylcholine (ACh) is released → diffuses across the synaptic cleft → causes rapid depolarization of the muscle fiber

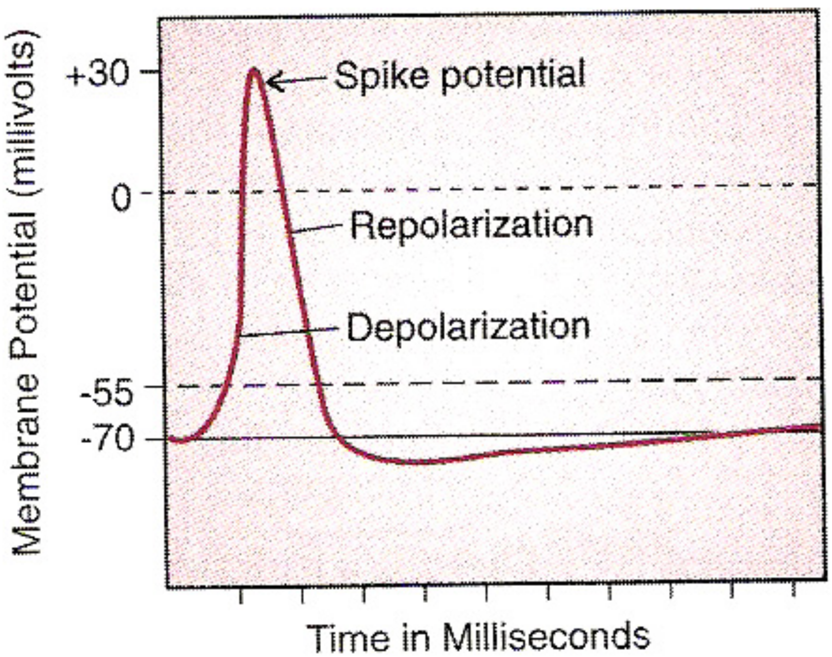
Action potentials zip along the axon and at the neuromuscular junction, ACh comes across the junction and diffuses across the synaptic cleft (where the motorneuron is inervating) and causes rapid depolarizaiton of the muscle fiber.

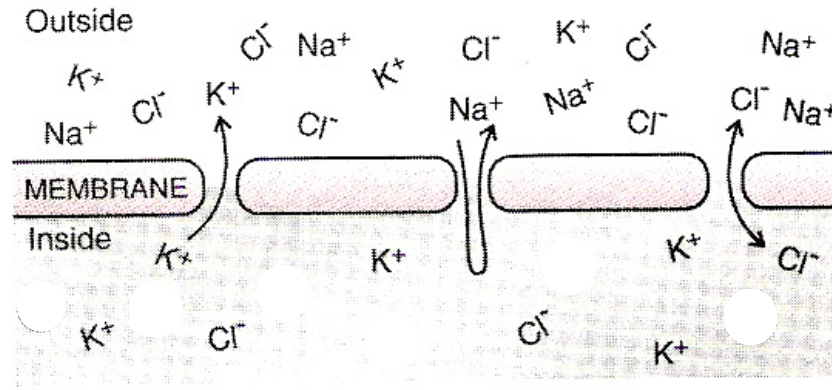
Spinal cord



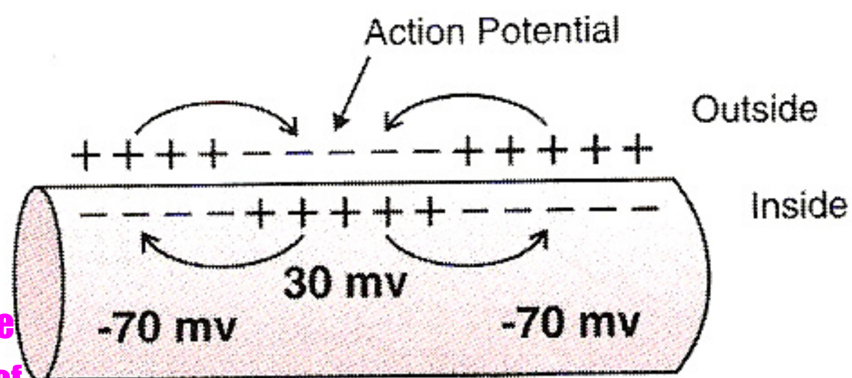
Neurophysiology of Muscle Contraction

Propagation of an Action Potential down the nerve





Exchange of Ions Across Membrane



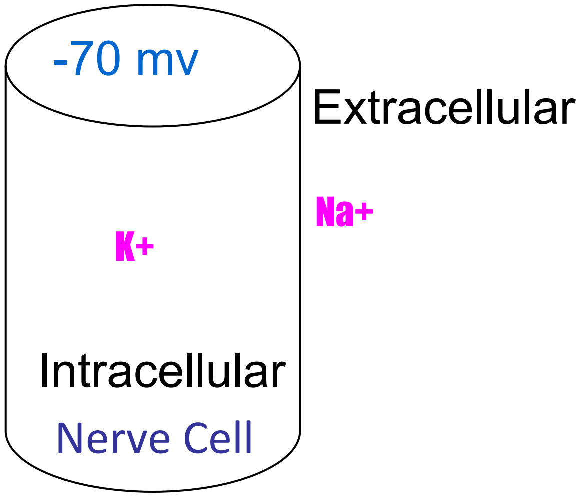
Action Potential Generated Through Change in Electrical Potential

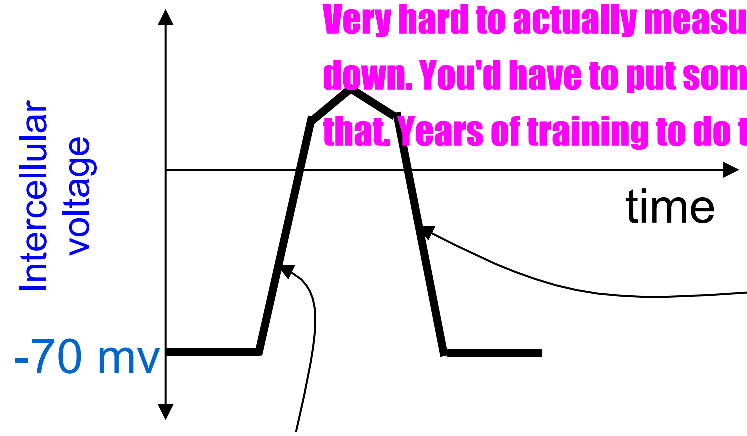
At the action potential, you can measure it. On the y axis, there is the membrane potential vs time in milliseconds, the time of the response changes depending on the muscle and the type of neuron. Exchange of ions across a membrane. Exchange of ions that occur coming in and out of the cell. Across the sodium-potassium gradient, starts to change the polarity of the muscle fibers themselves. It's not that they're positive ions, some are just more positive than the other. Typically inside, it is negative (more negative than outside that is). Have a change in the electrical potential of the cell itself. You have an action potential that is coming down and that's how a muscle flexion is delivered.

Origin of Electromyography

EMG does not measure tension directly….

Very hard to actually measure the action potential coming down. You'd have to put something into the spinal cord to do that. Years of training to do this.





High amount of K+ inside the cell. Got sodium on the outside of the cell. K+ exits the cell and Na+ floods into the cell when the gates open. Intracellular matrix. Goes from -70 mv and becomes a little more positive. Becomes less negative (+30 mv). Spike potential then a repolarization as it comes back to its resting position. The neural impulse (action potential) needs a strong enough stimulus. If AP is not strong enough, then there is no AP initiator.

- Active transport: Sodium-Potassium pump
- Equilibrium…until the balance is upset by

  Nerve impulse (stimulation)

  - **Depolarization:** causes increase in permeability to Na+; Na+ flows in, K+ flows out

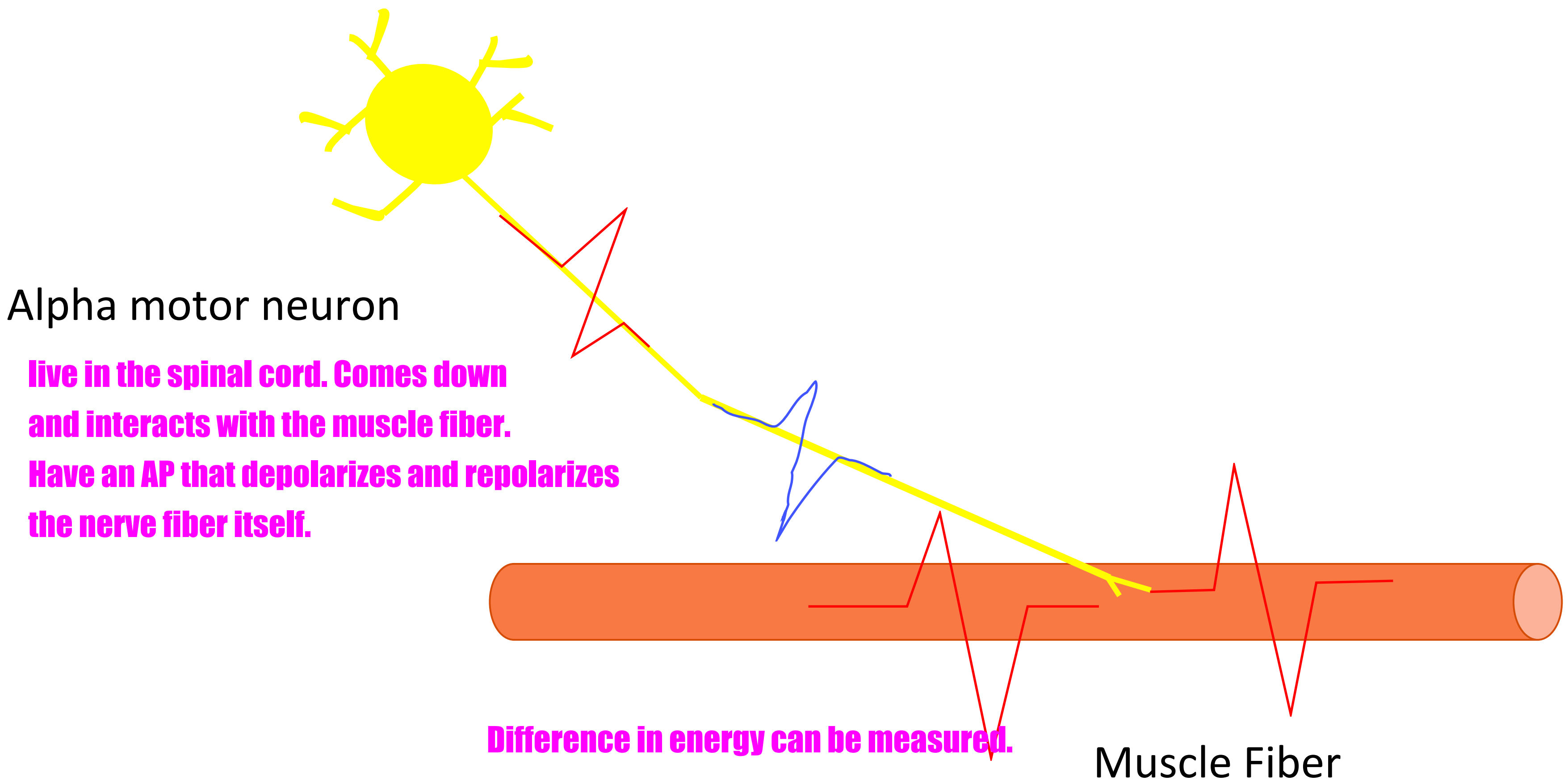
Resting Potential is increased!

If stimulus strong enough,

Action Potential initiated

Neurophysiology of Muscle Contraction

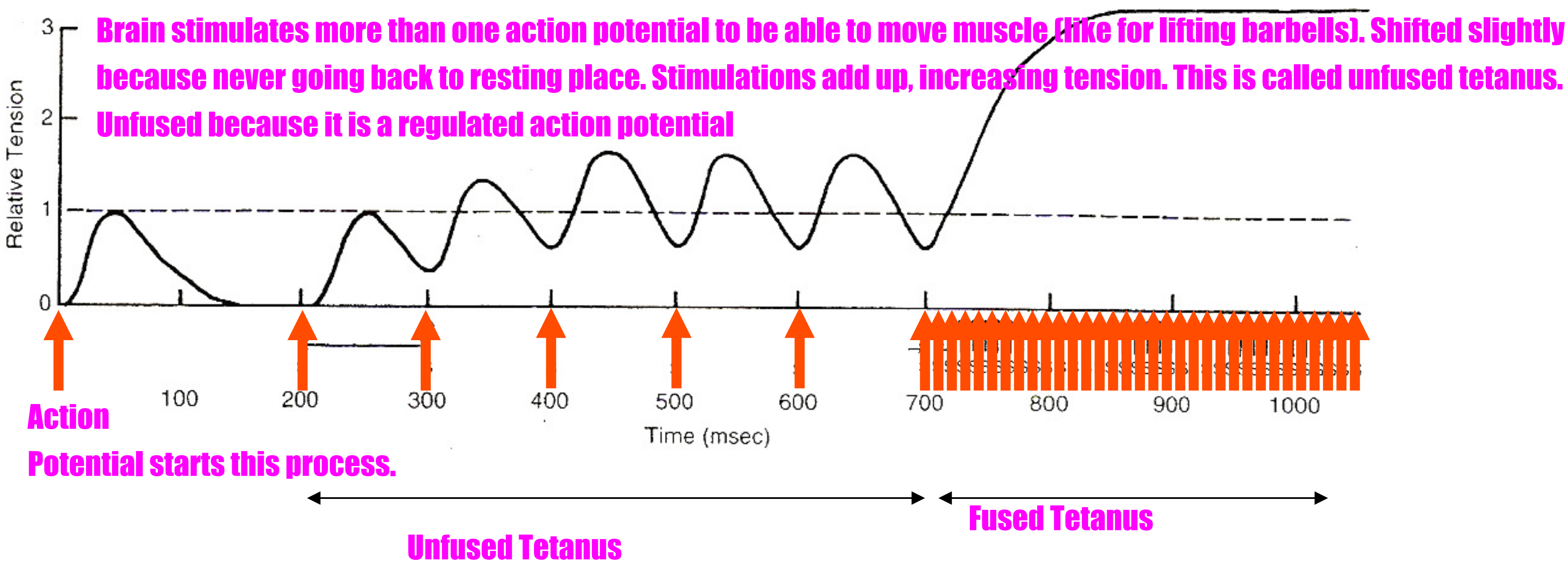
Initiation of a muscle contraction



Action potential (depolarization/repolarization) travels down the nerve axon AND the muscle fiber membrane

Action at a SINGLE muscle fiber

Twitch Force: Smallest amount of measurable force from a muscle fiber. The amount of tension produced by a muscle fiber from a SINGLE action potential.



So many AP at a fast rate, start to develop significant forces being generated within our muscles.

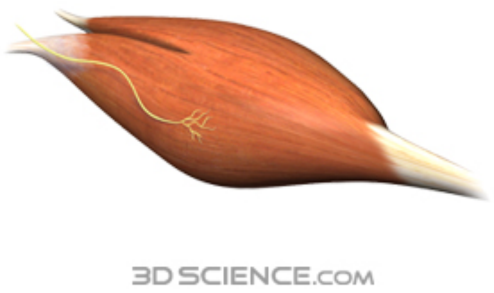
Wave summation: Second contraction is induced before muscle has been completely relaxed; more Ca^{2+} is released. Contractions are summed

Tetanus: the usual manner of muscle contraction …… volleys of impulses rather than single twitch impulses

= smooth continuous contraction

This is typically how we generate forces. An annoying twitch in your eye is an unfused tetanus situation.

Motor Unit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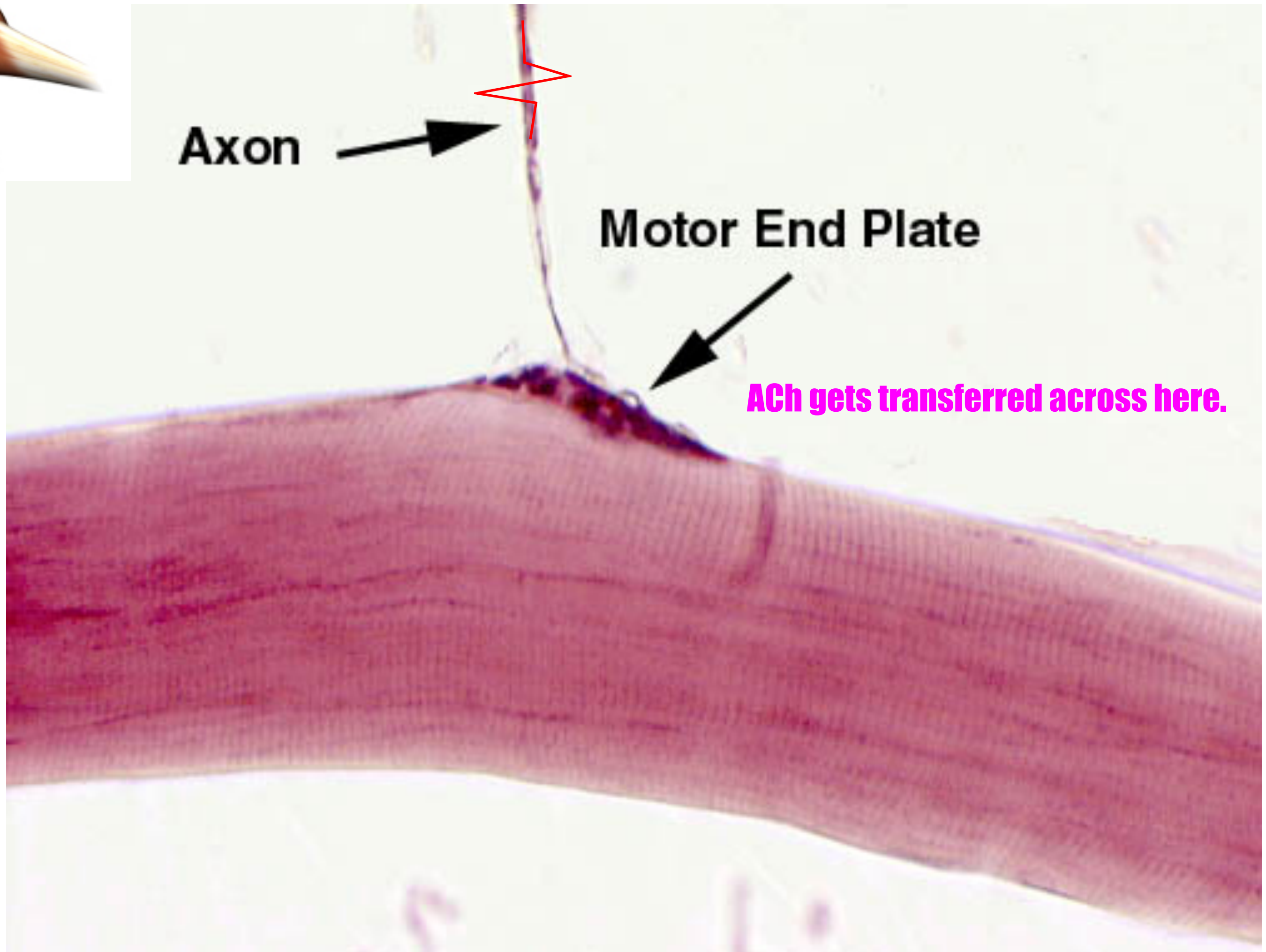
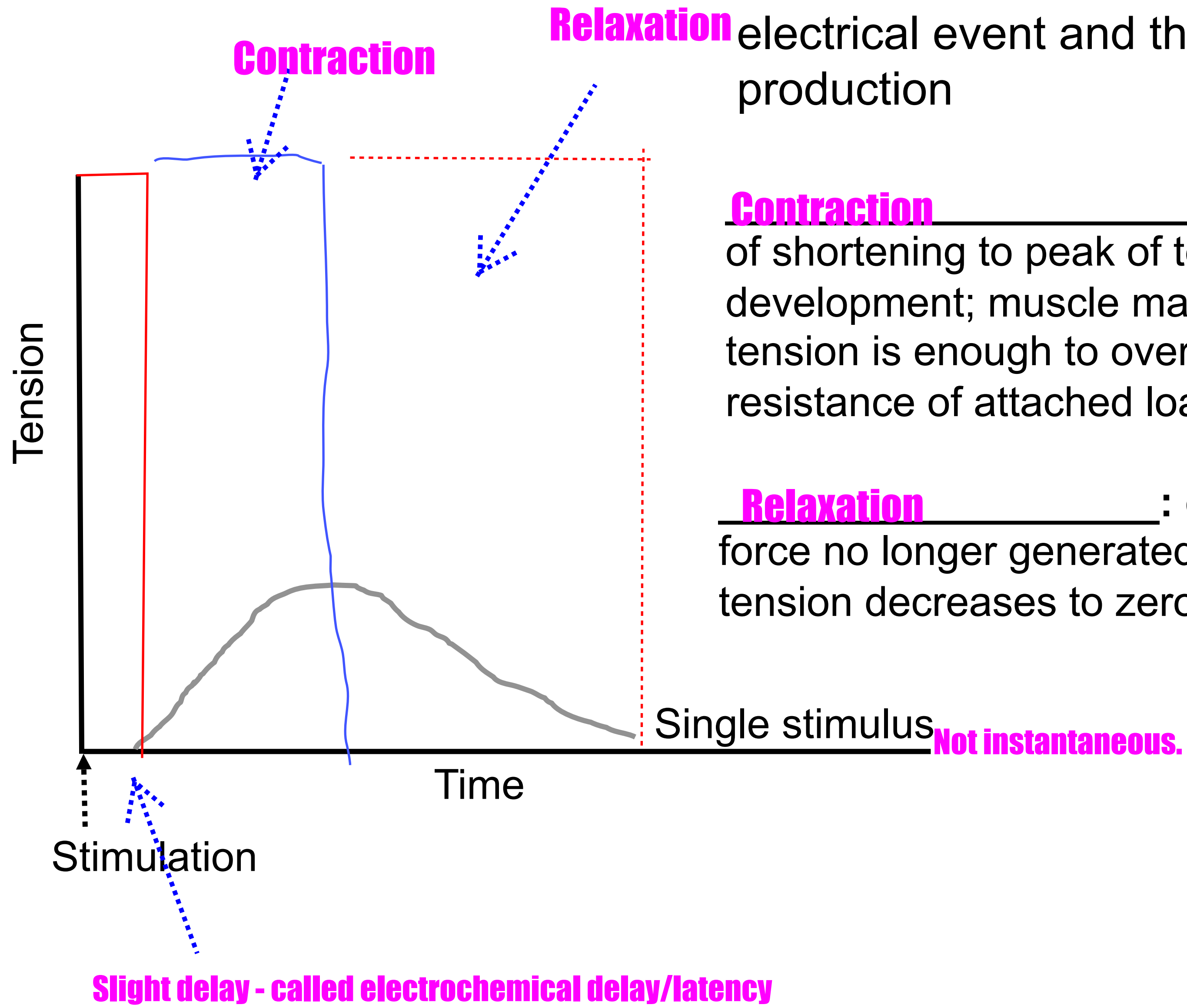

Axon
Motor End Plate
ACh gets transferred across here.

Muscle Twitch: response of a muscle to a single brief threshold stimulus

Twitch – Smallest measurable force. Lower level of activation. Assume twitch does happen.



Electromechanical delay

the time between the electrical event and the force production

Contraction: from onset of shortening to peak of tension development; muscle may shorten if tension is enough to overcome resistance of attached load

Relaxation: contractile force no longer generated; muscle tension decreases to zero.

Muscle Fiber Types

3 different types of MUSCLE FIBERS

IMPORTANT: All muscle fibers within a MU are of the same type!

Time is different for each graph. The twitch force is quite small.

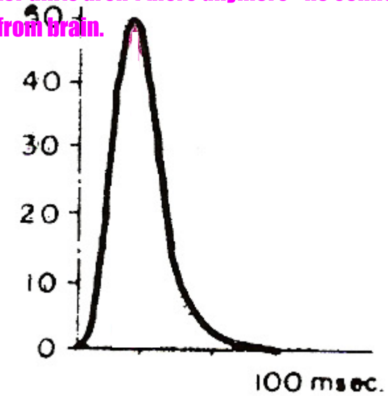
Fast twitch - glycolytic

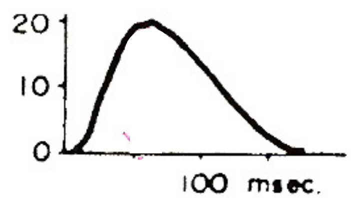
As you get older, you tend to gravitate towards oxidative/glycolytic and oxidative activities. Our motor units as we get older start to die. Starts to happen in your 40s. Those muscle fibers within the body themselves are still there, but the motor units aren't there anymore - no connection from brain, can't receive signals from brain.

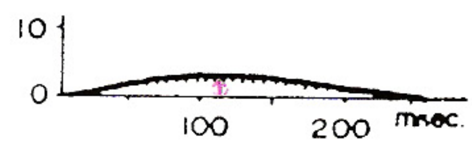
Fast twitch - oxidative/glycolytic

Slow twitch - oxidative

Twitch Force





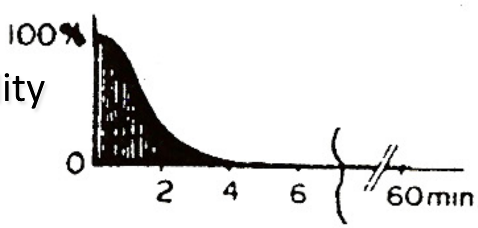


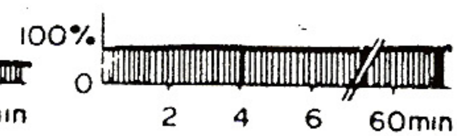
Crash pretty quickly. Can't sustain muscle contractions for more than 100 ms.

Hybrid between oxygen energy source and glycolytic energy source.
Slope is a little less; max peak is about 20.
Not nearly as powerful as muscle fiber but more lastivity.

Just standing for x number of hours a day (like a cashier). Can last much longer, using a lot less energy. Collectively, our bodies' genetics determine your type of muscle fibers. Can train it but there is a ceiling effect that you'll hit.

Fatiguability

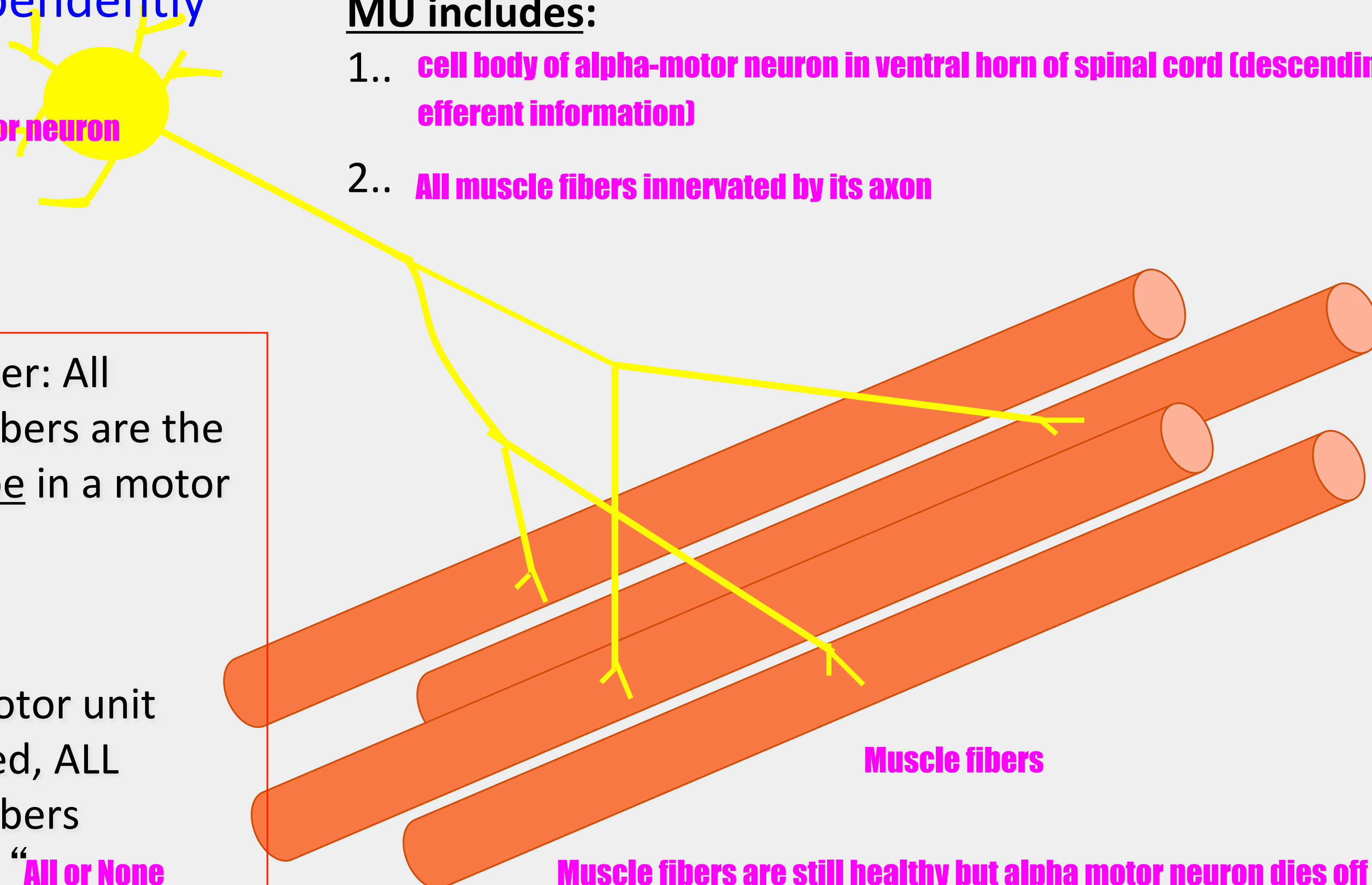




100 means well rested, well hydrated.
Everyone has slightly different muscle morphologies.
In this initial fiber type, you get high force production, and you fatigue very quickly.
Glycogen and sugar are what supply this. At around 50%, this is where lactate acid starts to build up.

Motor Units

Motor Unit – functional unit of skeletal muscle
Smallest part of muscle that can contract independently



MU includes:

1.. cell body of alpha-motor neuron in ventral horn of spinal cord (descending, efferent information)

2.. All muscle fibers innervated by its axon

Remember: All muscle fibers are the same type in a motor unit

So…

When motor unit stimulated, ALL muscle fibers respond, "All or None principle"

Muscle fibers are still healthy but alpha motor neuron dies off as you get older. Not sure why it happens but it does.

Motor Units

All or None Principle:

Muscle fiber: contracts when ALL sarcomeres shorten simultaneously in "all-or-none" fashion

Motor Neuron: Cell body containing the nucleus of the nerve cell

Motor Unit: When motor neuron depolarizes, then all muscle fibers that it innervates depolarize and contract.

Motor Unit Innervation Ratio:

The number of muscle fibers in a motor unit

Includes the alpha motor neuron, all the axons, as well as the muscle fibers themselves.

Small # of fibers = Fine movement, control - as few as 3 muscle fibers! E.g. fingers

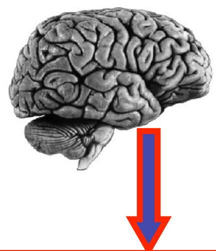
large # of fibers = Large movements, power - as many as 2000 fibers!

Small number of fibers - can turn some on and off.

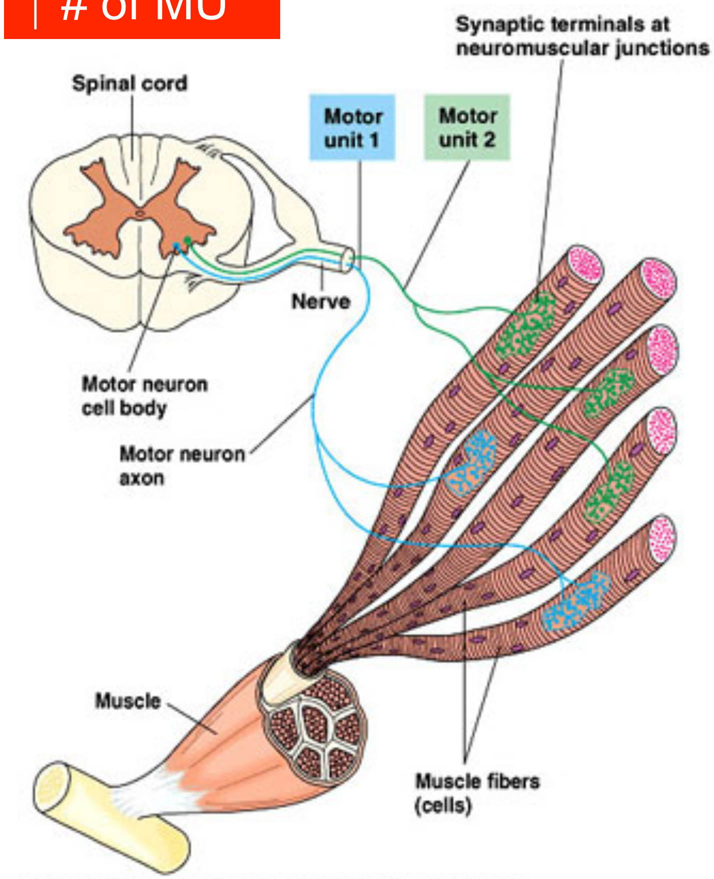
If a motor unit is sending a pulse to contract, everything contracts at the same time. Lots of sacromeres living inside just one muscle fiber, and can generate movement in such a controlled way. All muscles (big or small) work essentially the same way but the motor unit innervation ratio is different. Depending on where the muscle is, there is a different ratio.

Muscle Tension/Force and Recruitment

Graded Muscle Responses



↑ # of MU



(Marieb, 1989)

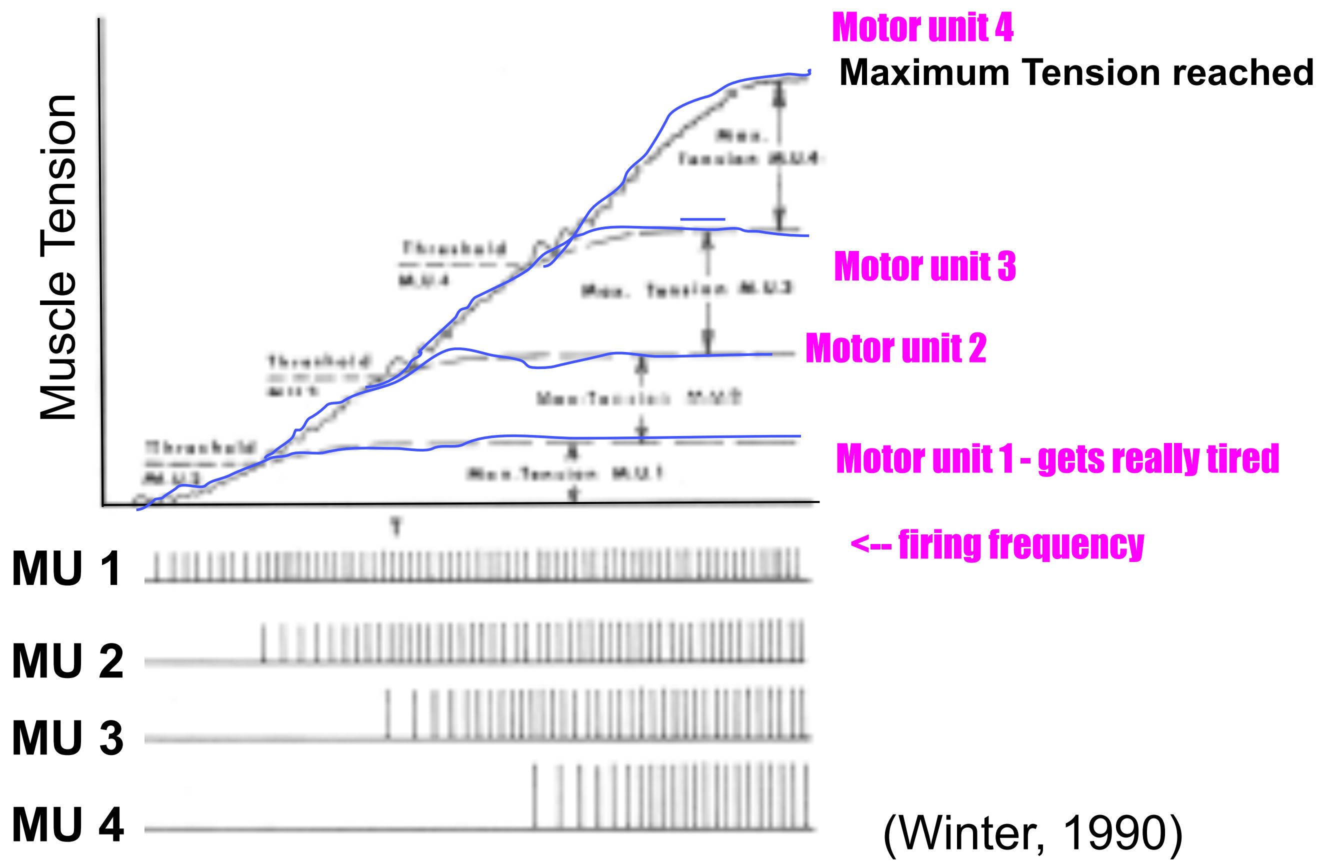
2 ways a muscle response can be graded:

1. Recruit more motor units to produce multiple motor unit summation. This diagram shows that alpha motor neurons that innovate different muscles. One innovates two, the other innovates three. Can do a small muscle contraction and just turn on motor unit 1 and get a small motor contraction. If need more force, can turn on motor unit 2. If even more force needed, can turn on both to gradually increase force.

2. Rate coding: CNS increase nerve stimulation: increase firing rate and therefore wave summation; also called the Cinderella principle; have a certain number of force needed and start with slowly working muscle fibers then increase rapidly.

Muscle Tension/Force and Recruitment

Graded Muscle Responses



(Winter, 1990)

x-axis: Time

Typically turn on slow twitch (oxidative) muscle fibers first because they can sustain muscle contractions longer (in this example, it would be motor unit 1)

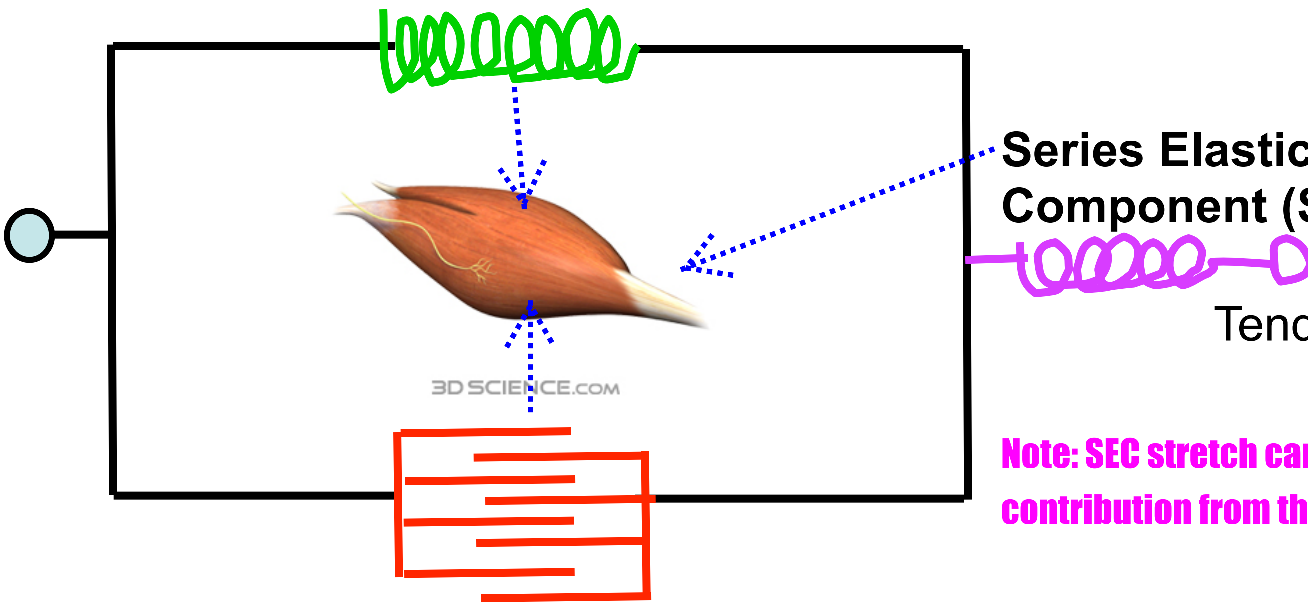
Force – Length Relationship

Schematic of Musculo-Tendinous Unit

Role: Generate tension, independent of CC

Parallel Elastic Component (PEC)

Epimyosin, perimyosin, endomyosin…



Series Elastic Component (SEC)

Tendons

Note: SEC stretch can only occur if there is a contribution from the CC element

Contractile Component (CC)

Myofibrils: Actin/Myosin

If it was a shortening, tendons would stretch - happens because they are arranged in series. Tendons stretch while muscles lengthen. PEC is like seran wrap that surrounds the muscle - generates tension independently. Muscles have shape and function, even if dead - small amount of force coming even post mortem.

Got lots of different passive tissue structures providing support for tissue itself. Got muscle anchor on either side by tendons. On one side, you'd have SEC. If you do not contract muscle, you have no change in series component (so it is like a series circuit). Active component where you can see the rachening happening.

Force – Length Relationship

Active Component of Muscle - CC element

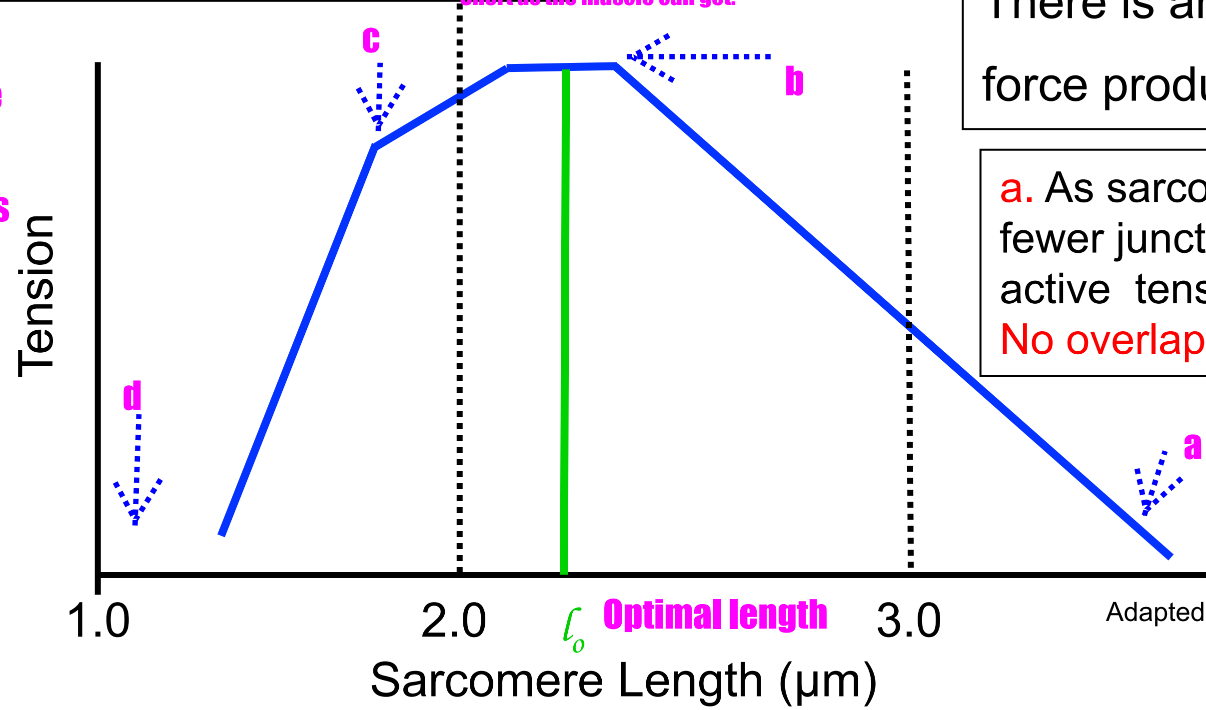
d. As sarcomere shortens less than resting length, ↓ tension because overlapping of thin filaments: no force generation possible!

No overlap

No where else for myosin heads to connect.
Short as the muscle can get.

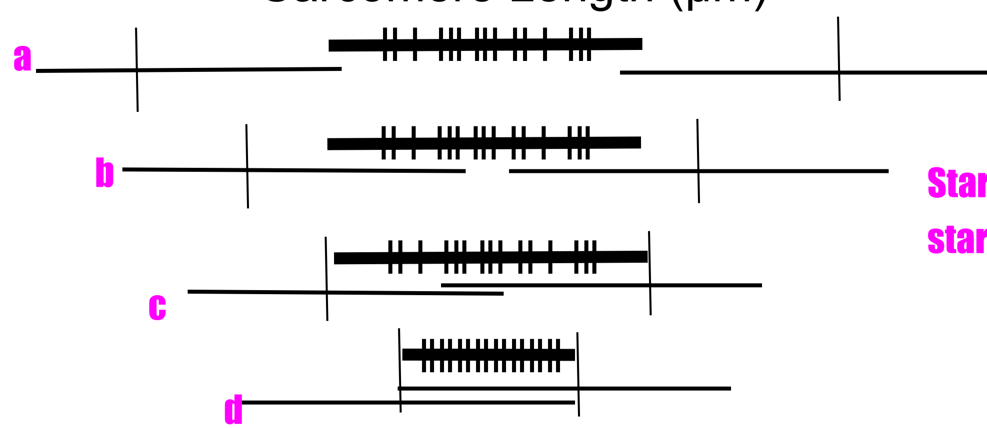
There is an optimal length for force production = l_o

Backbone of muscle contractions.
Sacromeres, lengths determined by meausring z lines.



a. As sarcomere lengthens, fewer junctions b/w filaments: active tension ↓
No overlap: no tension

Adapted from Bagshaw, 1993

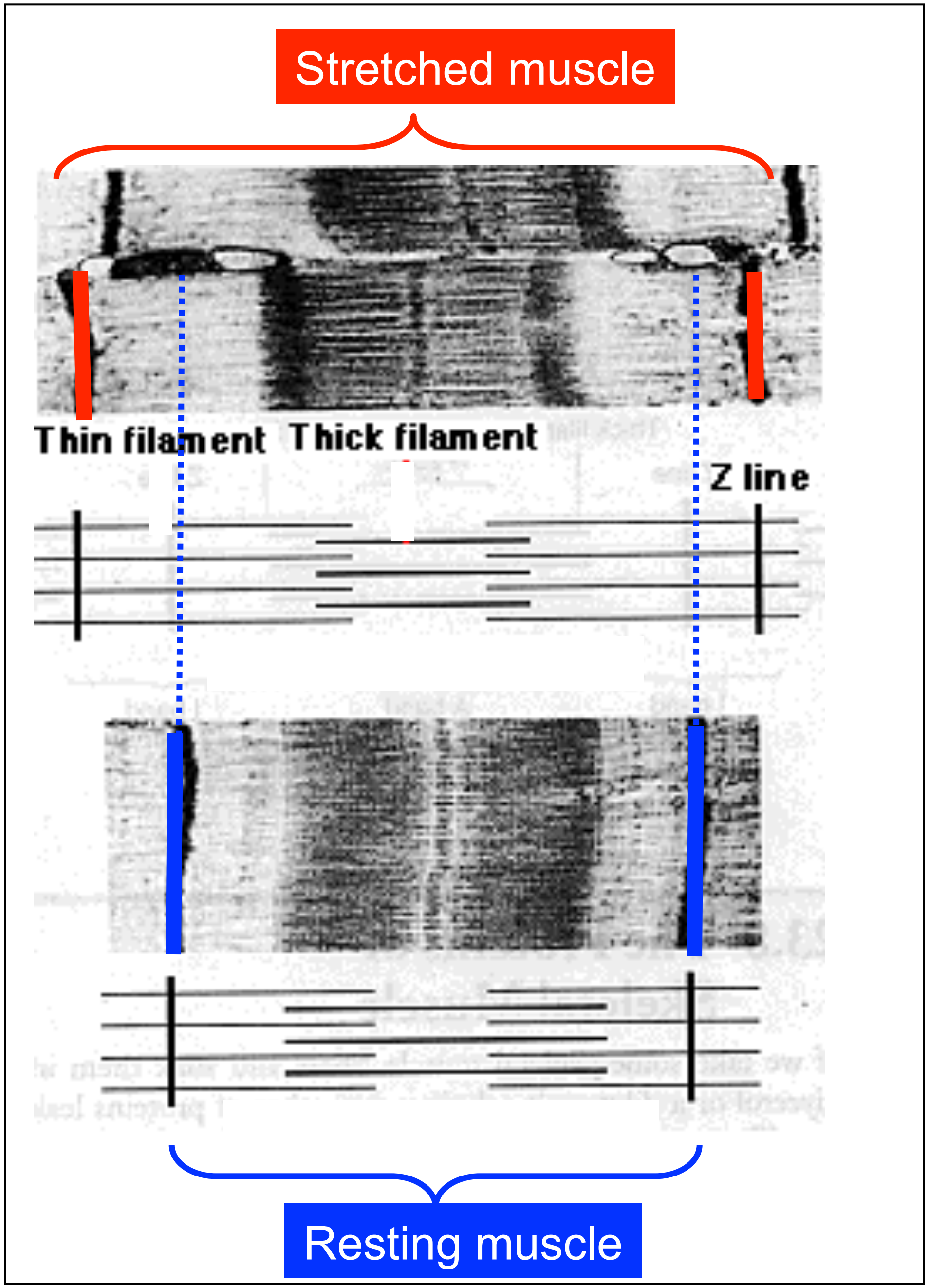


Start to see muscles lengthening but muscles starting to stretch farther away.

Muscle Mechanics
- Skeletal Muscle

Sarcomere Lengthening

Eccentric component of contraction.



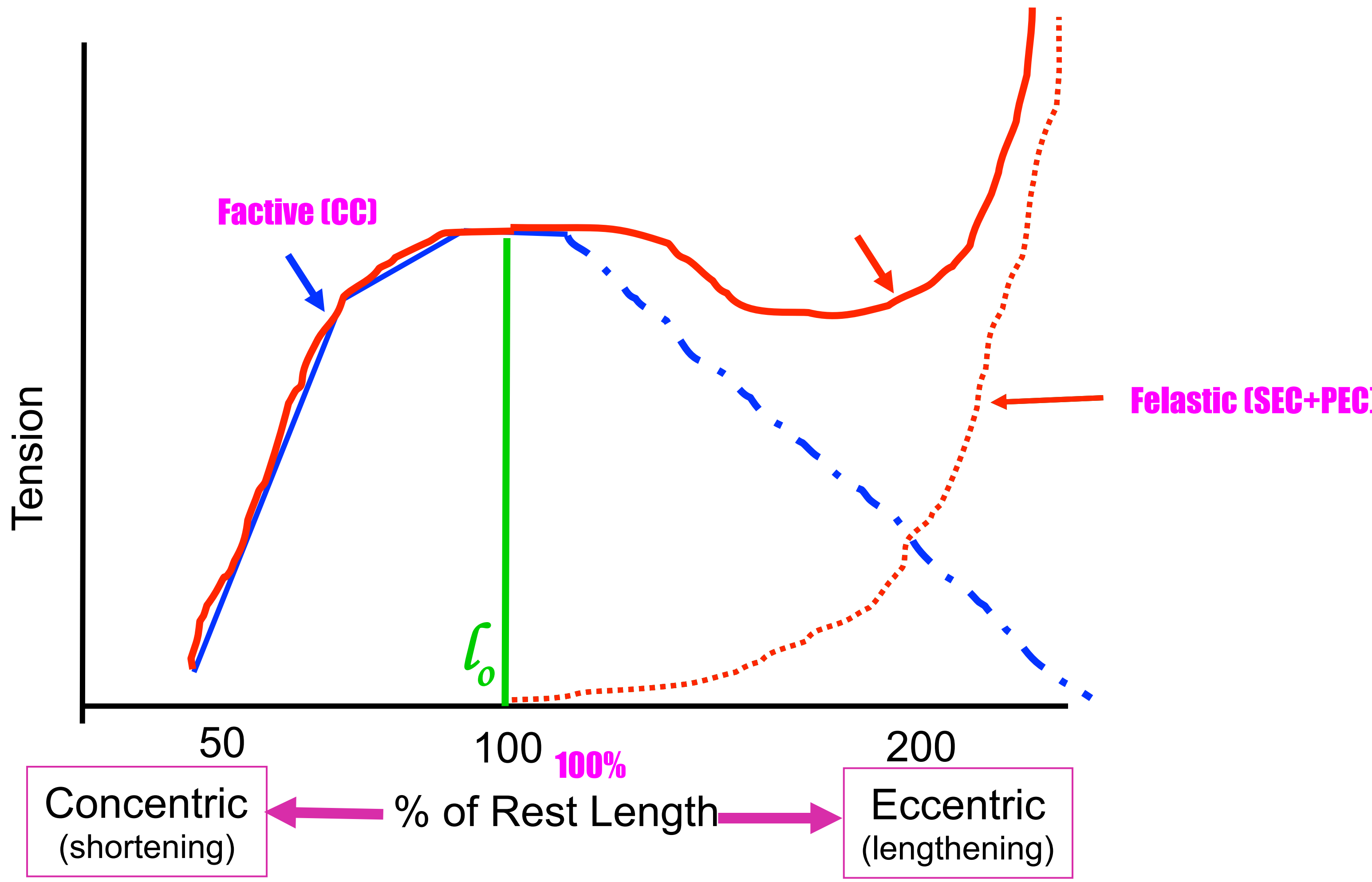
Sarcomere Shortening

http://highered.mcgraw-hill.com/olc/dl/120104/bio_b.swf

Force – Length Relationship

WHOLE MUSCLE

This is what's happening to the elastic components.



Past resting length; tendons start to lengthen as we extend. As muscle lengthens, we increase force production. When you add up the contractile components plus the elastile components, get a slight dip then an increasing rise in force. At this point in time, need high force and range of motion, get hyperextension. Want high force production (eccentric are rate limiting - stop you from injuring yourself). Eccentric provides stability for the joints.

Force – Velocity Relationship (A.V. Hill)

NOTE: This curve is for 100% activation

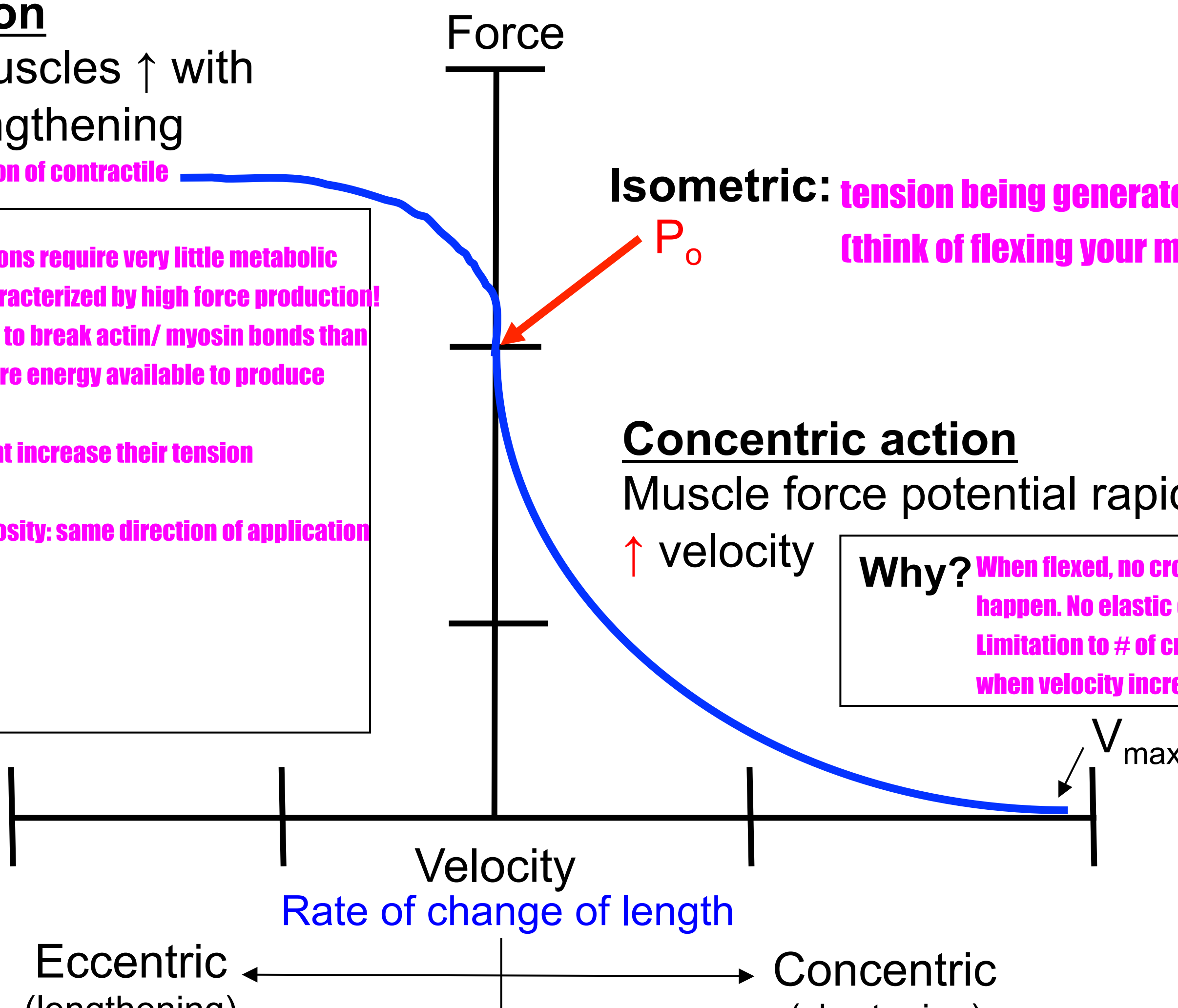
We are significantly stronger during eccentric action.

Eccentric action

Force within muscles ↑ with ↑ velocity of lengthening

We are much stronger eccentrically. Summation of contractile and elastile.

Why: Eccentric contractions require very little metabolic activity, yet are characterized by high force production!
1. takes less energy to break actin/ myosin bonds than to form them --> more energy available to produce force.
2. Elastic component increase their tension development
3. Force due to viscosity: same direction of application of direction!



Isometric: tension being generated but no shortening (think of flexing your muscles)

Concentric action

Muscle force potential rapidly ↓with ↑ velocity

Why? When flexed, no cross bridges for actin and myosin to happen. No elastic component being added to it. Limitation to # of cross bridges that can be formed when velocity increases

NOTE:
At the same velocity eccentric strength is <u>greater</u> than concentric strength.

When Active Muscles Lengthen: Properties and Consequences of Eccentric Contractions

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Get way more force at moderate metabolic cost.

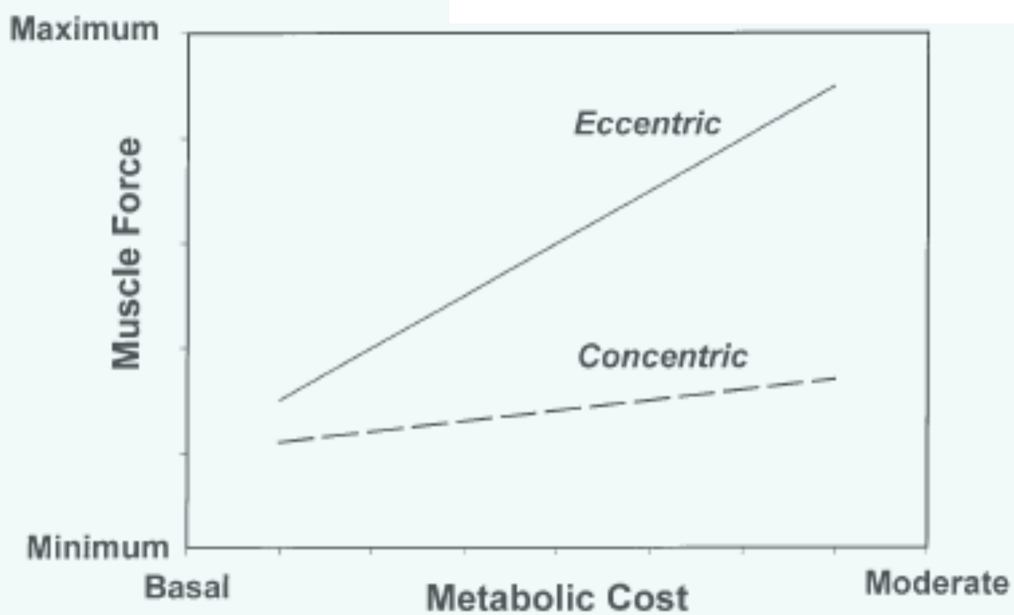


FIGURE 4. Bigland-Ritchie (2) first plotted oxygen uptake against work show-

6 to 7 times reduction in metabolic cost to achieve same magnitude of work

of work (negative vs. positive). If we reverse the axes, it is apparent that at iden-
tical exercise intensities (measured as oxygen uptake) **much more force can be generated eccentrically than concentrically at moderate metabolic cost**

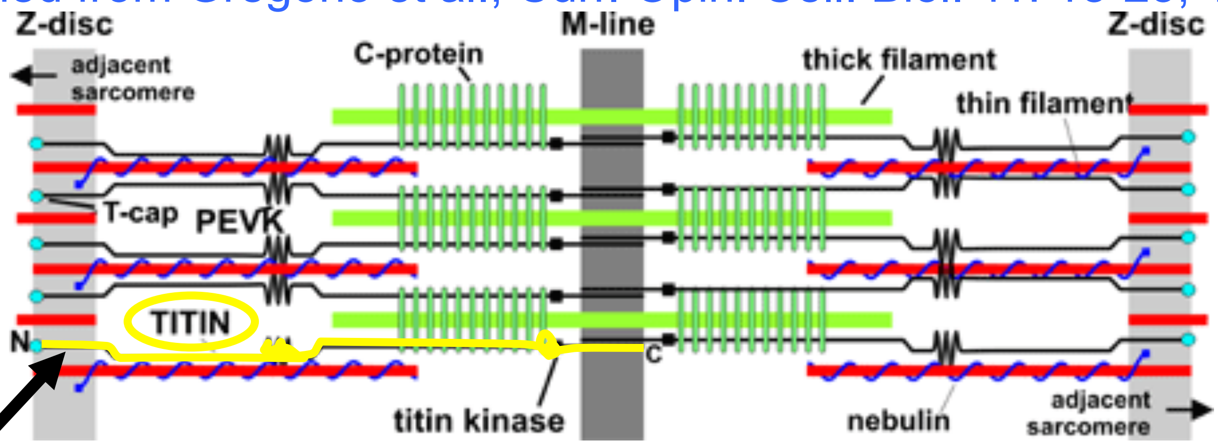
New research in this area- at the cellular level investigating the role of TITIN

Eccentric Contractions—Muscle Actively Lengthening

For example, the quadriceps (knee extensors) are active just after heel strike while the knee flexes.

The basic mechanics of eccentric contractions are still a source of debate since the cross-bridge theory that so nicely describes concentric contractions is not as successful in describing eccentric contractions.

Schematic diagram of the sarcomere
(modified from Gregorio et al., Curr. Opin. Cell. Biol. 11: 18-25, 1999).



Titan lives within structure of sacromere.
Titan plays a role in elastic recoil storage.

- “Titin forms a continuous filament system along the muscle fiber in vertebrate striated muscle, overlapping in the M-line and in the Z-disc. Titin interacts with a plethora of sarcomeric proteins”.

Titin’s role in lengthening contractions may also include the initiation of cellular signaling to enhance cross-bridge recruitment while decreasing the cost. Hence, a differential expression of titin isoforms could alter the magnitude of elastic recoil storage and subsequent utilization as well as effect cross-bridge cycling and efficiency.

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Proceedings of the National Academy of Sciences of the United States of America

Mechanoenzymatics of titin kinase

PNAS | September 9, 2008 | vol. 105 | no. 36 | 13385–13390

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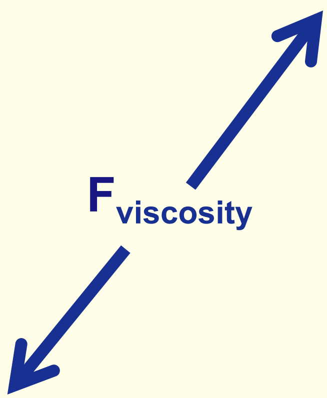
Takes less energy to break bonds but also get recoil

The 3D animation shows a zoom inside the muscle up to the smales protein building blocks to visualize how contraction is generated by myosin and actin filaments. In their center, these motor strand are connected and aligned through the elastic titin-network, which contains the molecular force sensor titin kinase.

http://www.youtube.com/watch?v=HROJU0X1YdQ&feature=related

…Consider Force and viscosity of a visco-elastic material

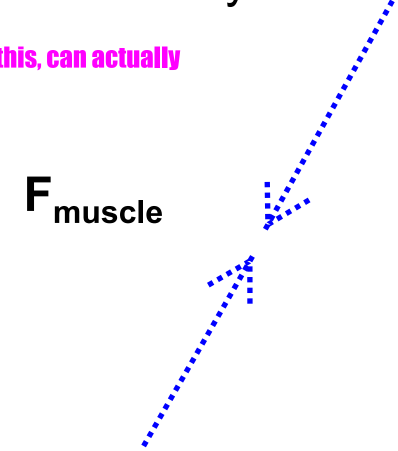
Force due to viscosity is always in same direction (due to line of action of muscle pull)



In Concentric contractions

Muscle force is in opposite direction ;
CANCELS => less force for a given velocity

Muscle force is in opposite direction of Fviscosity, so because of this, can actually cancel out viscosity component.



And !

In Eccentric contraction

Muscle force is in same direction;
SUMMATES = greater force, same velocity!

In same direction, so can add up the two forces. Summate the muscle contraction itself and the force of viscosity - can generate higher force with the same velocity.