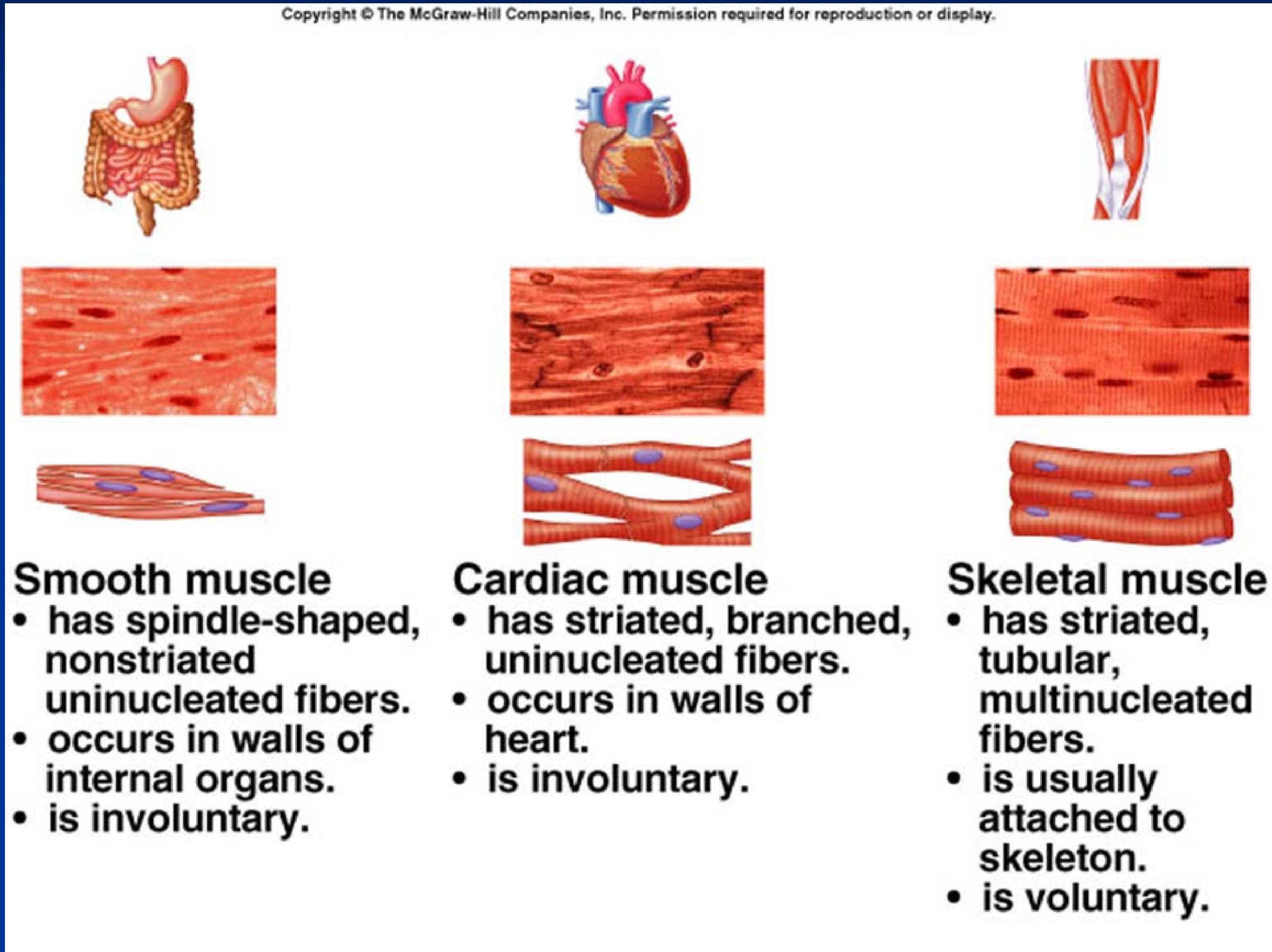
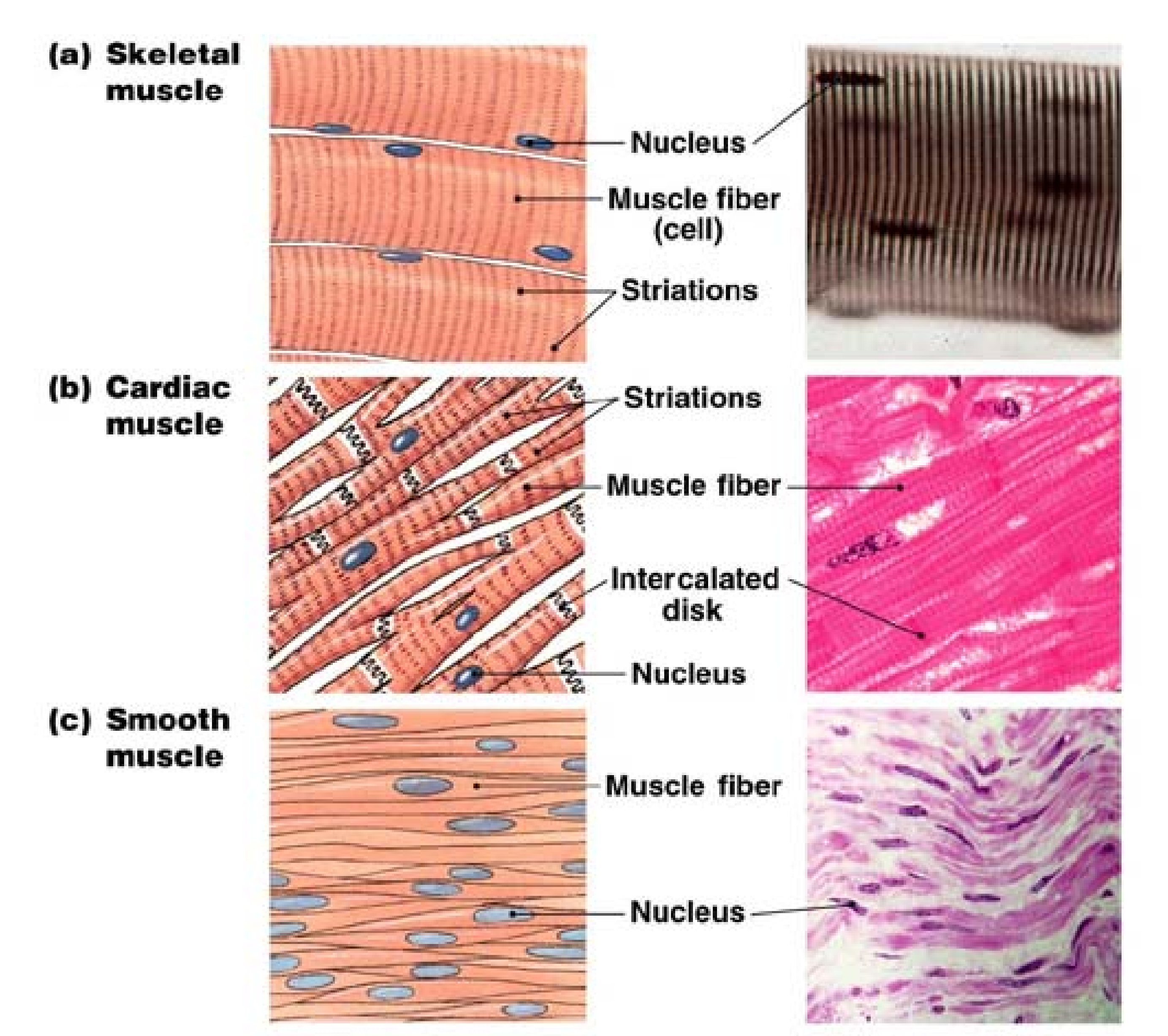
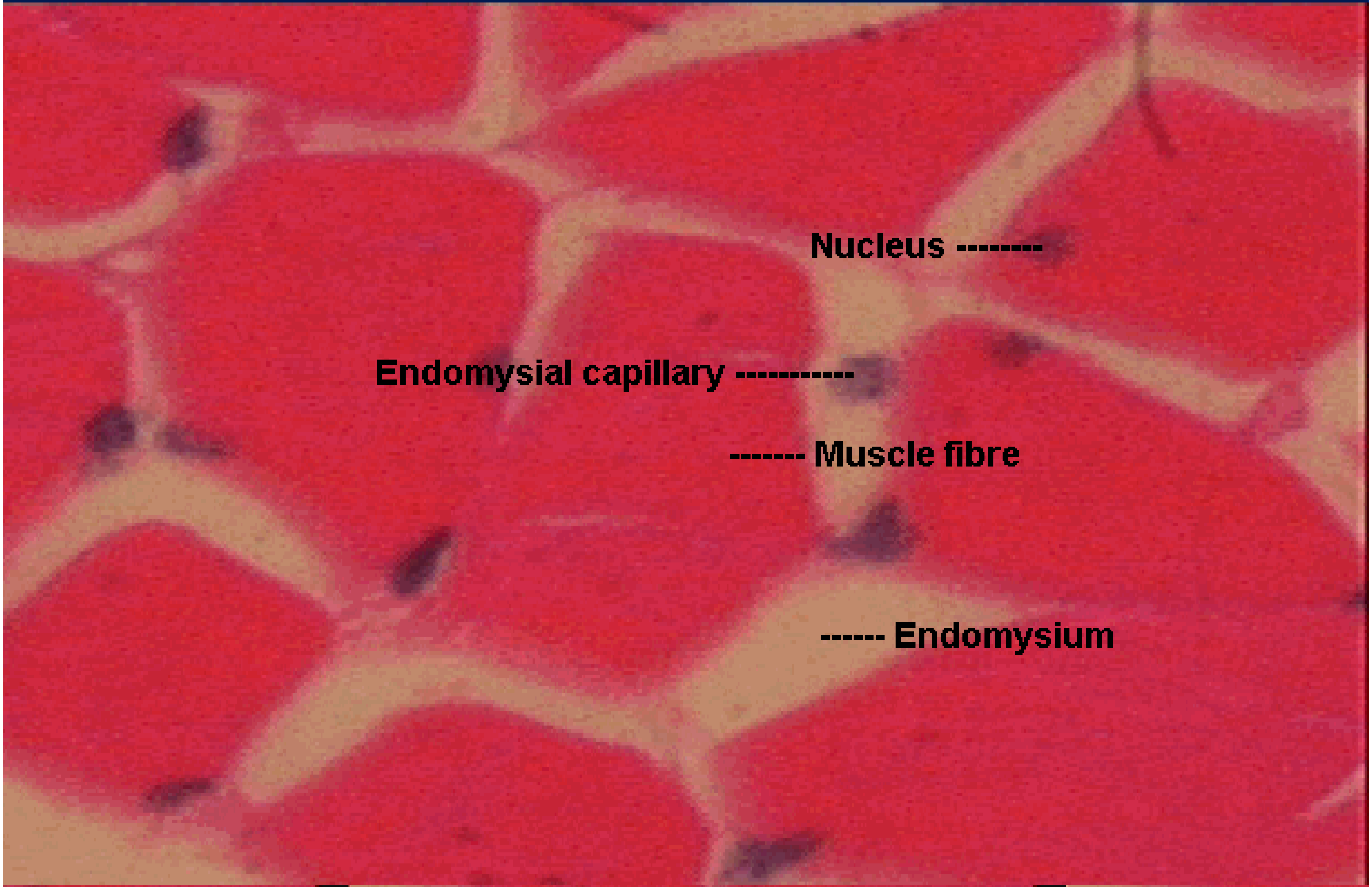
Muscle Mechanics

Muscle Types

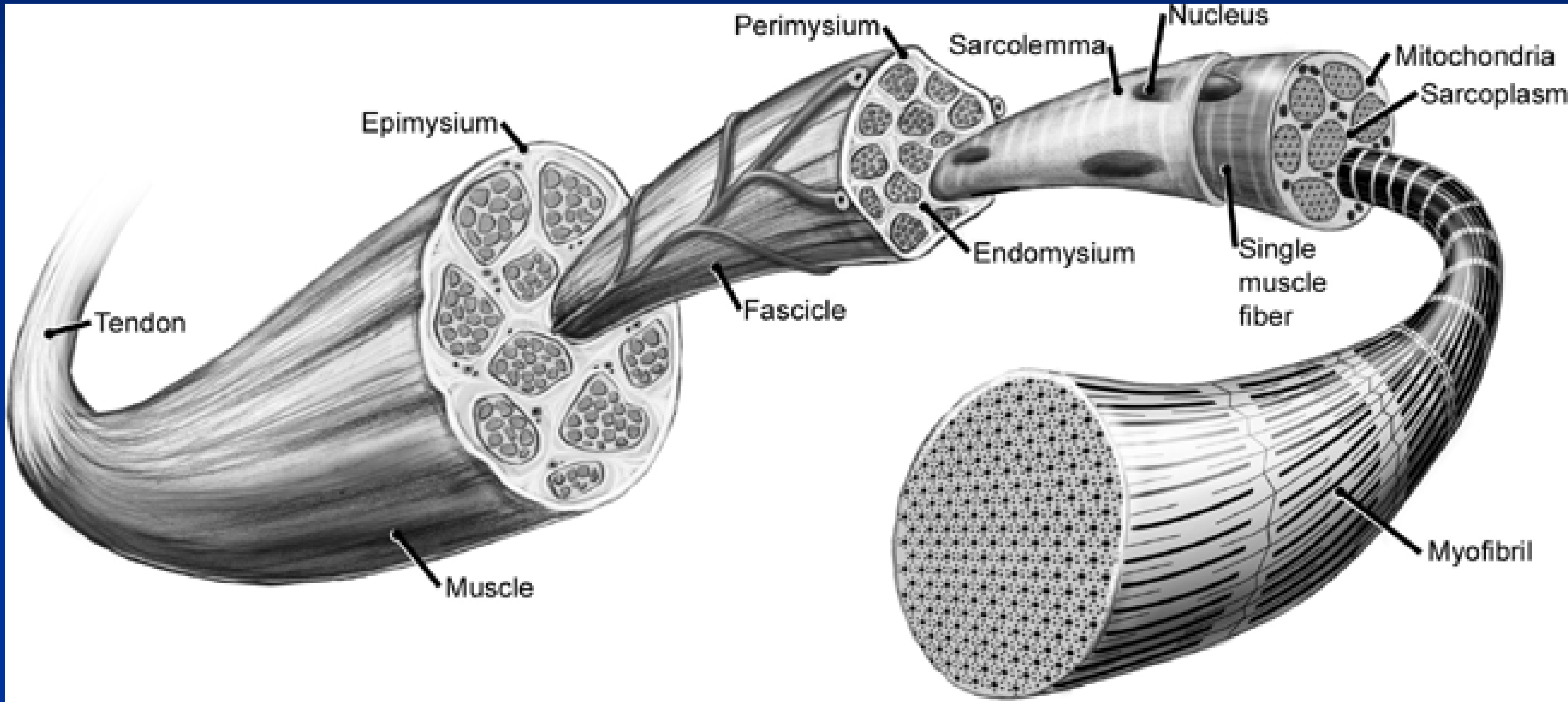


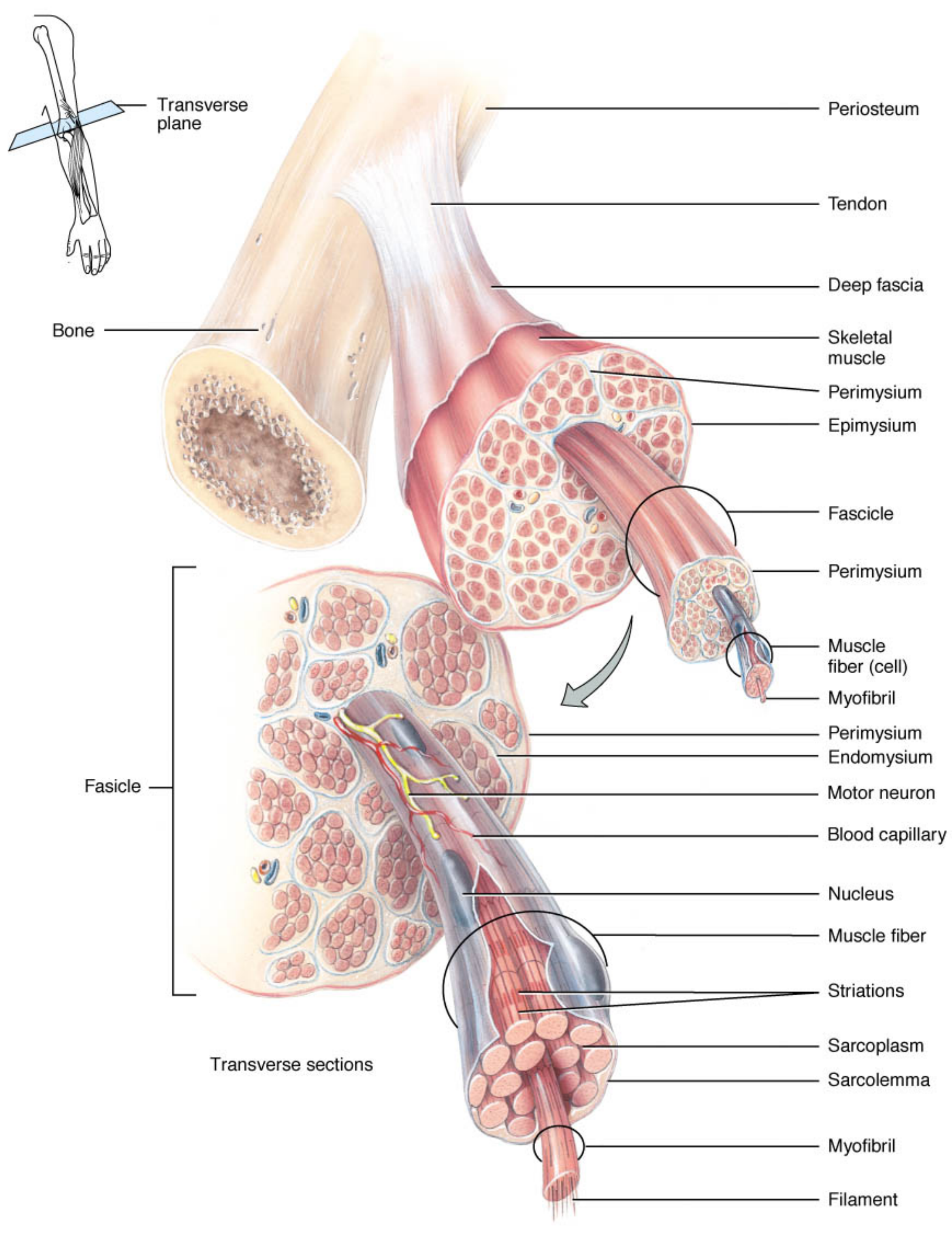

(a) Skeletal muscle
Nucleus
Muscle fiber (cell)
Striations
(b) Cardiac muscle
Striations
Muscle fiber
Intercalated disk
Nucleus
(c) Smooth muscle
Muscle fiber
Nucleus

Cross-Sectional View of Skeletal Muscle



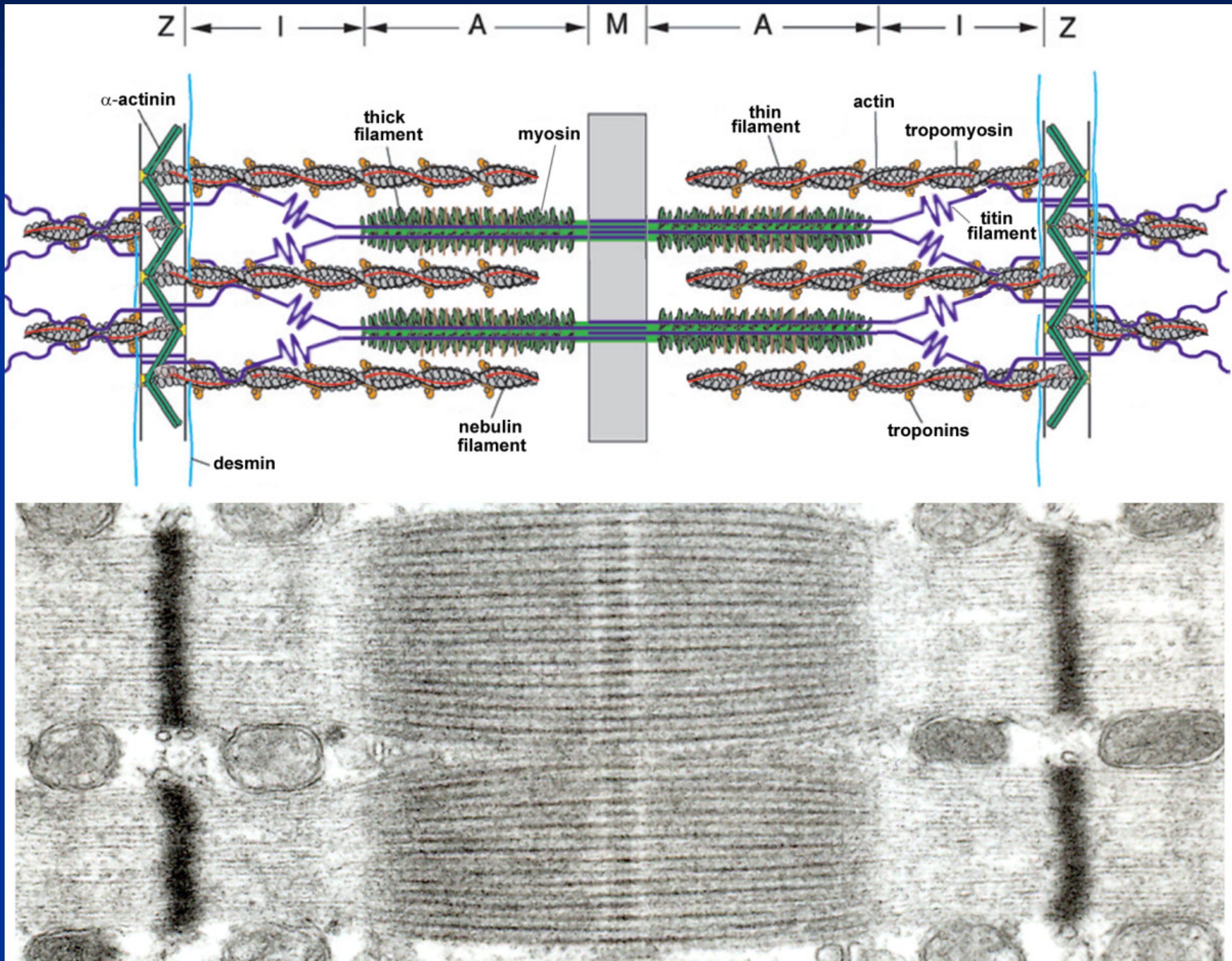
Skeletal Muscle Cytology





http://classroom.sdmesa.edu/eschmid/Chapter8-Zoo145.htm

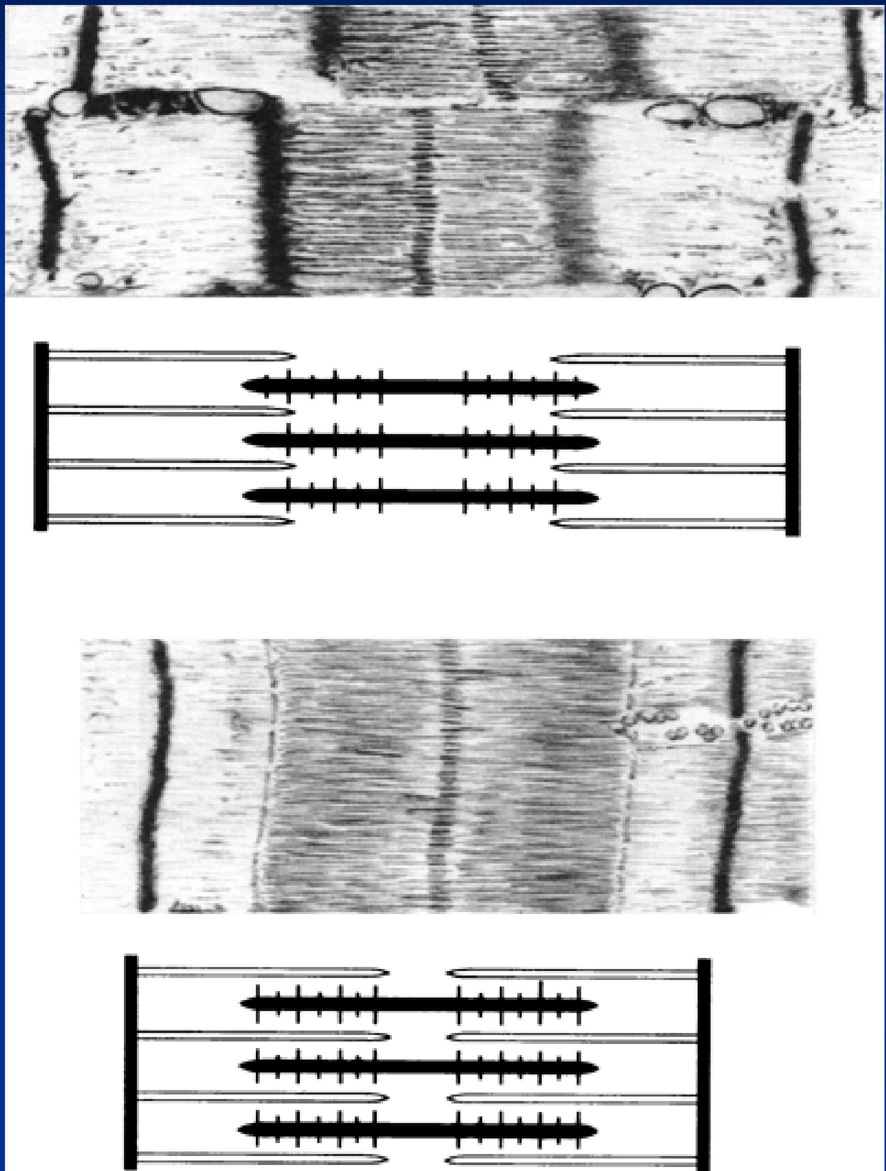
Electronmicroscopic photograph of the ultrastructural organization of sarcomeres in parallel



Simplified model of two muscle sarcomeres in parallel.

Ottenheijm et al. Respiratory Research 2008 9:12

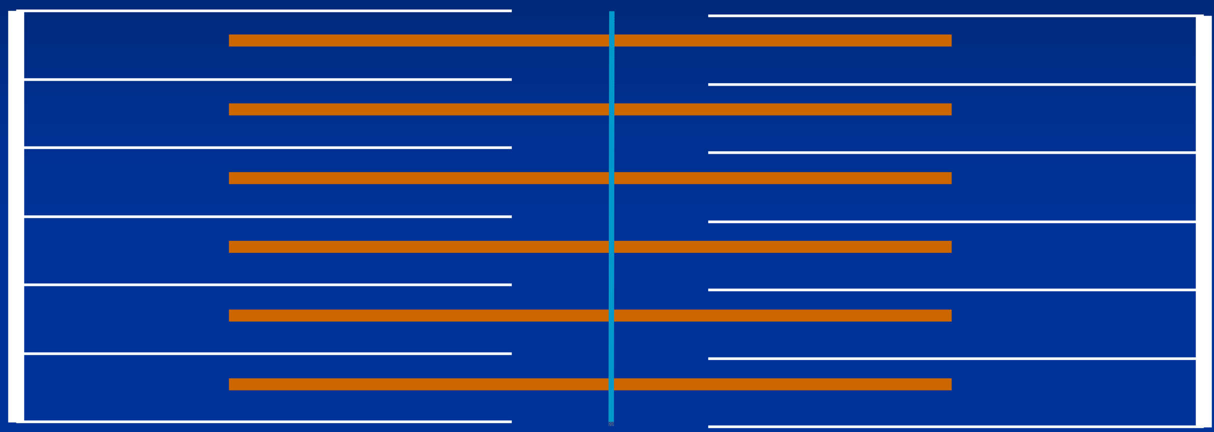
Sarcomere



- Sarcomeres are the basic unit of muscle contraction.
- They are made of myosin, actin, tropomyosin, and troponin proteins.

Sarcomere

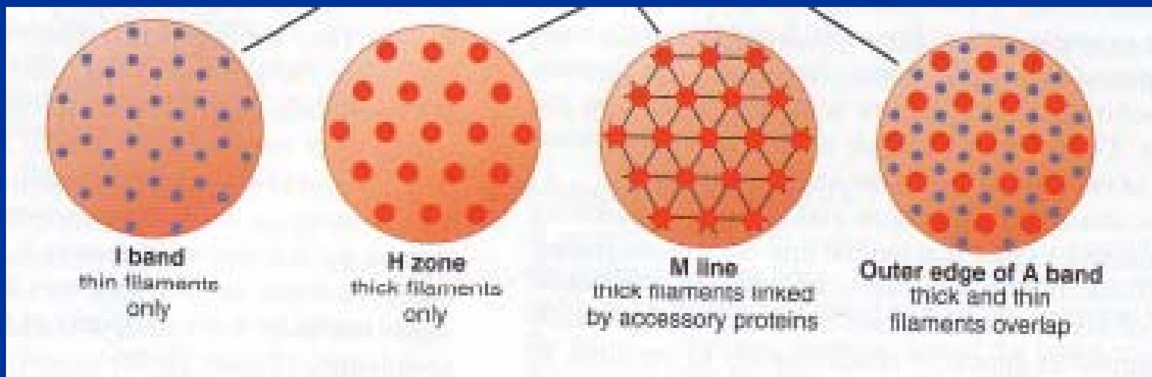
<--I-Band---><-------------------A-Band---------------> <--I-Band--->



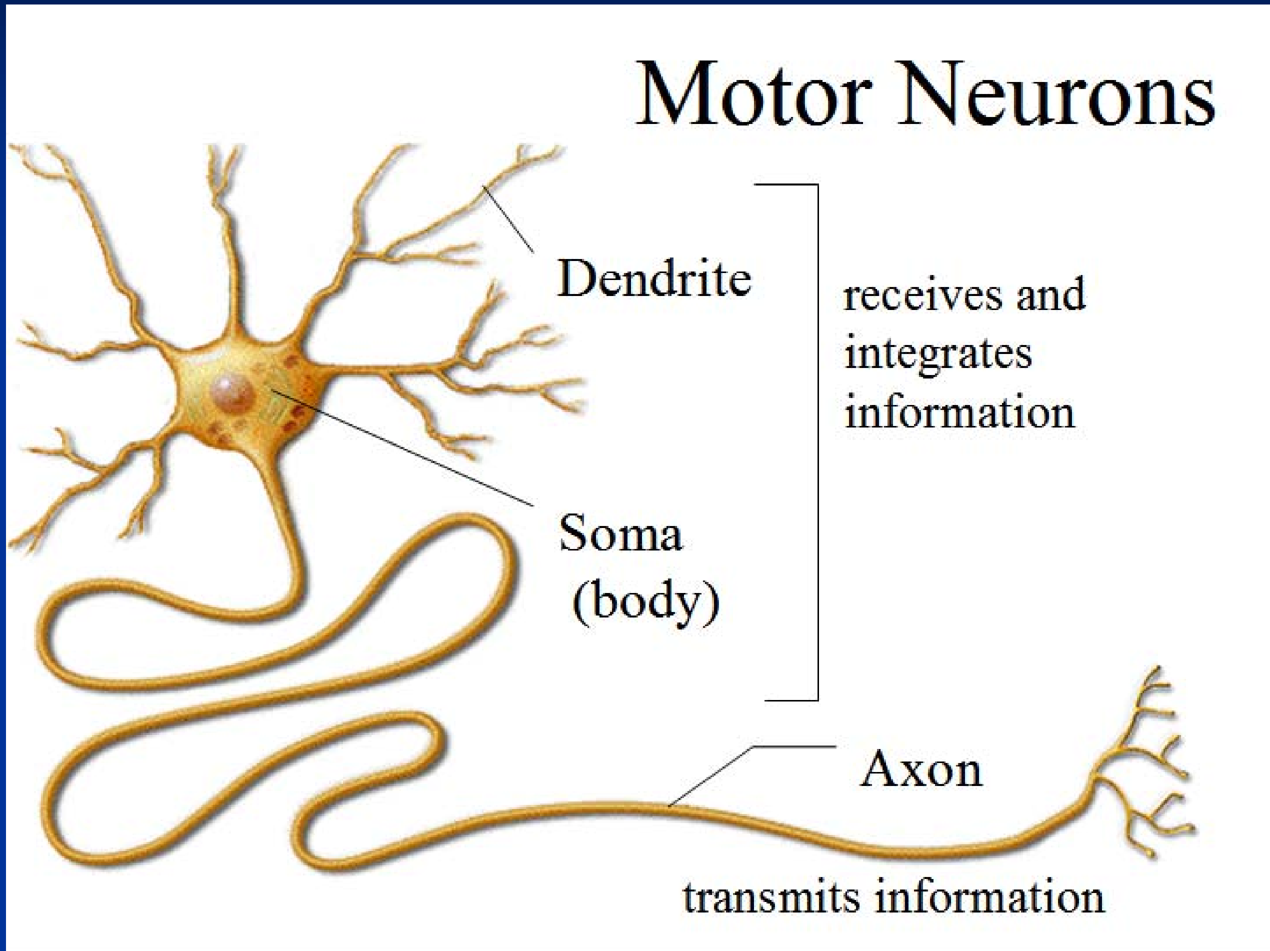
<-H-Zone->

Z-Disc

M-line



Motor Neuron



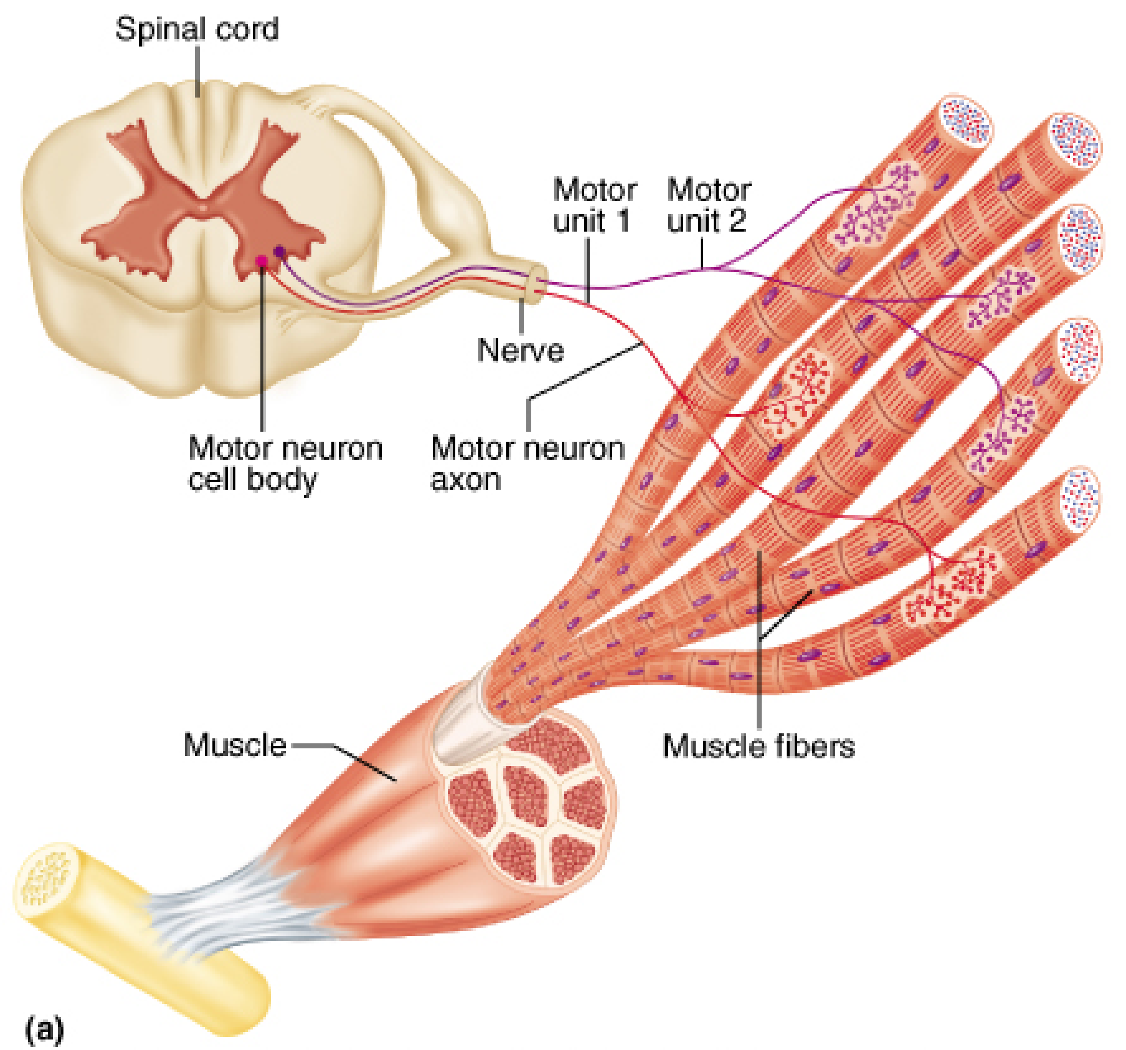
Motor neuron is a nerve cell (neuron) that originates in the motor region of the cerebral cortex or the brain stem, whose cell body is located in the spinal cord and whose fiber (axon) projects outside the spinal cord to control muscles.

Motor neurons are efferent nerves that carry signals from the spinal cord to the muscles to produce (effect) movement. Types of motor neurons are alpha motor neurons, beta motor neurons and gamma motor neurons.

Sensory Neuron

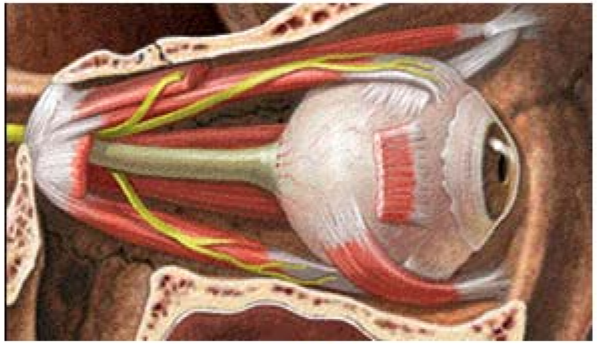
- Sensory neurons are nerve cells that transmit sensory information (sight, sound, feeling, etc.). They are activated by sensory input, and send projections to other elements of the nervous system, ultimately conveying sensory information to the brain or spinal cord.

Motor Unit



A motor unit is made up of a motor neuron and the skeletal muscle fibers innervated by that motor neuron.

Motor Unit



- each muscle has many motor units (MU)
- number of fibers in a MU is dependent on the precision of movement required of that muscle (average: 100-200 fibers per m.u.)
  - more precision is obtained with more neurons
  - 100 to 2000 motor neurons per muscle
- number of MU's in a muscle decreases in the elderly

Muscle Properties

- Irritability: Muscle can respond to stimuli.
- Contractility: Muscle can shorten in response to stimuli.
- Extensibility: Muscle can be stretched (passively or actively).
- Elasticity: Muscle can return to its resting length and shape after it has been stretched.

Muscle Functions

- Produce movement
- Maintain postures and positions
- Stabilize joints
- Non-movement-related functions:

• support and protect visceral organs
• control pressure within body cavities
• produce heat to maintain body temperature
• control entrances and exits to the body

Control of Tension

- excitation of each motor unit is an all-or-nothing event
- increased tension can be accomplished by:
  - increasing the number of stimulated motor units (**recruitment**)
  - increasing the stimulation rate of the active motor units (**rate coding**)

Recruitment

- each motor unit has a stimulation threshold at which it will begin to produce force
- small motor units have a lower threshold than large motor unit, therefore they are recruited first (**size principle**)

Muscle contraction

- **Sliding filament theory:** Muscle shortens as a result of the sliding between two sets of filaments containing the proteins myosin and actin.
  - AF Huxley and HE Huxley* (1954)
  - Light and Electron microscopy
  - Both published results same time in Nature
  - Does not explain lengthening contractions

* Huxley AF, Niedergerke R (1954). Nature 173, 971–973. Huxley HE, Hanson J (1954). Nature 173, 973–976.

Muscle contraction

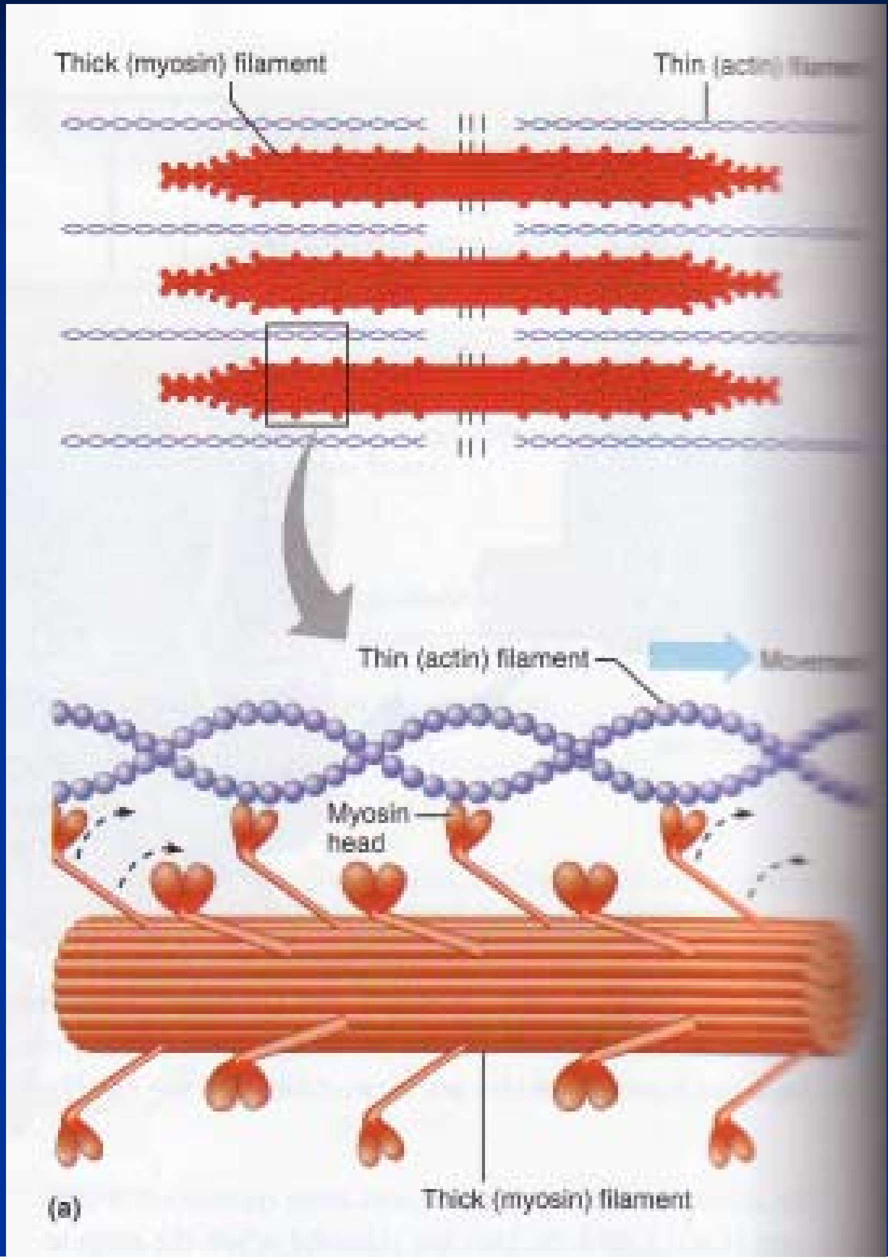
Sliding filament theory was refined in 1957 by A. Huxley **

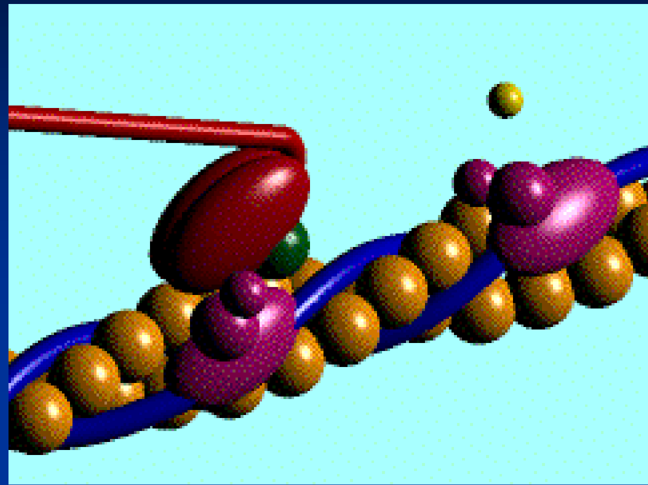
⇨ **Cross bridge theory**

Cross-bridge theory: The cross-bridge theory of muscle contraction states how force is produced, and how the filaments actin and myosin are moved relative to each other to produce muscle shortening.

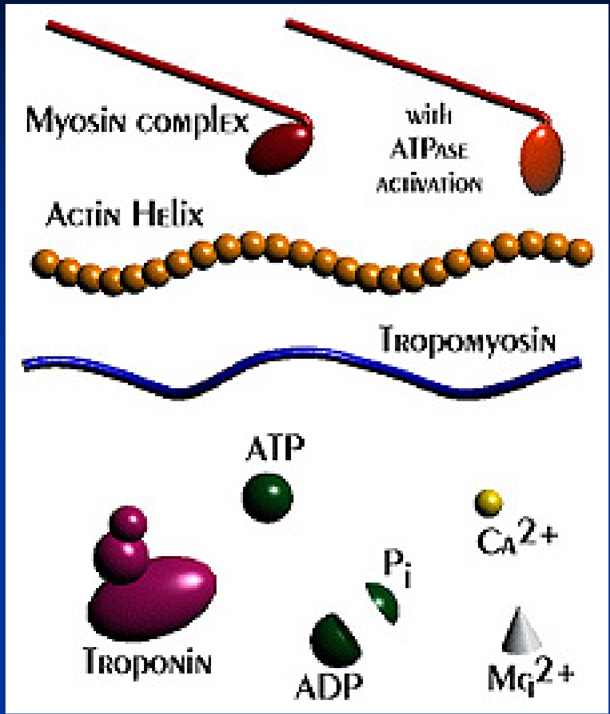
** A. F. Huxley. Muscle structure and theories of contraction. Prog. Biophys. Biophys. Chem., 7:255–318, 1957.
A.F. Huwley & Simmons, R. M., Proposed mechanism of force generation in striated muscle Huxley, A. F. Nature 233, 533-538, 1971.

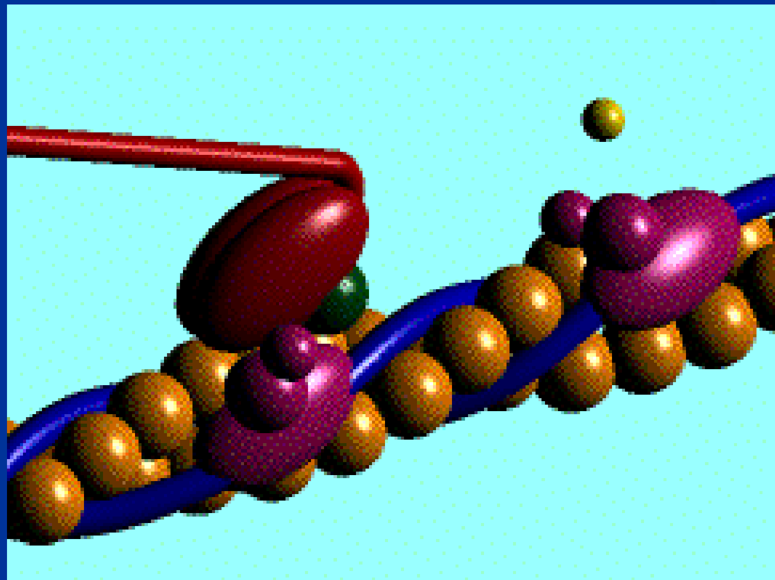
Cross-bridge theory





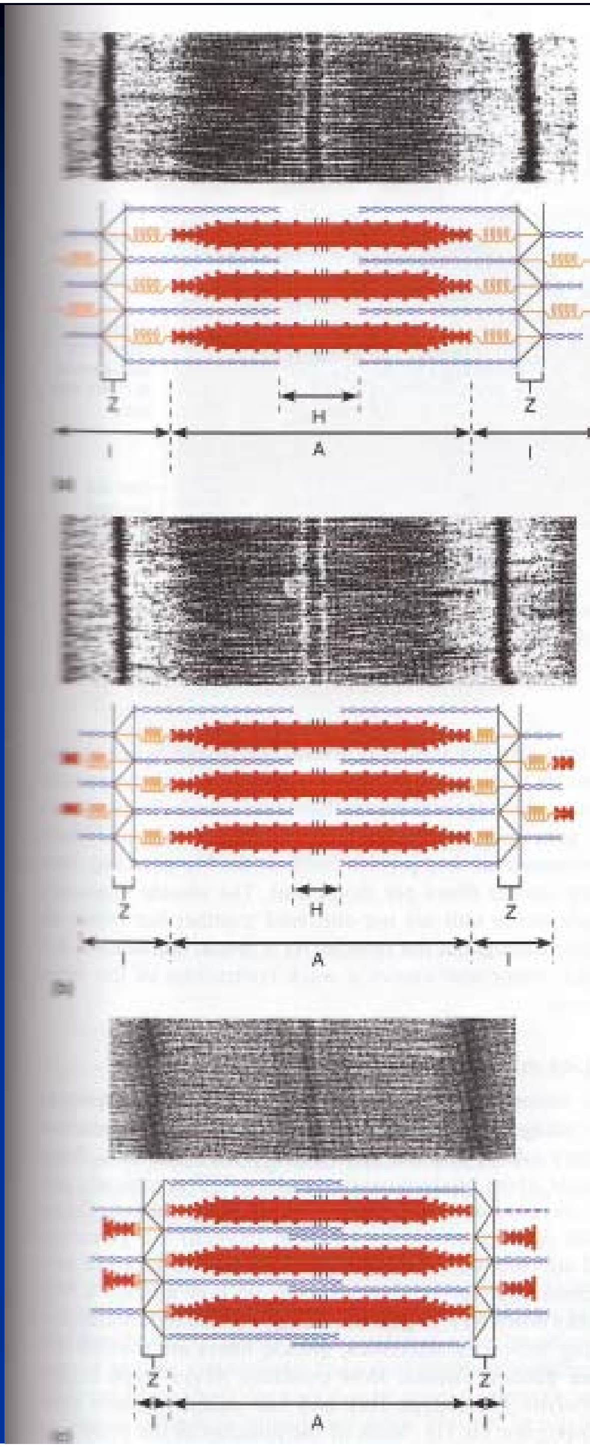
muscle force is proportional to the number of cross bridges attached


Myosin complex
with
ATPase
activation
Actin Helix
Tropomyosin
ATP
Troponin
ADP
P_i
Ca^{2+}
Mg^{2+}



Cross-bridge theory

- A band stay the same
- I band shorten



A single functional unit in a muscle contraction is a

A) fascicle
B) fiber
C) myofibril
D) sarcomere

According to sliding filament theory, during a contraction the distance between the M and Z lines

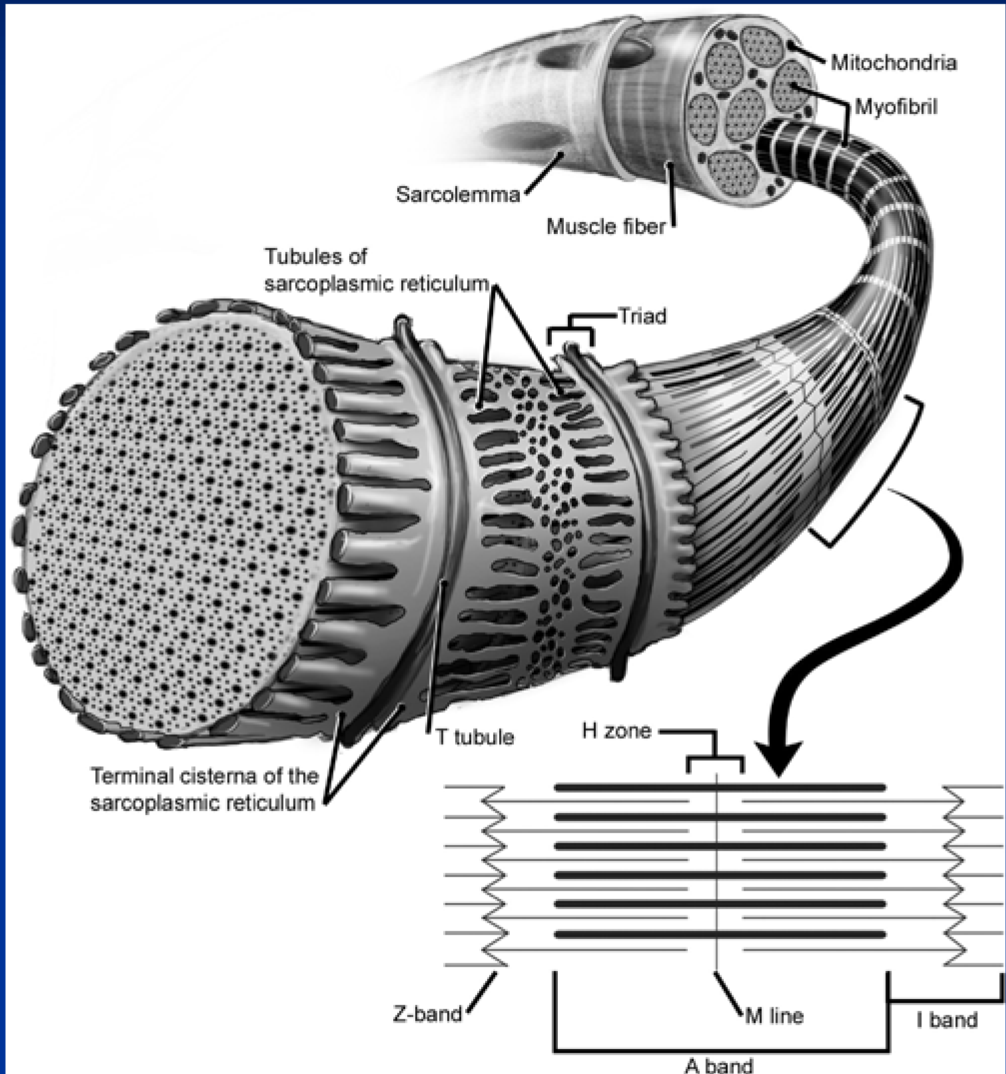
A) increases

B) decreases

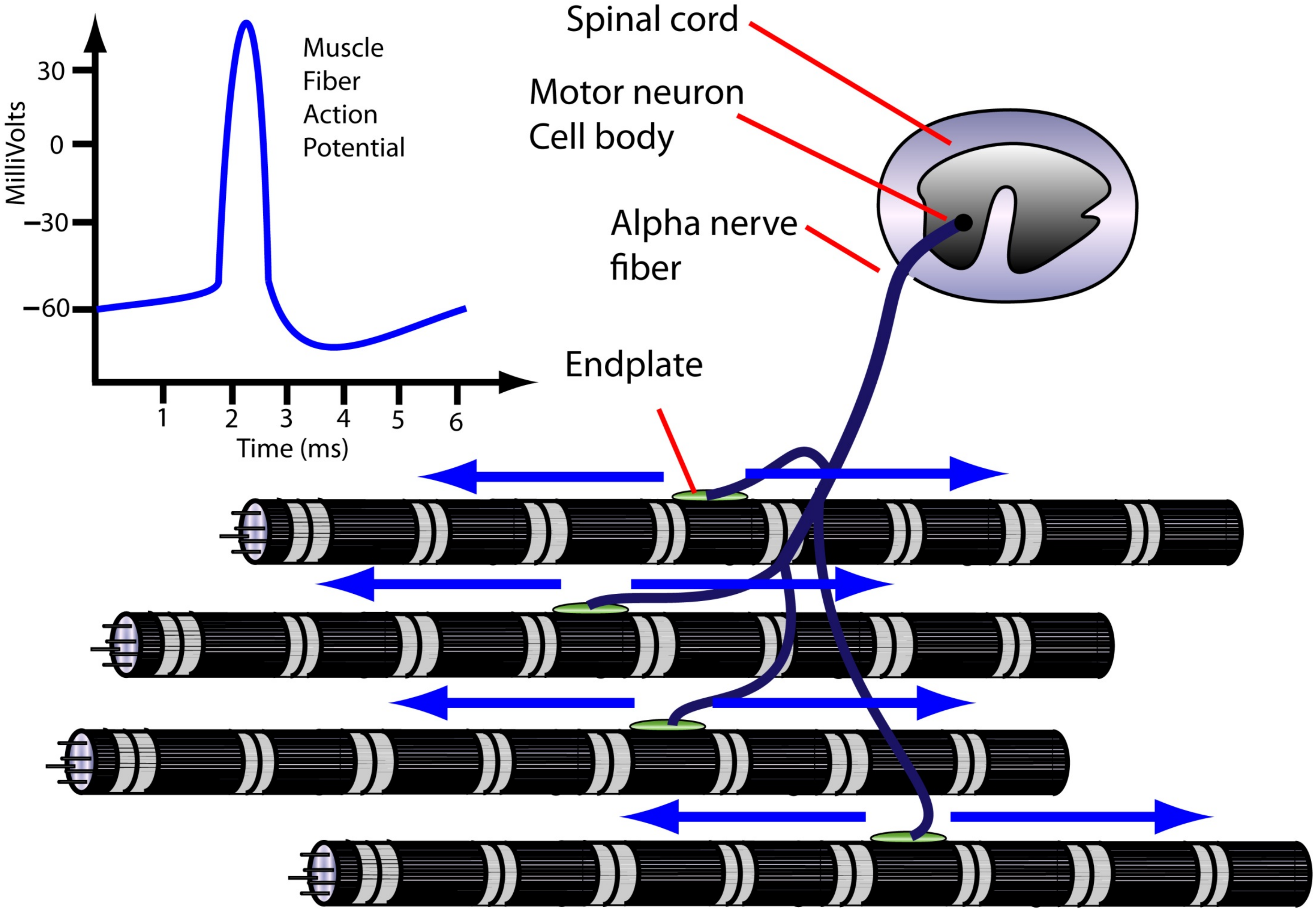
C) stays the same

D) need more information

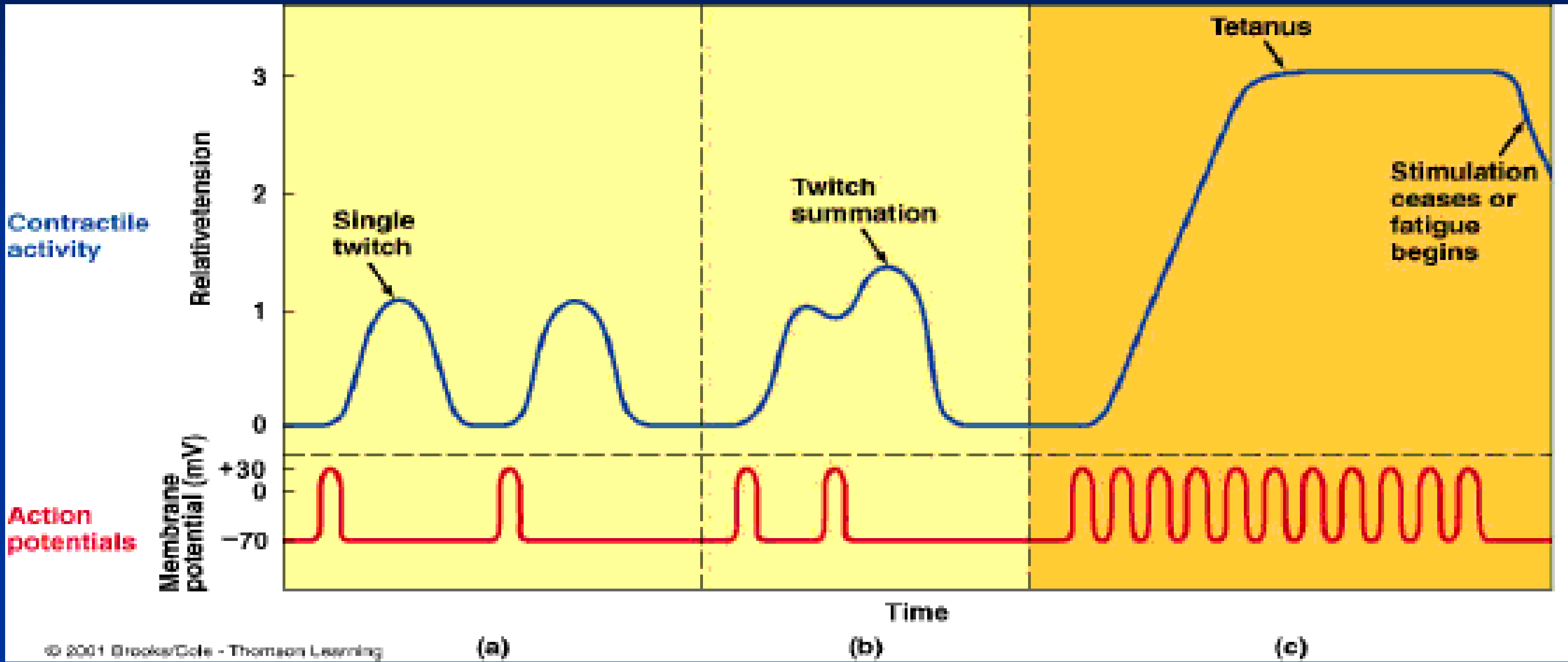
Sliding Filament Theory



- The length of the thick and thin filaments remains constant during contraction, but the overall sarcomere length becomes shorter.
- The I band becomes shorter with contraction as the thick filaments slide past the thin filaments in a process known, appropriately, as the sliding filament model of muscle contraction.


Muscle
Fiber
Action
Potential
MilliVolts
30
0
−30
−60
1
2
3
4
5
6
Time (ms)
Spinal cord
Motor neuron
Cell body
Alpha nerve
fiber
Endplate

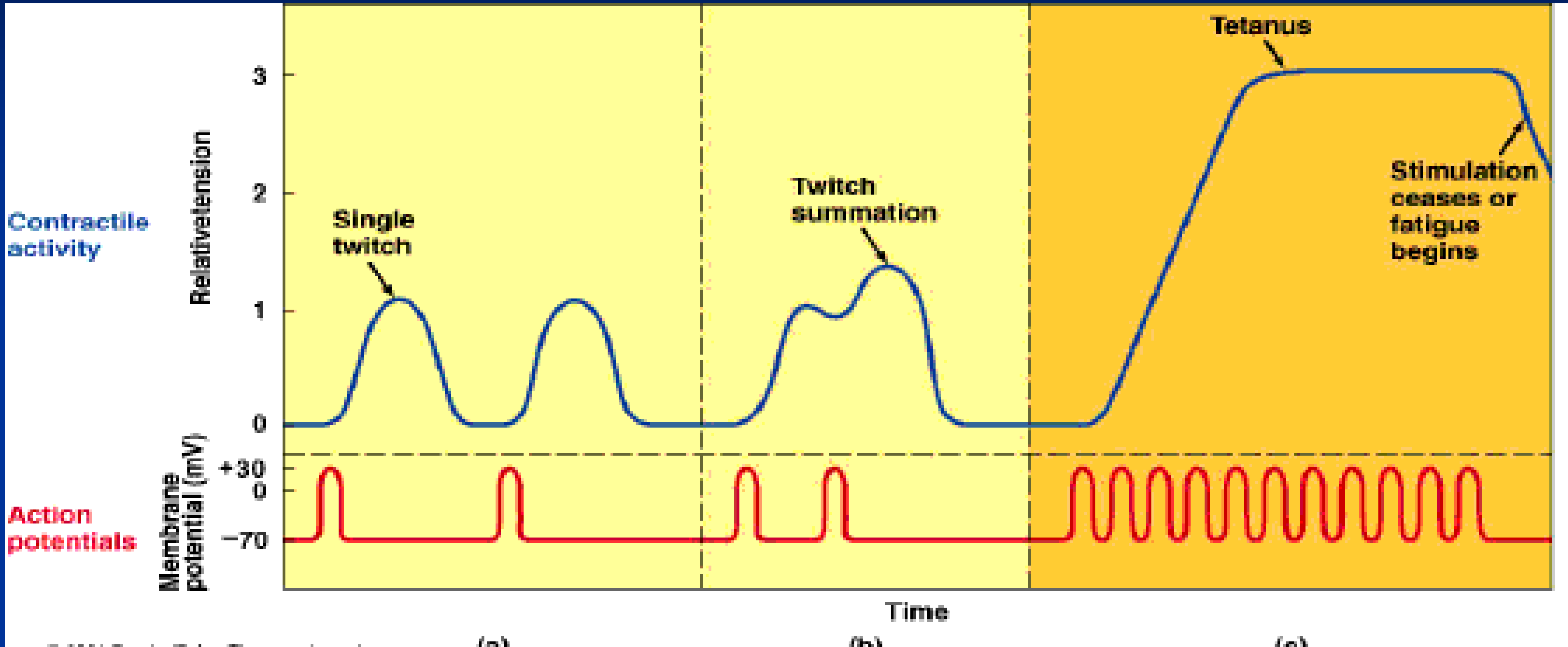
Muscle Twitch and Tetanus



• In response to a single stimulus of adequate strength, a momentary rise in tension known as a twitch is produced.

•If a second stimulus reaches the muscle fiber after the relaxation phase of a twitch, no increase in muscle tension occurs, and another twitch of identical tension takes place.

Muscle Twitch and Tetanus

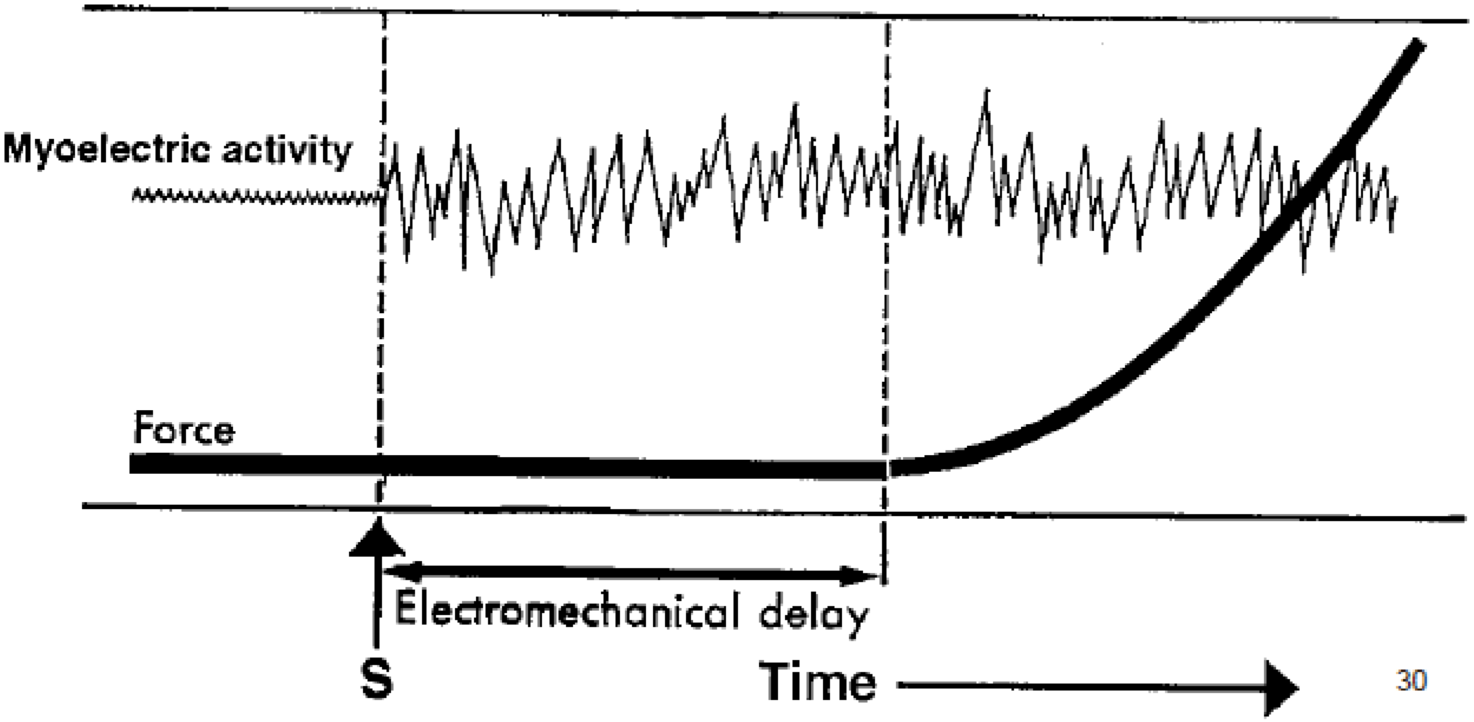


•A second stimulus of adequate intensity reaches the fiber before completion of the relaxation phase, an increase in tension above that of the first twitch is possible. This summation is known as an unfused tetanus.

•The temporal summation of twitch tension increases proportionately with the stimulation frequency. As the stimulation frequency increases, the amount of tension produced is increased proportionally until reaching a maximum level known as a fused tetanus.

Electromechanical Delay

Muscles do not produce force instantaneously when they are stimulated.



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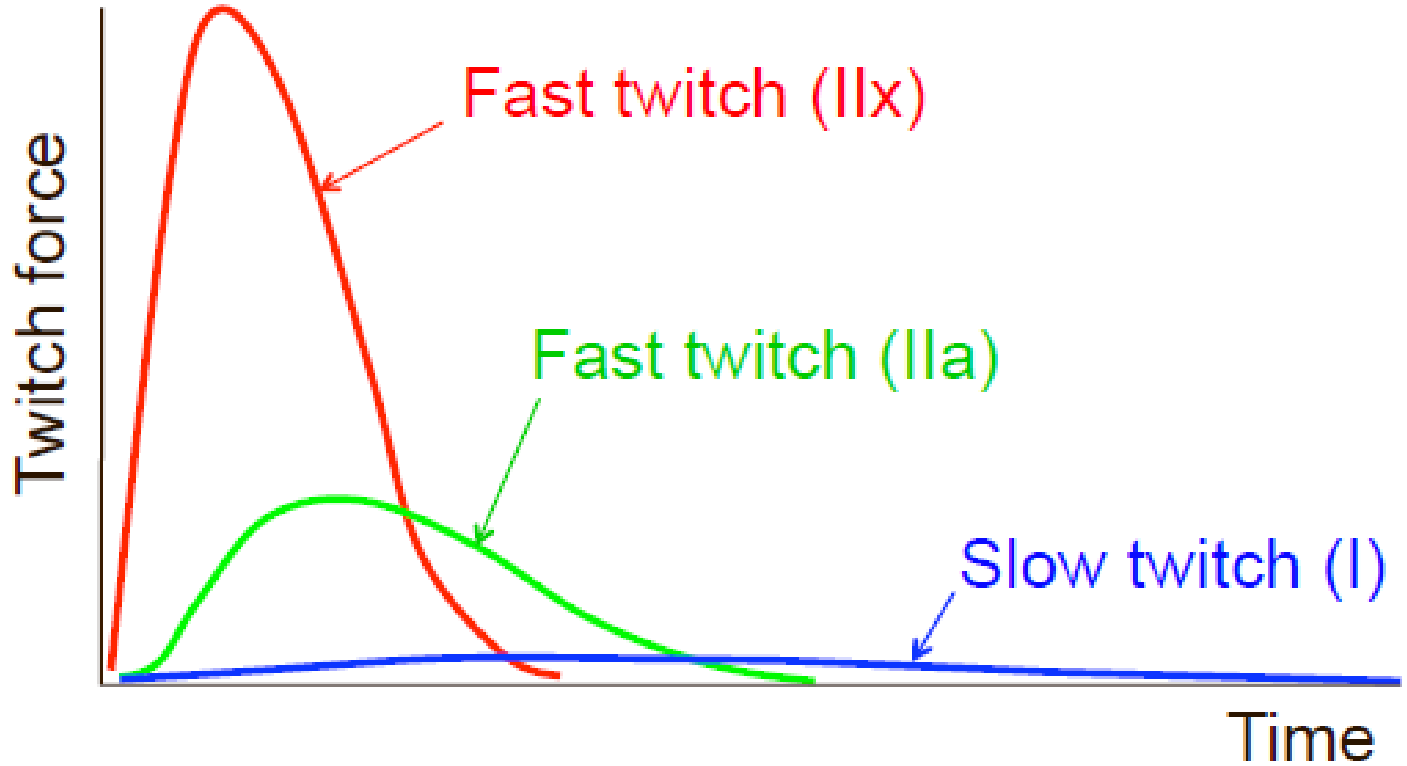
Fiber Types

Muscle fibers vary in type and can be differentiated by their histological, biochemical, and physiologic properties.

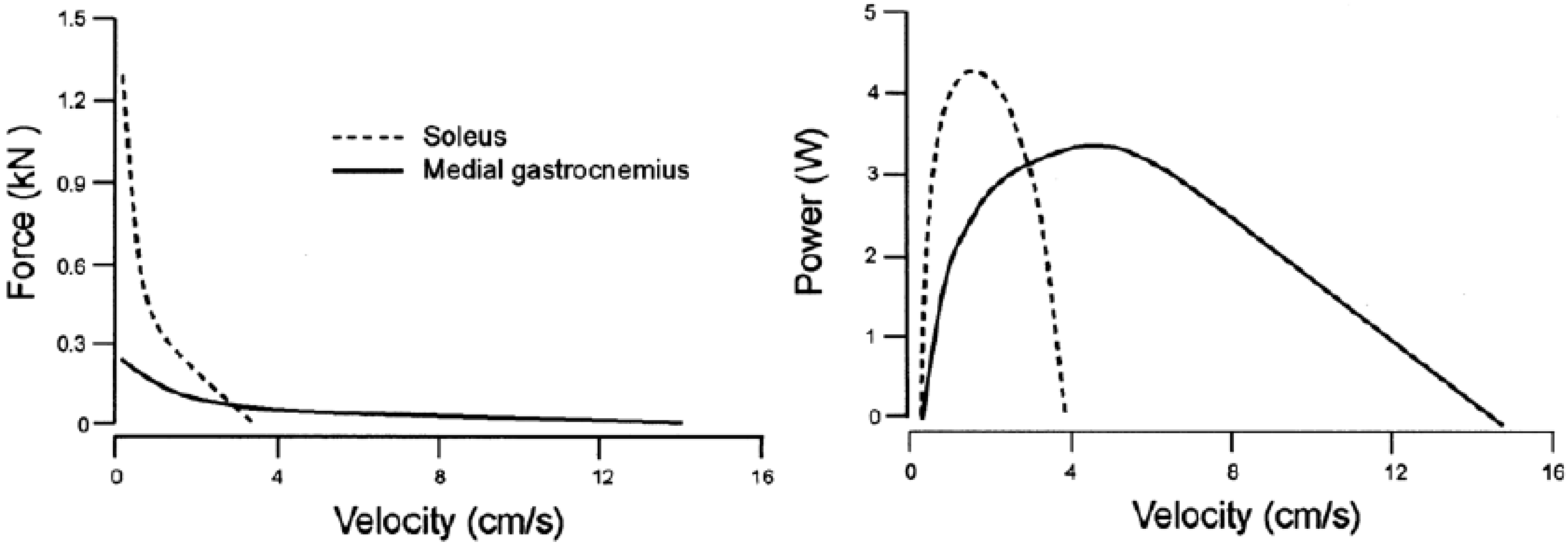
Characteristics of Human Skeletal Muscle Fiber Types			
	Type I	**Type IIA**	**Type IIB**
Other Names	Red, slow twitch (ST) Slow oxidative (SO)	White, fast twitch (FT) Fast oxidative glycolytic (FOG)	Fast glycolytic (FG)
Speed of contraction	Slow	Fast	Fast
Strength of contraction	Low	High	High
Fatigability	Fatigue-resistant	Fatigable	Most fatigable
Aerobic capacity	High	Medium	Low
Anaerobic capacity	Low	Medium	High
Motor unit size	Small	Larger	Largest
Capillary density	High	High	Low

Muscle Fibre Type

Different types of muscle fibers produce different levels of force.



Different types of muscle fibers produce force at different velocities.



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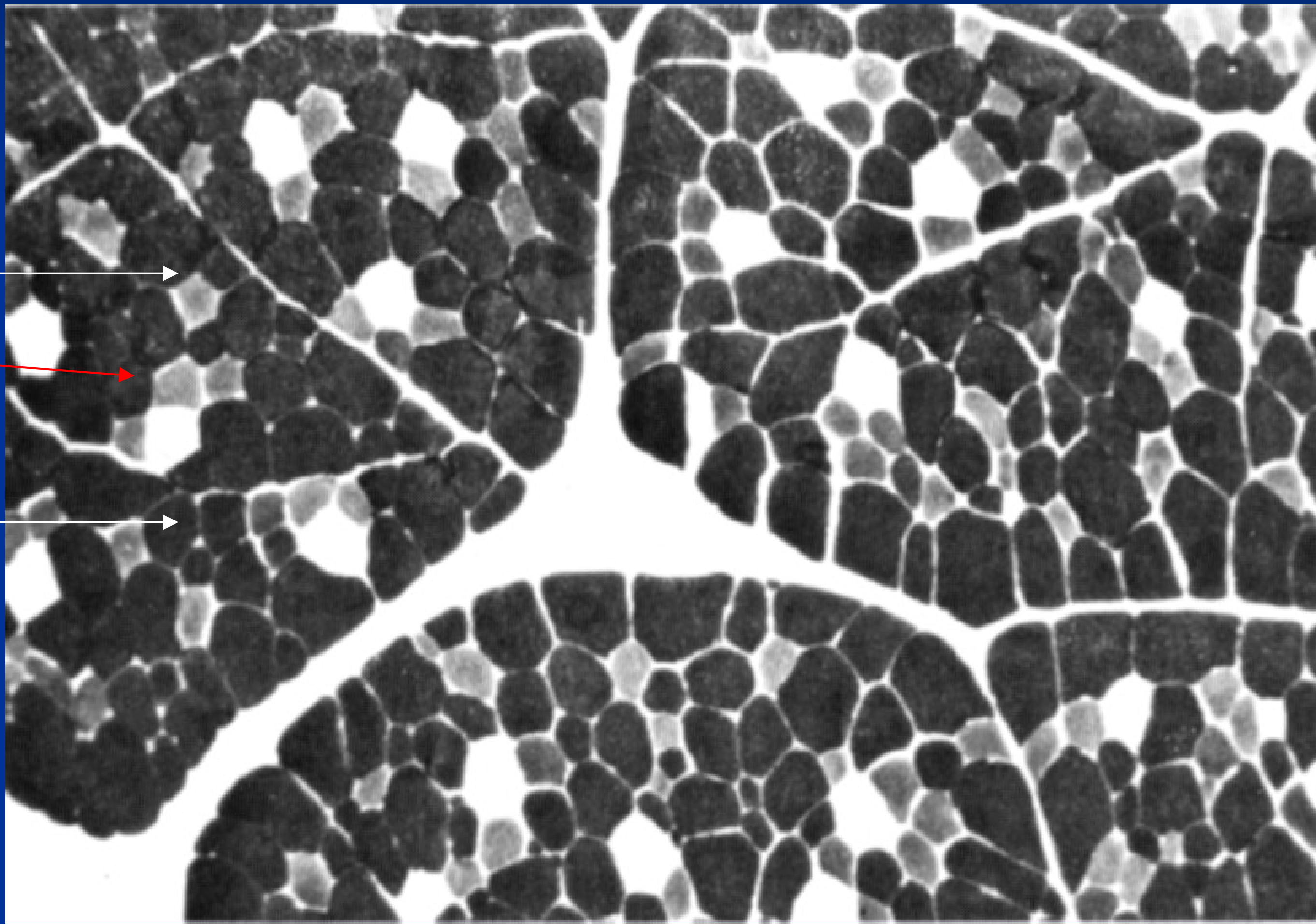
[Edgerton, 1986]

Histology of muscle

Type IIA

Type IIB

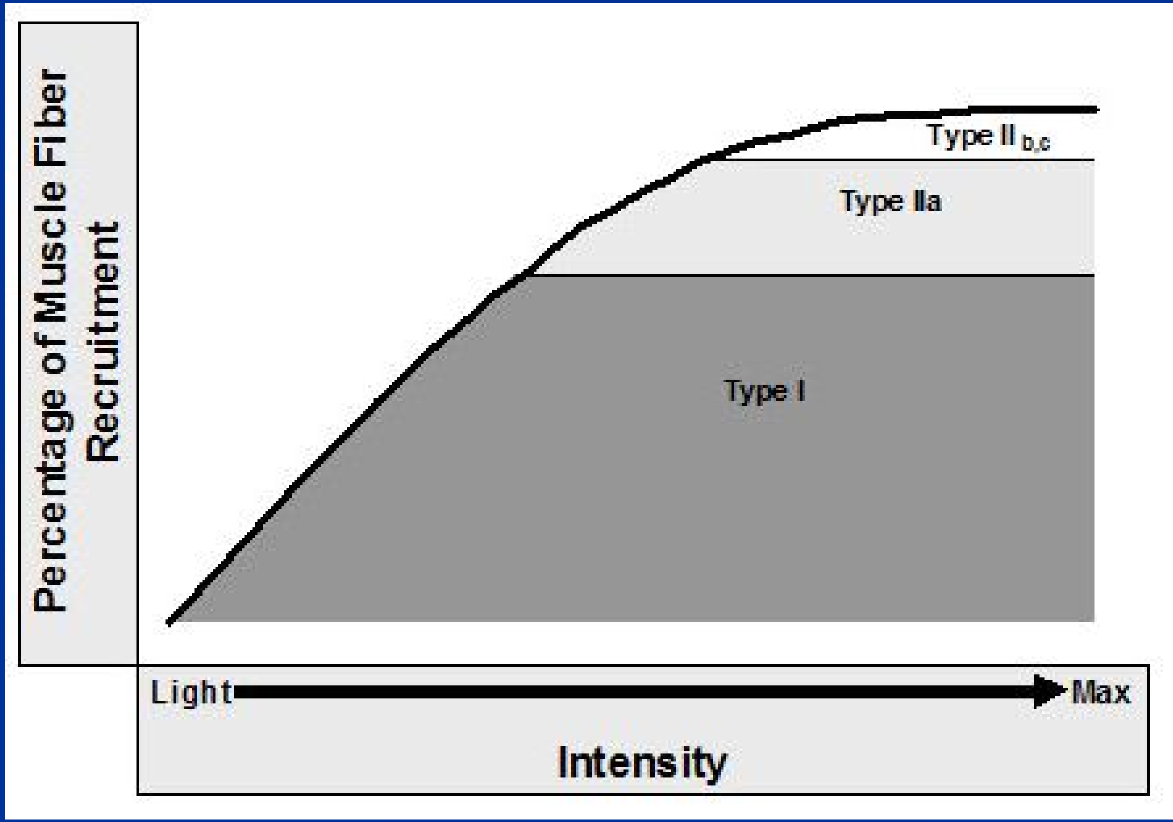
Type I



Eye muscle (Rectus lateralis)

Fiber Types

Order of muscle fiber (Cell) recruitment based on force requirements of exercise bout.



(http://www.thenutritiondr.com/figure-muscle-fiber-recruitment-based-on-force/)

With ageing

Ageing leads to reduction in

- number of Motor Units (nMU), and
- rate of fast twitch fibre within a muscle.

which causes muscle weakness and is accepted as normal change. Rapid changes in nMU and FFR are signs of disease or disuse atrophy.

With ageing

Sarcopenia: Loss of cells from the motor system occurs during the normal aging process, leading to reduction in the complement of motor neurons and muscle fibers. The latter age-related decrease in muscle mass has been termed "sarcopenia"

With ageing

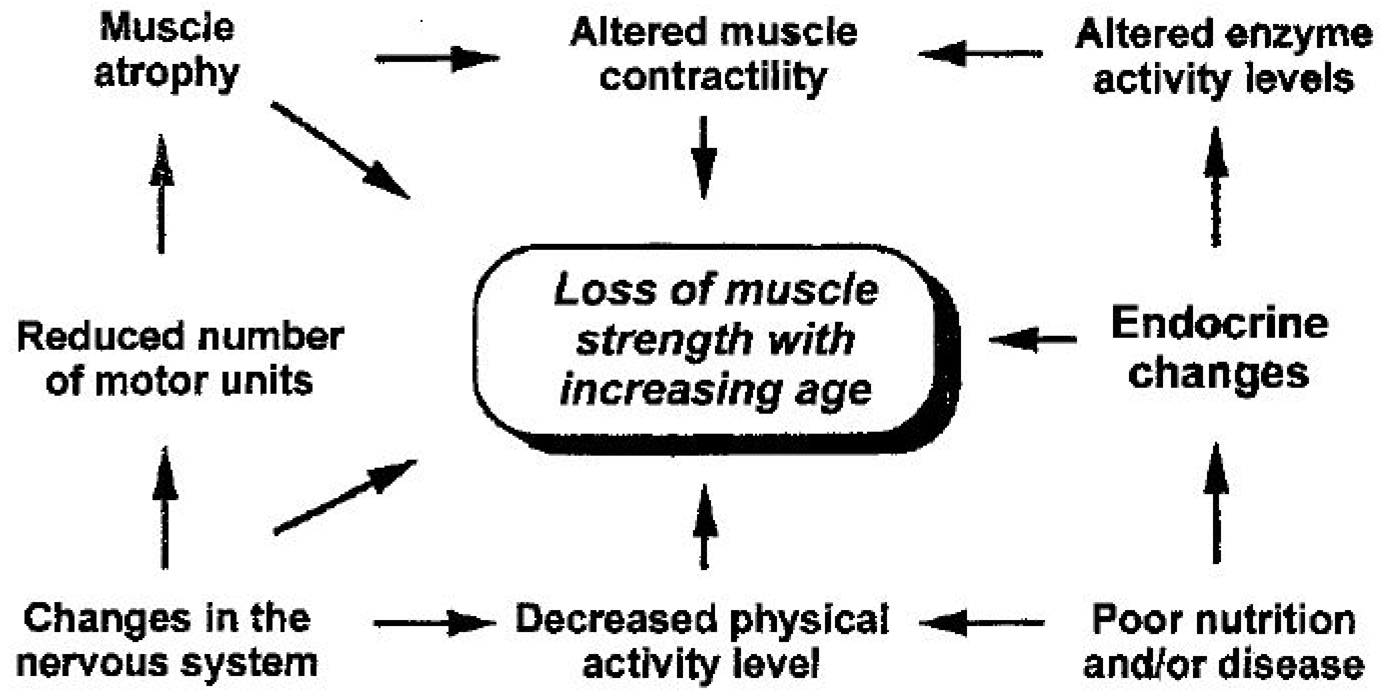
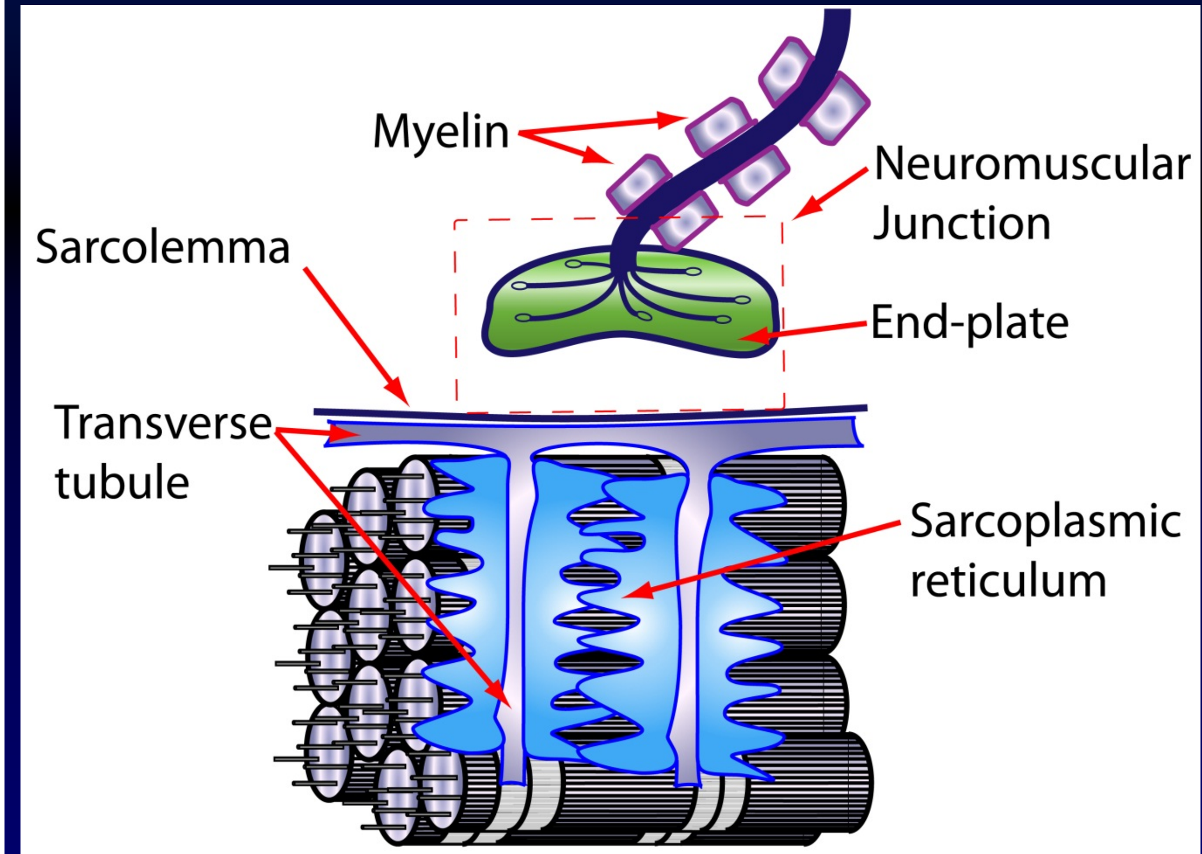


FIGURE 1. Multiple factors that cause loss of muscle strength with increasing age. Note that some influences are part of the normal biological aging process (e.g., motor unit loss), whereas other reversible effects are linked to lifestyle patterns.

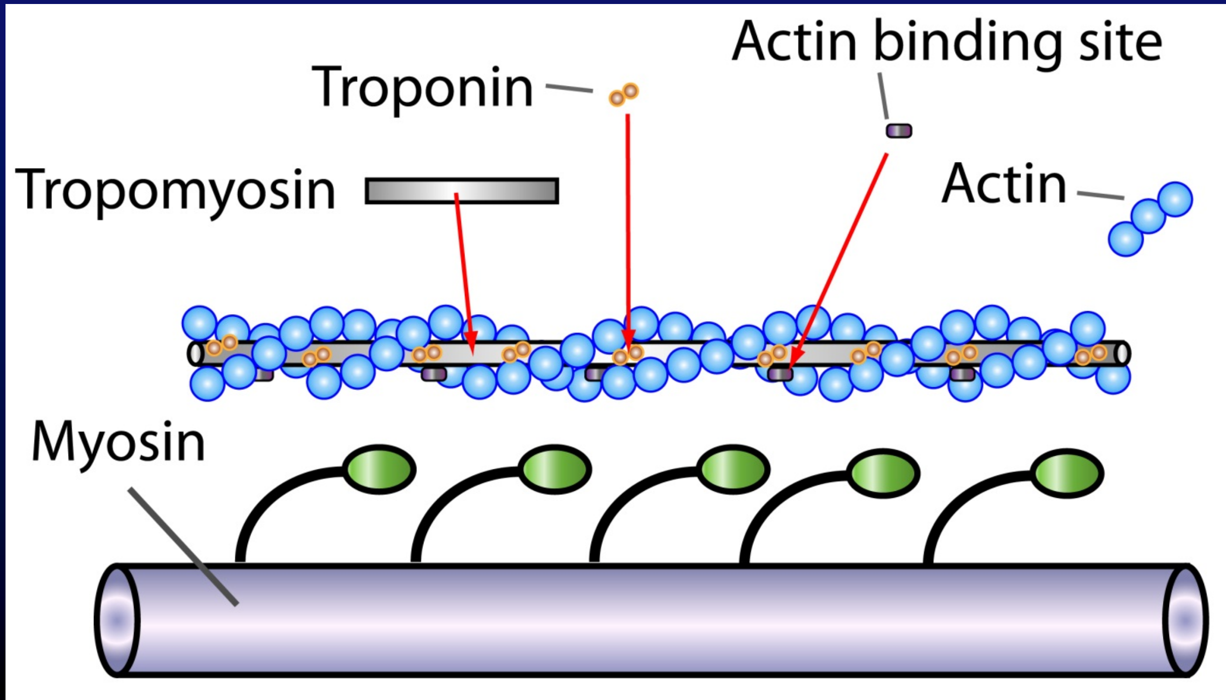
Vandervoort, Muscle&Nerve, 2002.

Muscle Excitation – Contraction Coupling
Cross-Bridge Theory

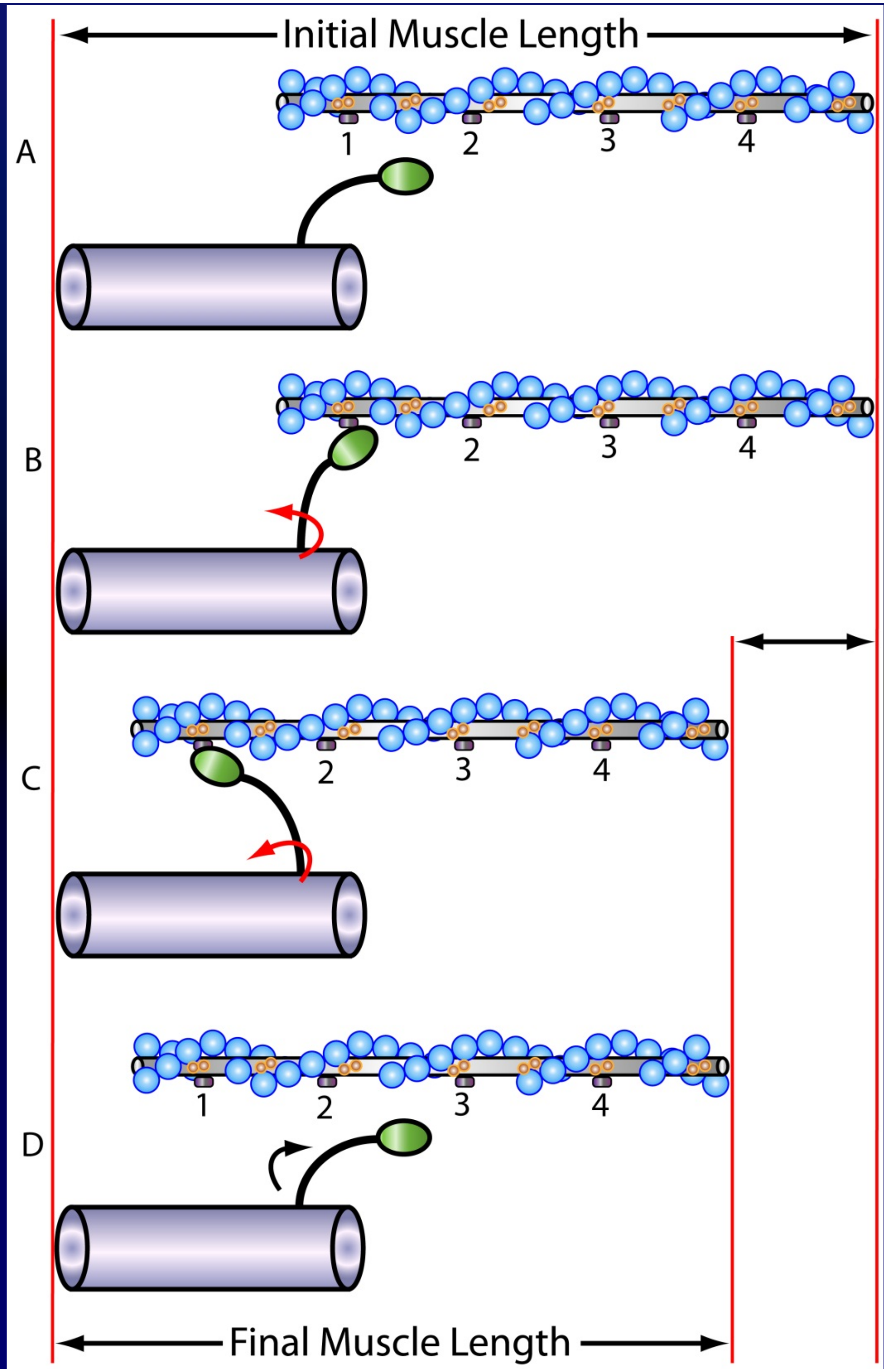
A single muscle fiber contains hundreds of myofilaments (Actin & Myosin) which are bundled together and surrounded by the muscle membrane (sarcolemma).



A muscle fiber has a diameter of 10 – 60 μm and a length of 10 – 300 mm.



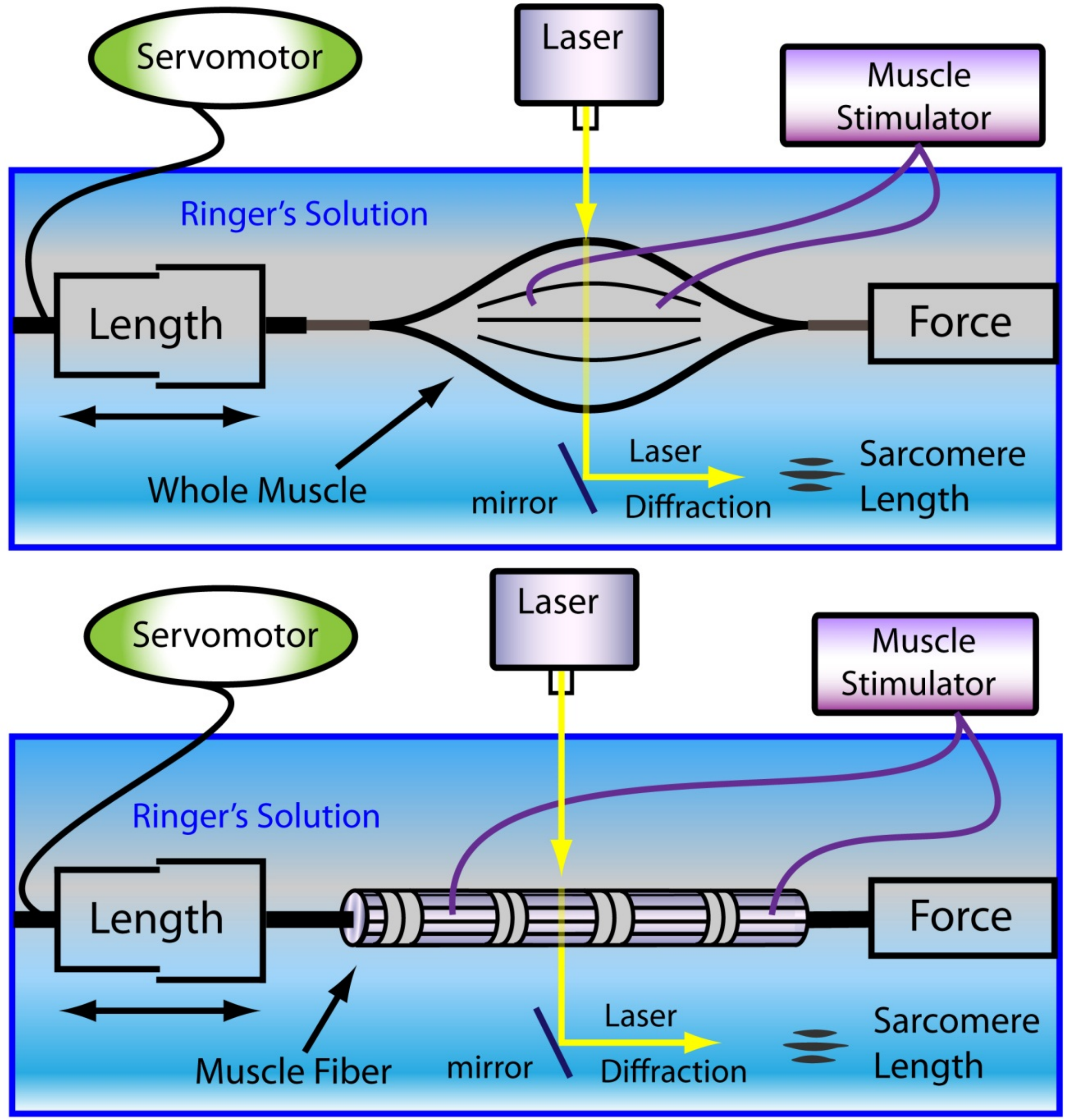
- Troponin and tropomyosin are regulatory proteins.
- Under resting conditions they form a crossbridge by binding of actin and myosin.



Concentric Cross-bridge Cycle

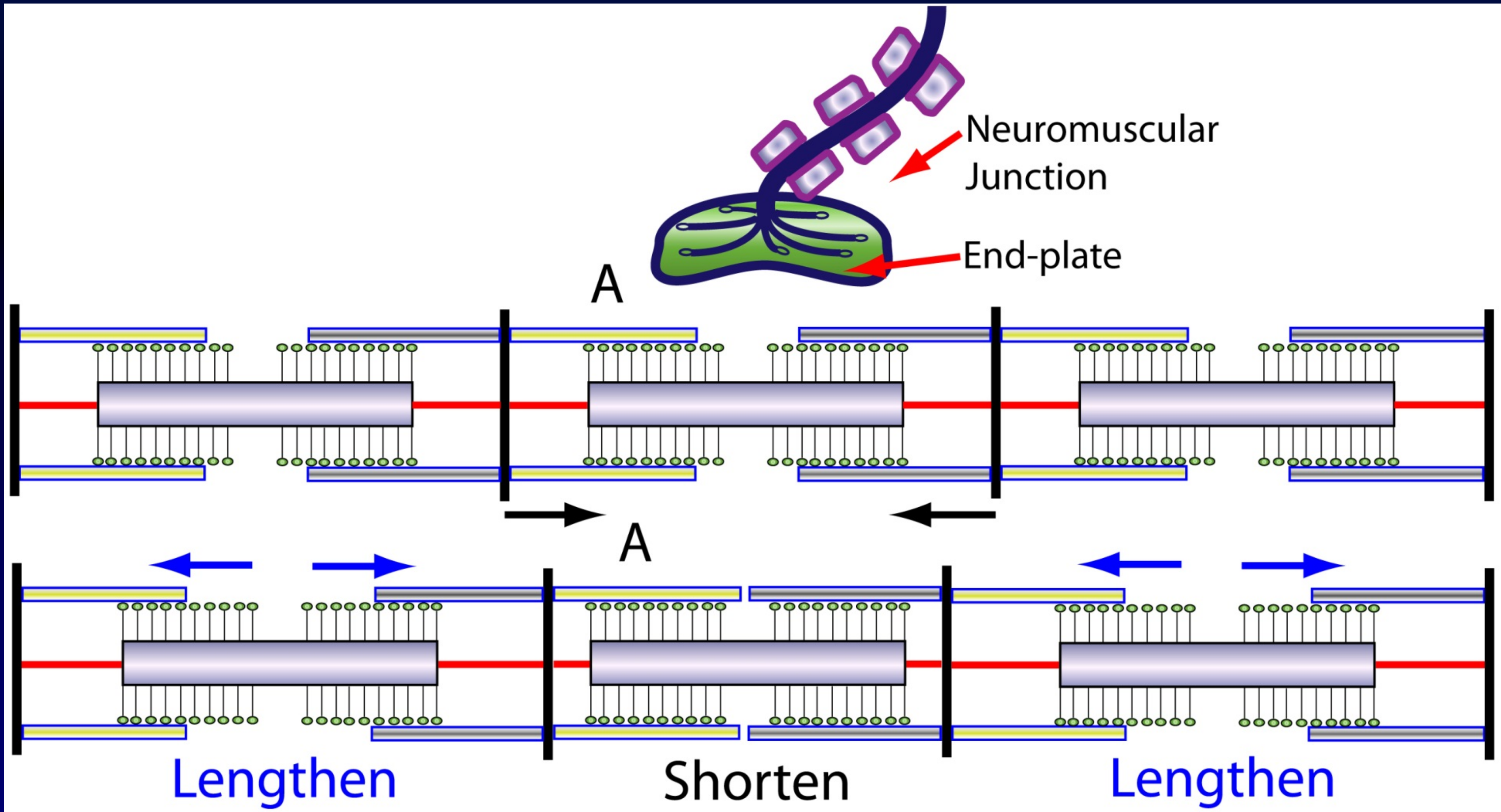
- Ca^{++} released from SR
- Ca^{++} binds with troponin
- Tropomyosin moves away from binding site.
- An Actin-Myosin cross-bridge is formed.
- ATP downgraded to ADP + Pi.
- Myosin does mechanical work on Actin, Myosin arm rotates shortening the muscle fiber.

Muscle Force-Length & Force-Velocity Relationships

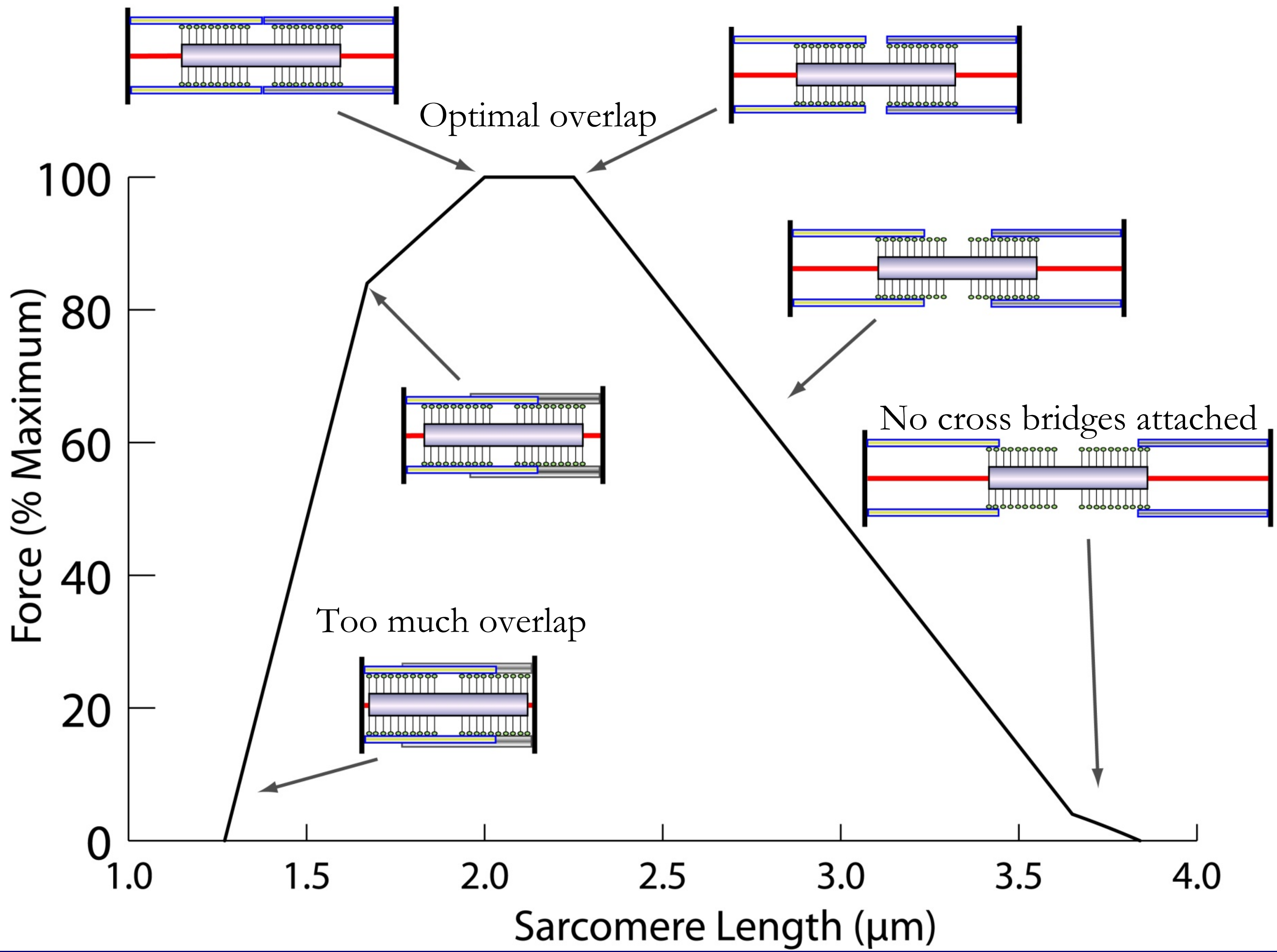


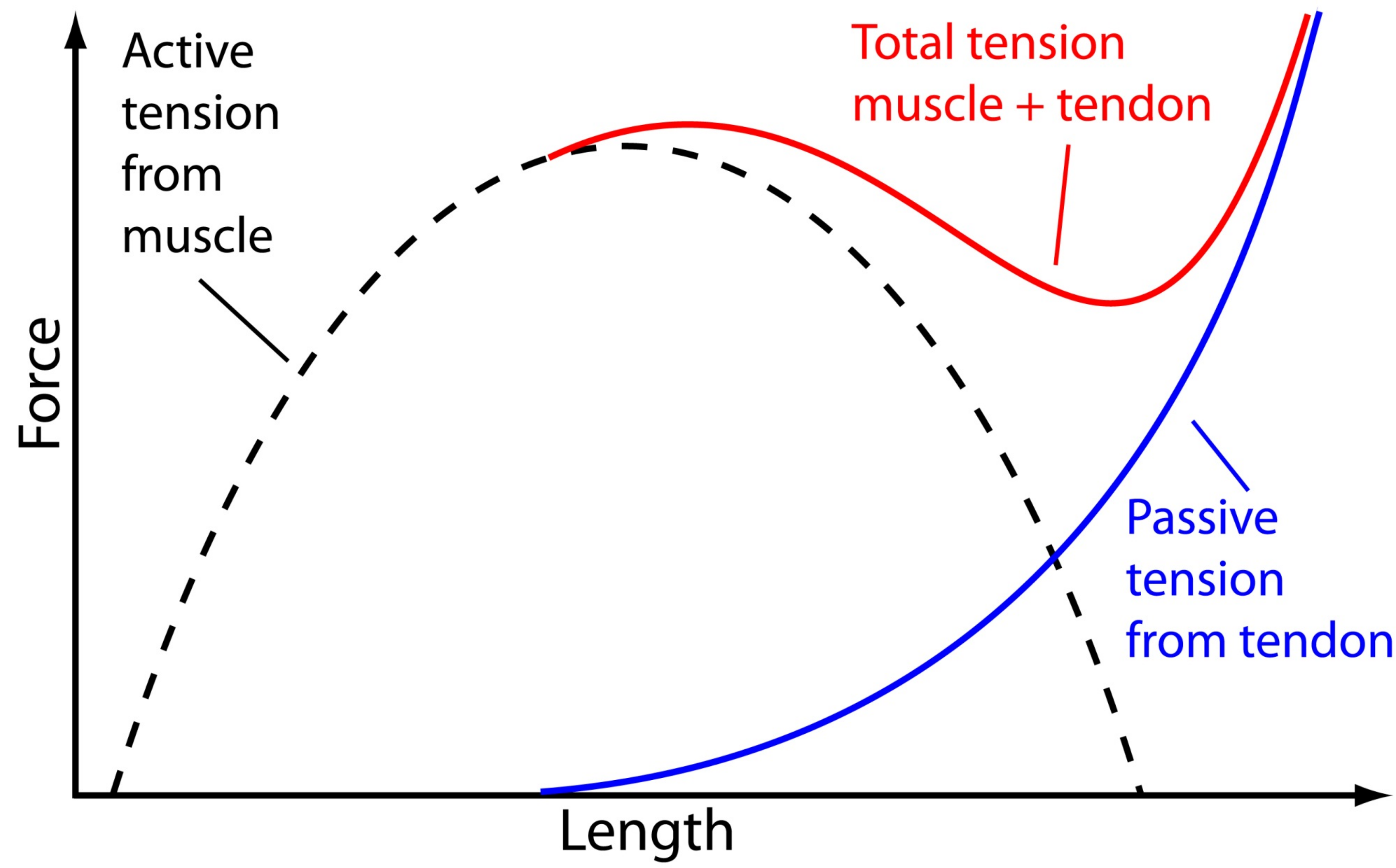
Instrumentation used to study muscle force-velocity and force-length relationship.

Length changes to an individual sarcomere during an isometric contraction. The sarcomere directly underneath the end-plate will be the first to develop tension which causes the sarcomeres to the right and left to lengthen.



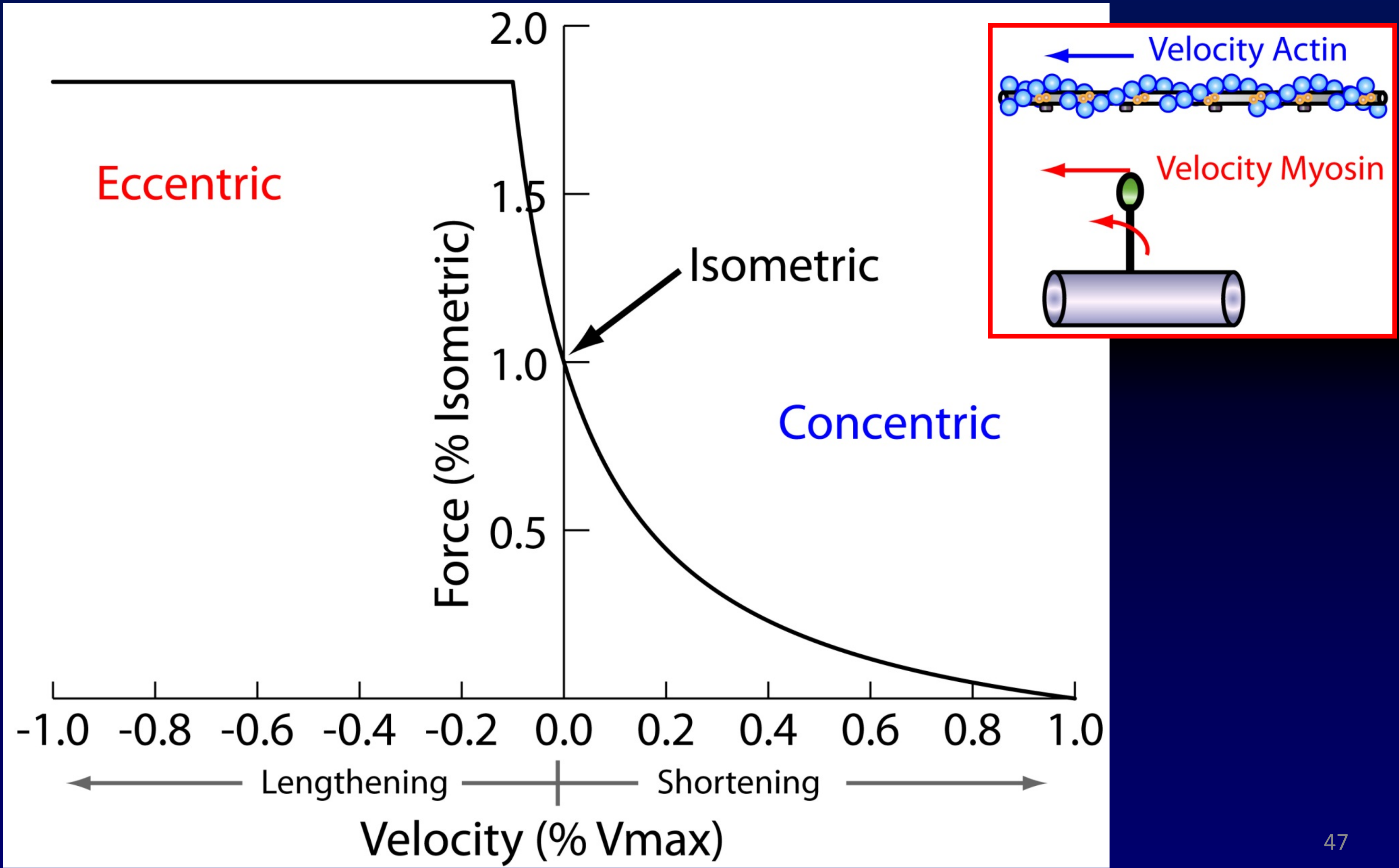
Sarcomere Force – Length Relationship



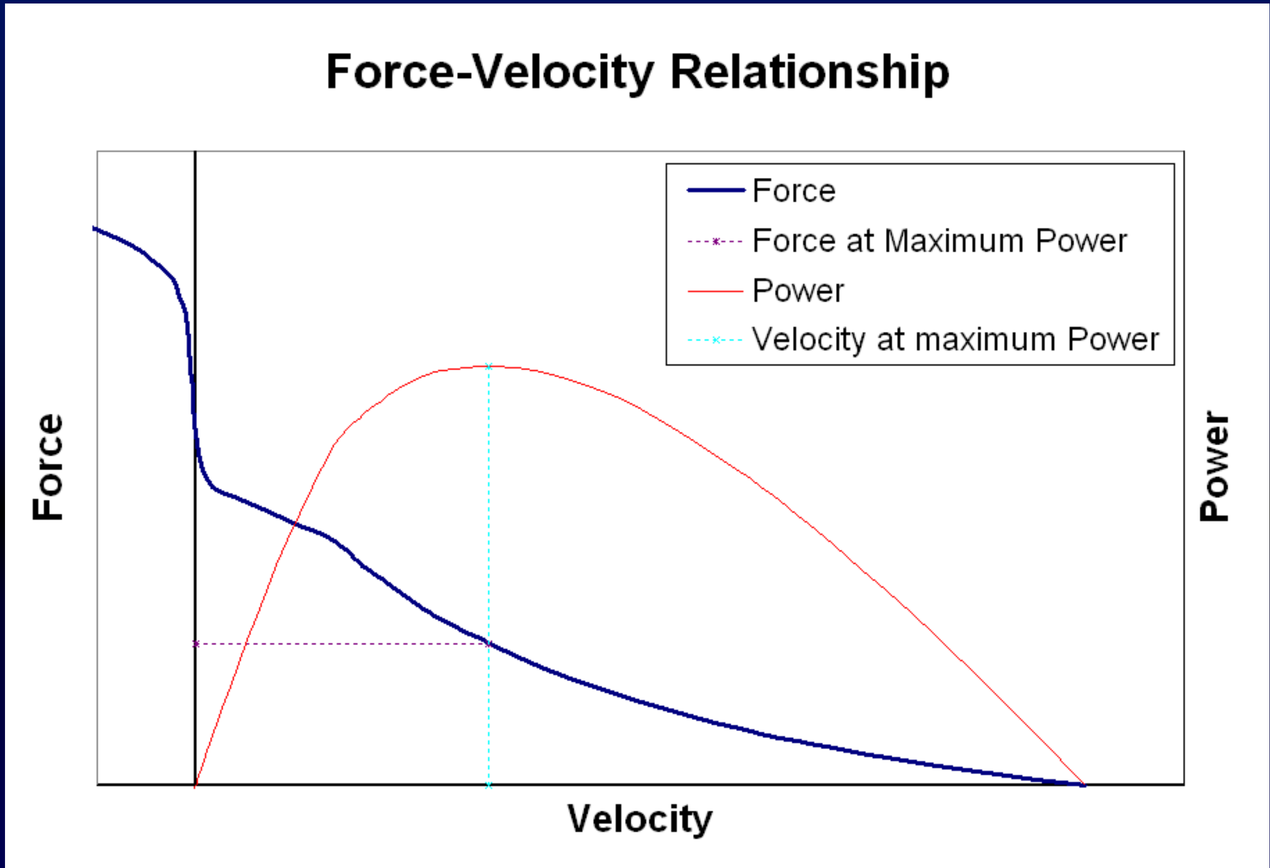

Active
tension
from
muscle
Total tension
muscle + tendon
Force
Passive
tension
from tendon
Length

Force – Velocity Relationship

$(P + a) V = b (Po – P)$



Power

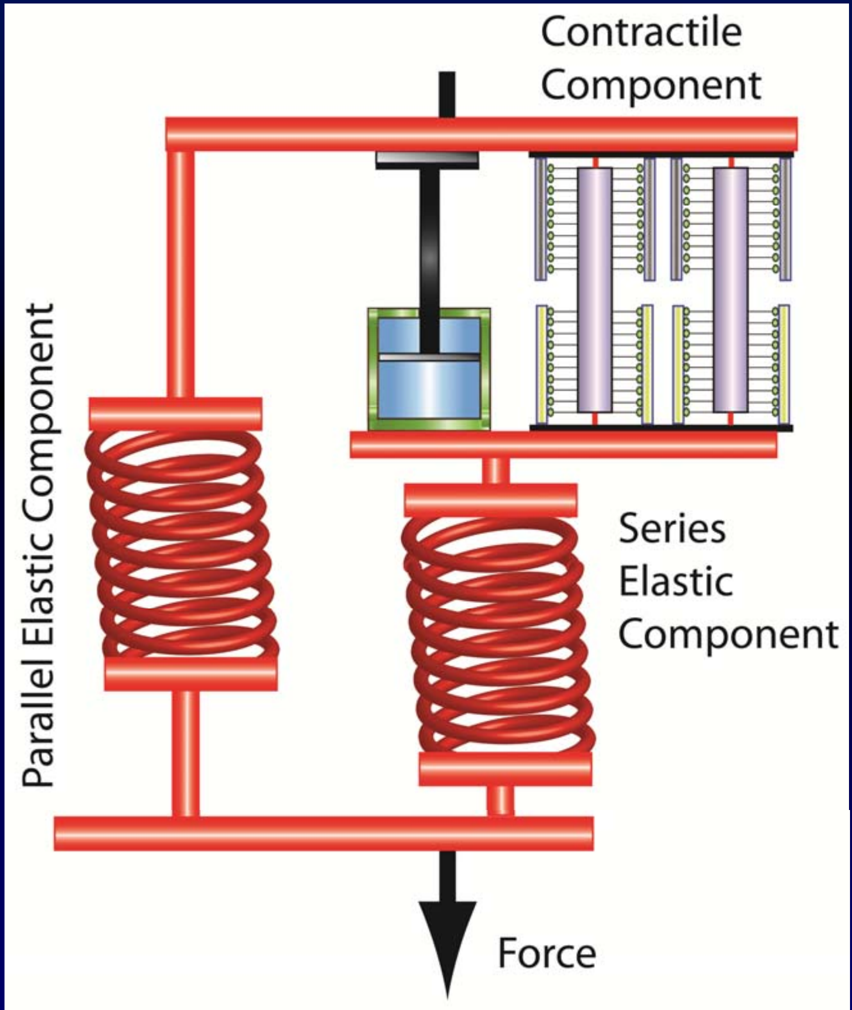


$P = F \times v$

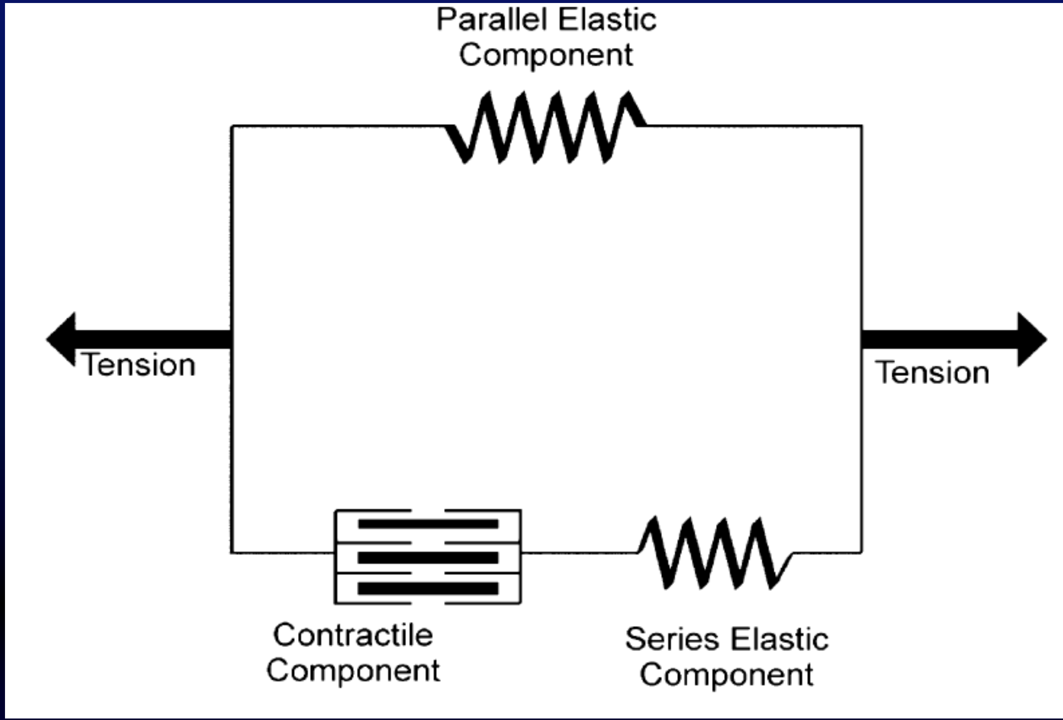
Optimal power is not necessarily the same as maximum power. Athletes must find a power output that is as high as possible AND that they can sustain for the duration of their event.

Three Component Muscle Model

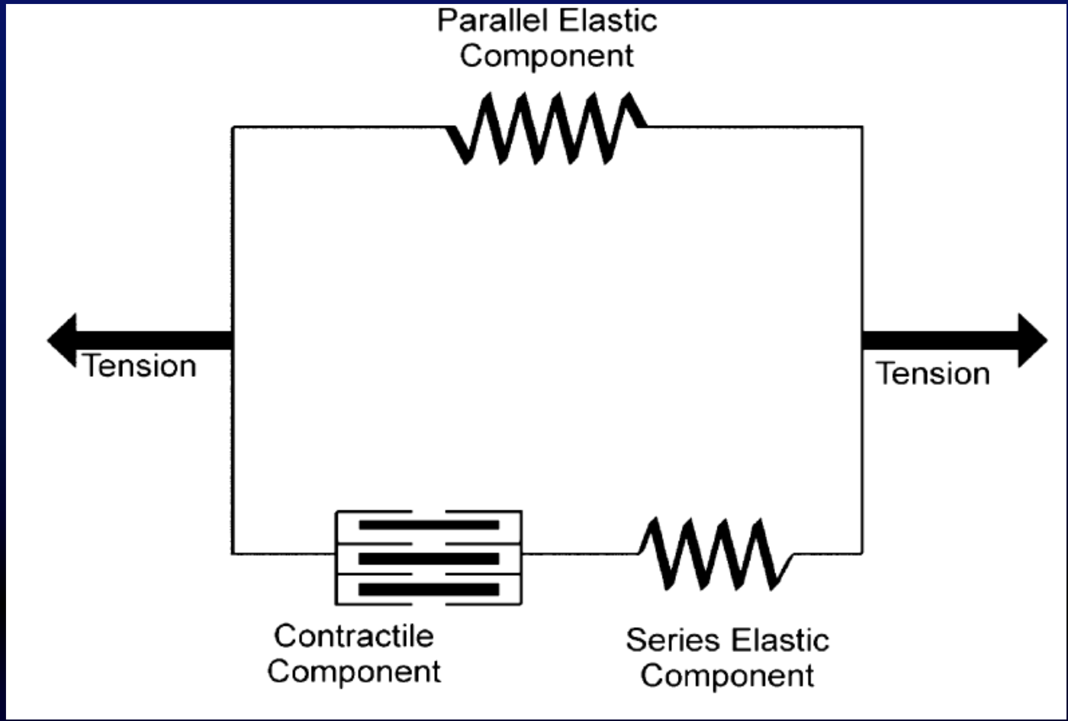
Describes the mechanical response of muscle.



- Contractile Component (CC) models active cross-bridges.
- Dashpot models muscle viscosity.
- Series Elastic Component (SEC) models elastic structures in series (tendon, passive cross-bridges, titin). The SEC explains extra work done in stretch-shorten and EMD.
- Parallel Elastic Component (PEC) models passive elastic structures (passive cross-bridges, connective tissue: endomysium, perimysium, epimysium, titin, desmin.



- The Hill model of muscle describes the active and passive tension created by the MTU. Active tension is modeled by the contractile component, while passive tension is modeled by the series and parallel elastic components.



CE: Contractile Element (active force generation)

SE: Series Elastic Element

  represents elasticity in:

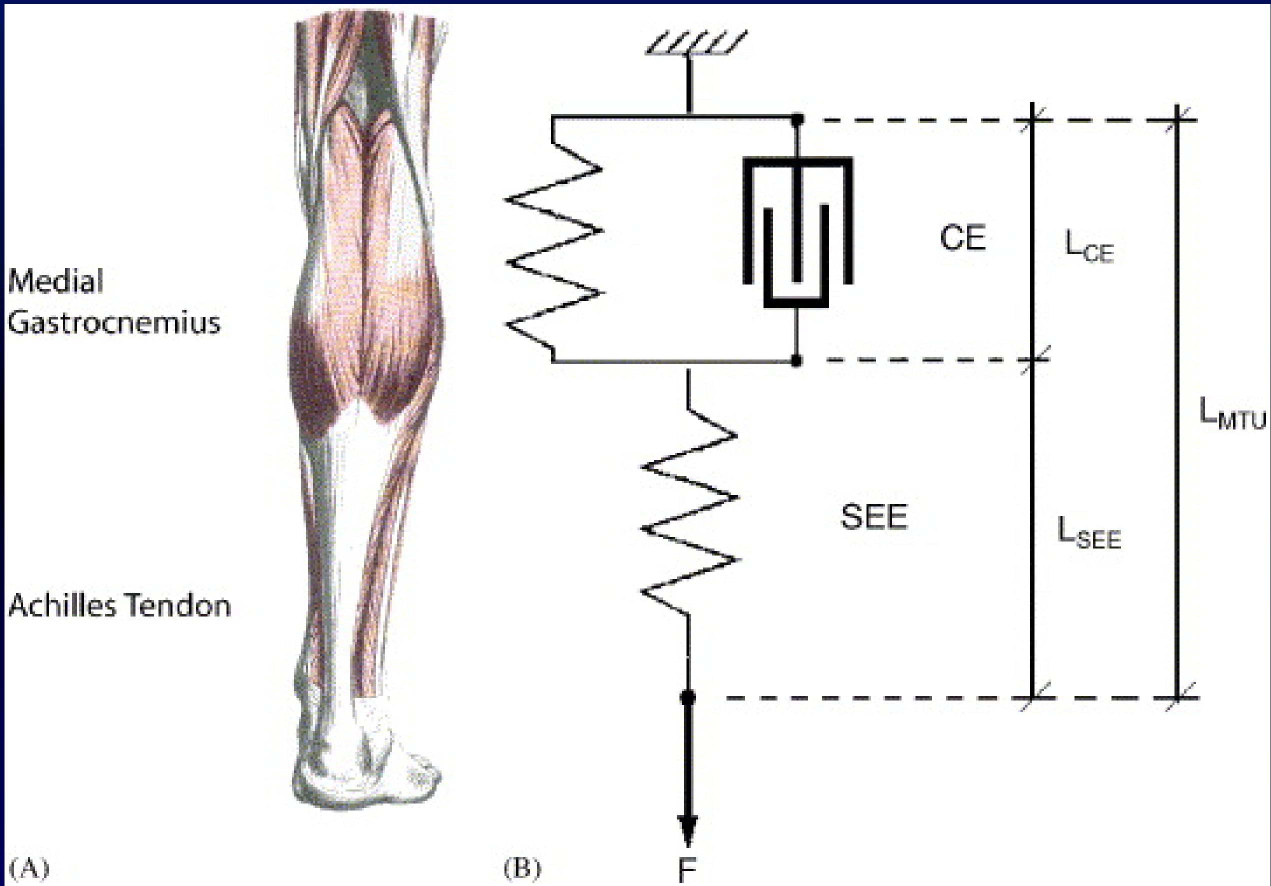
    cross-bridges and myofilaments

    tendon and aponeuroses

PE: Parallel Elastic Element

  connective tissue surrounding muscle fibers

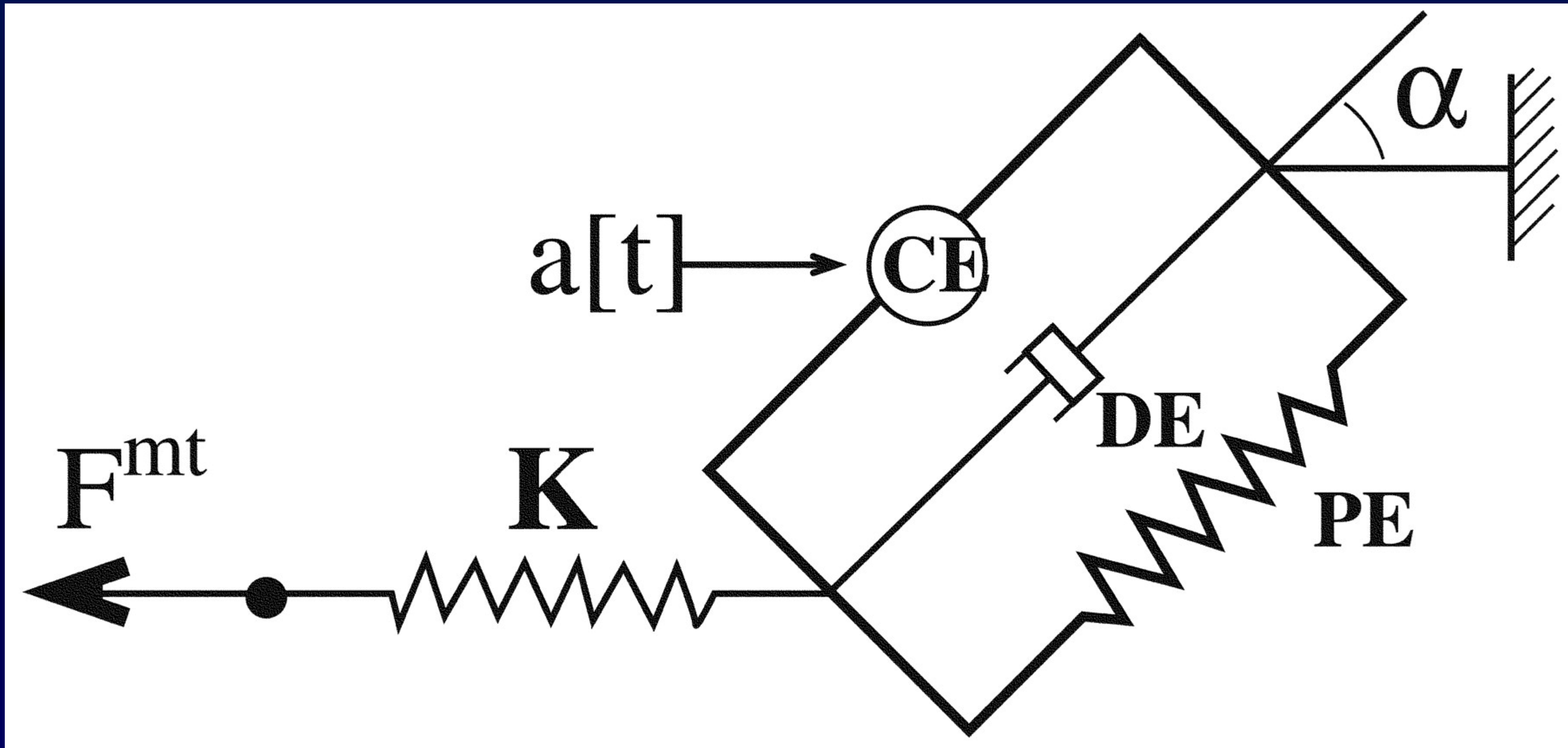
Hill Type Muscle Model



Lichtwarka&Wilsona, J.Bio, 2007.

Three-element muscle model representing the medial gastrocnemius (contractile element—CE) attaching to the Achilles tendon (series elastic element—SEE), with an elastic component in parallel with the CE (parallel elastic element—PEE). Total muscle tendon unit (MTU) length is calculated as the sum of the CE and SEE lengths.

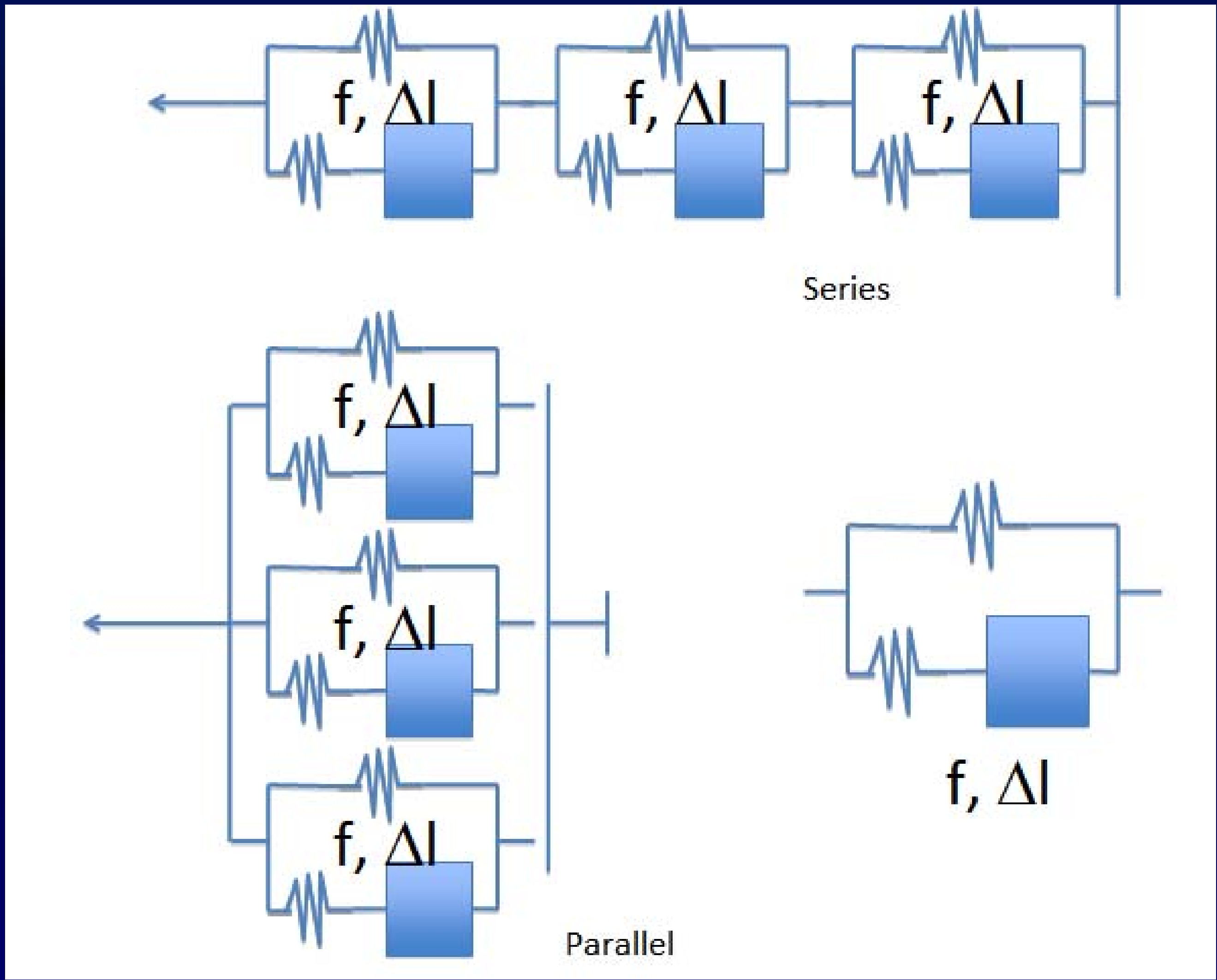
Hill Type Muscle Model



Hill Type Muscle Model

- Can Hill muscle model be used to illustrate effects of muscle length and width on muscle's
  - maximum force
  - maximum shortening velocity

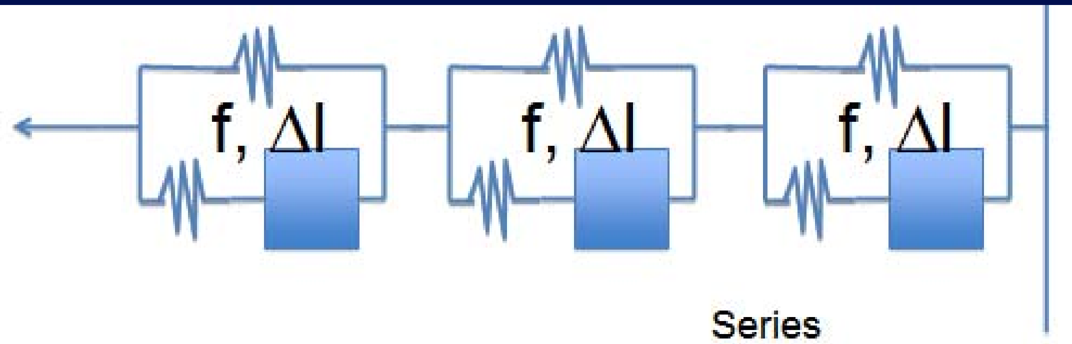
Hill Type Muscle Model



Hill Type Muscle Model

$F=?$

$\Delta L=?$



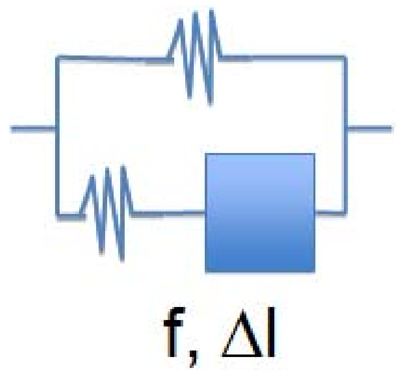
A) $F = f$; $\Delta L = \Delta l$

B) $F = 3f$; $\Delta L = 3\Delta l$

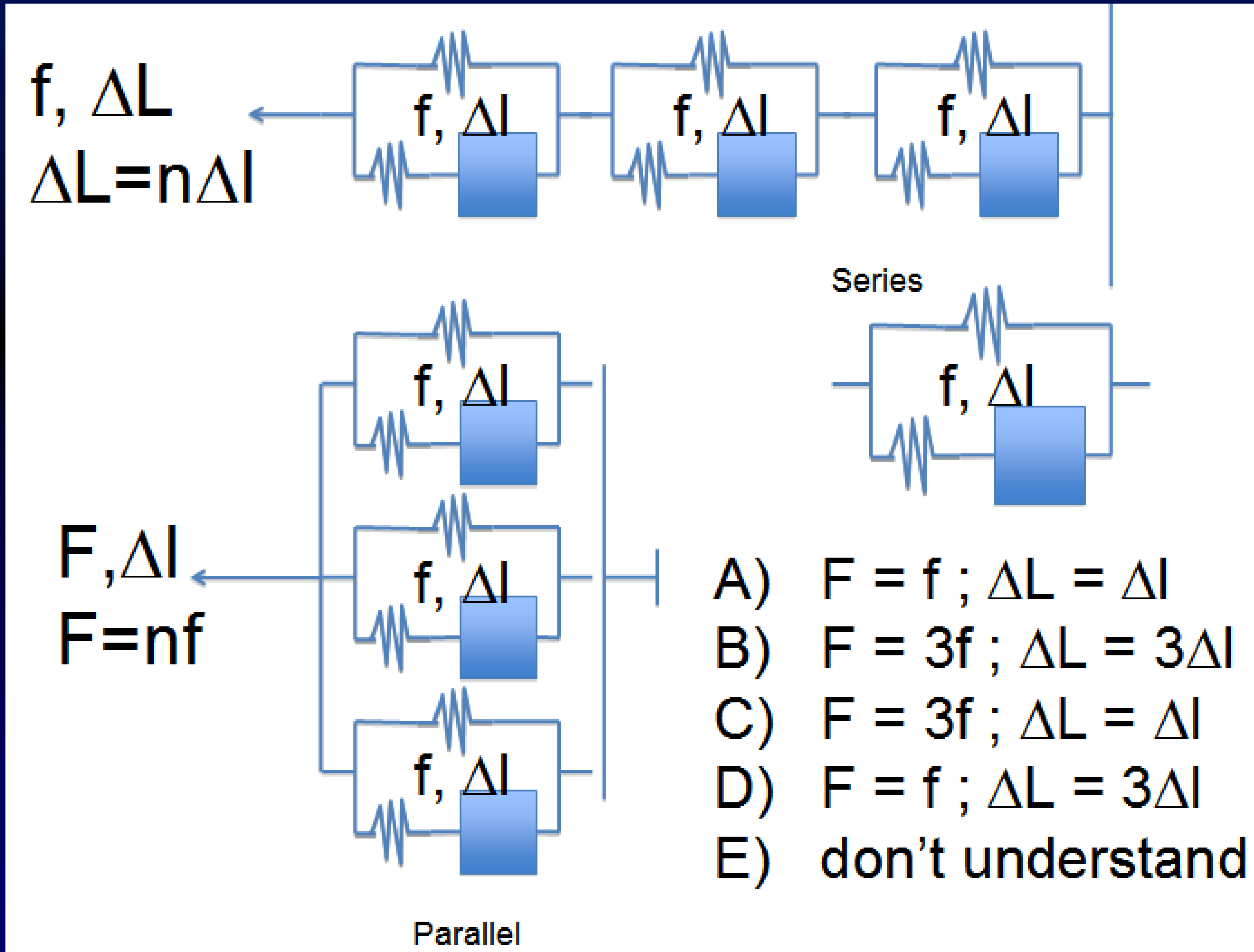
C) $F = 3f$; $\Delta L = \Delta l$

D) $F = f$; $\Delta L = 3\Delta l$

E) don't understand

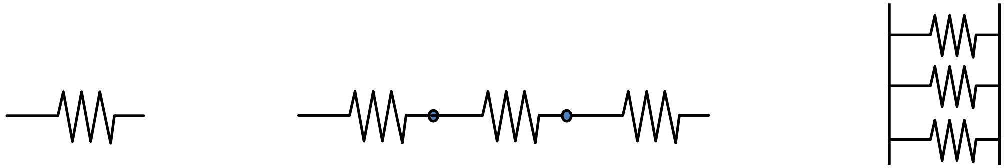


Hill Type Muscle Model

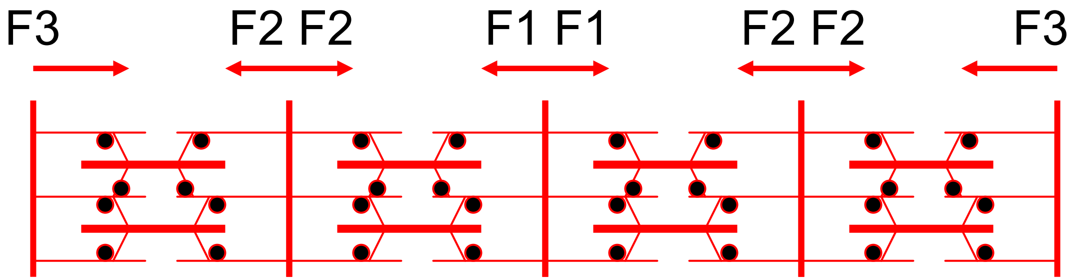


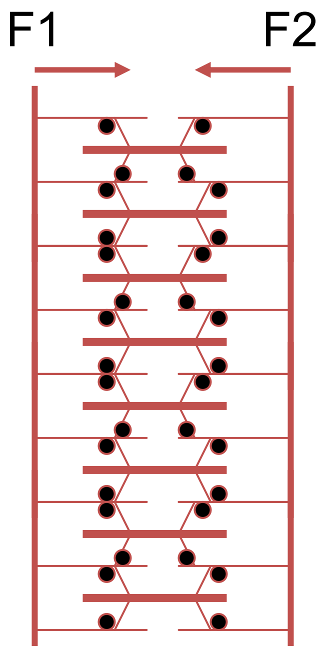
Sarcomere organization example:

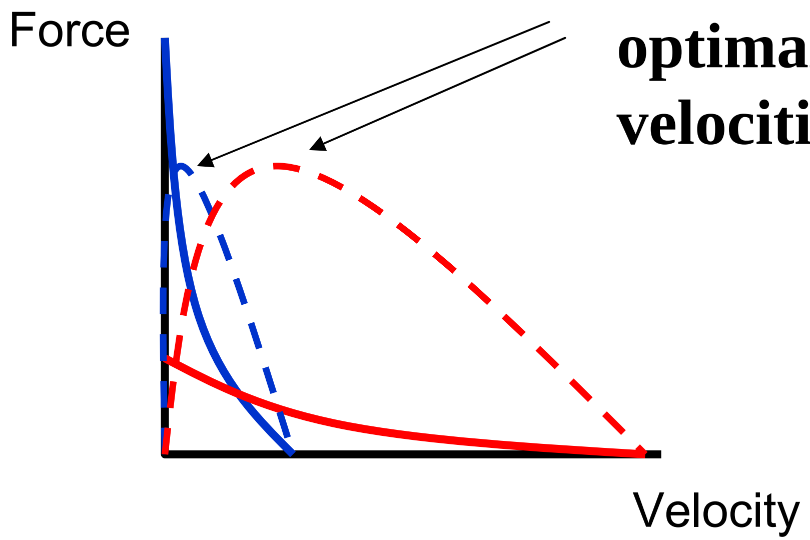
Note that the values are not representative of actual sarcomeres.



	1 sarcomere	3 sarcomeres in series	3 sarcomeres in parallel
Force	1 N	1 N	3 N
Range of motion	1 cm	3 cm	1 cm
Time	1 sec	1 sec	1 sec
Velocity	1 cm/sec	3 cm/sec	1 cm/sec

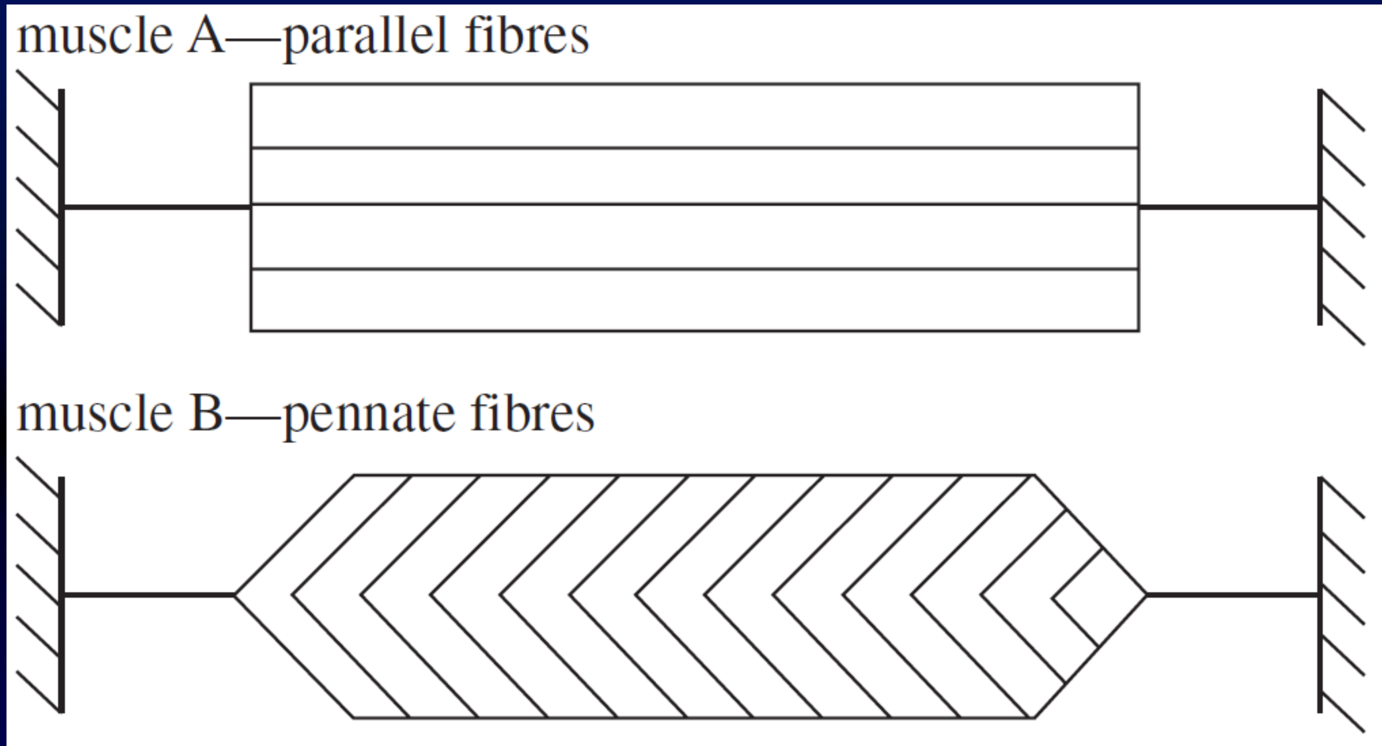




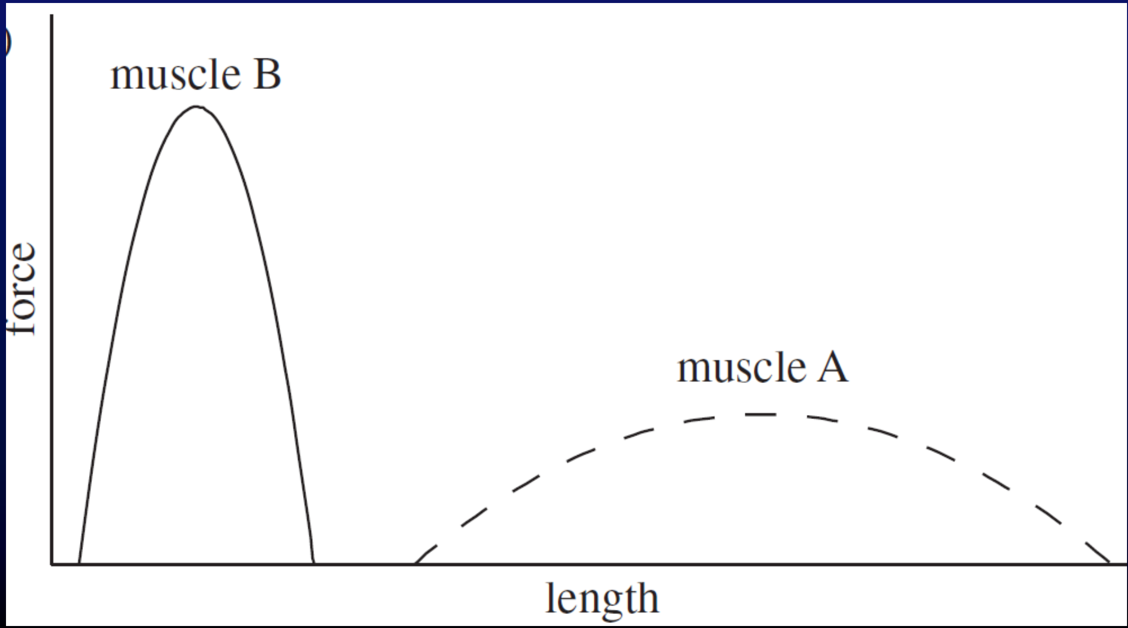


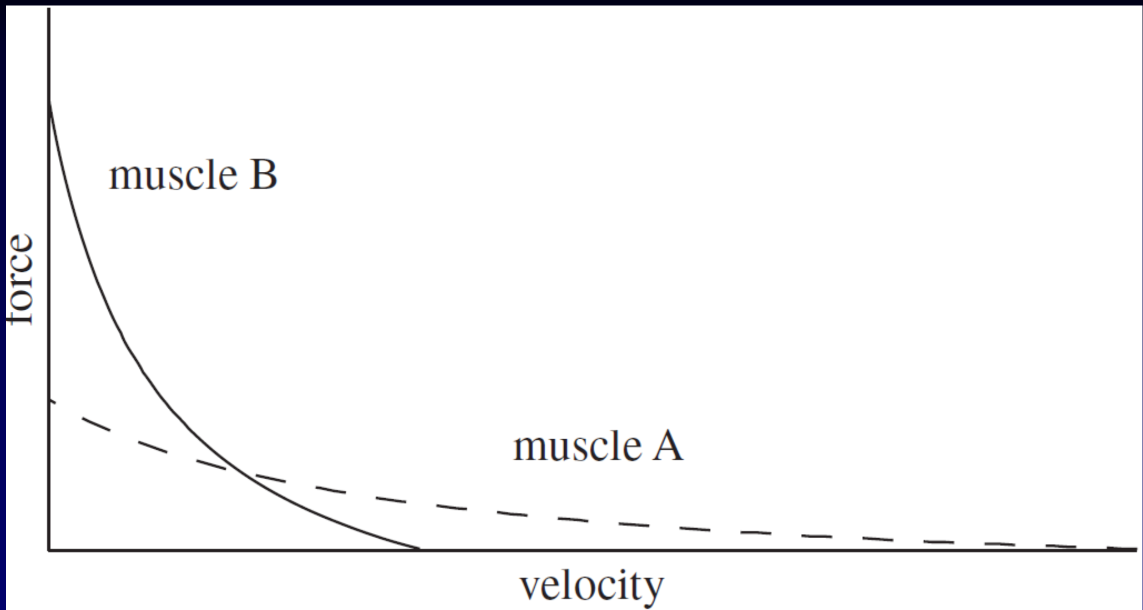
Same power, but different optimal velocities

Pennated vs. Paralel Muscles

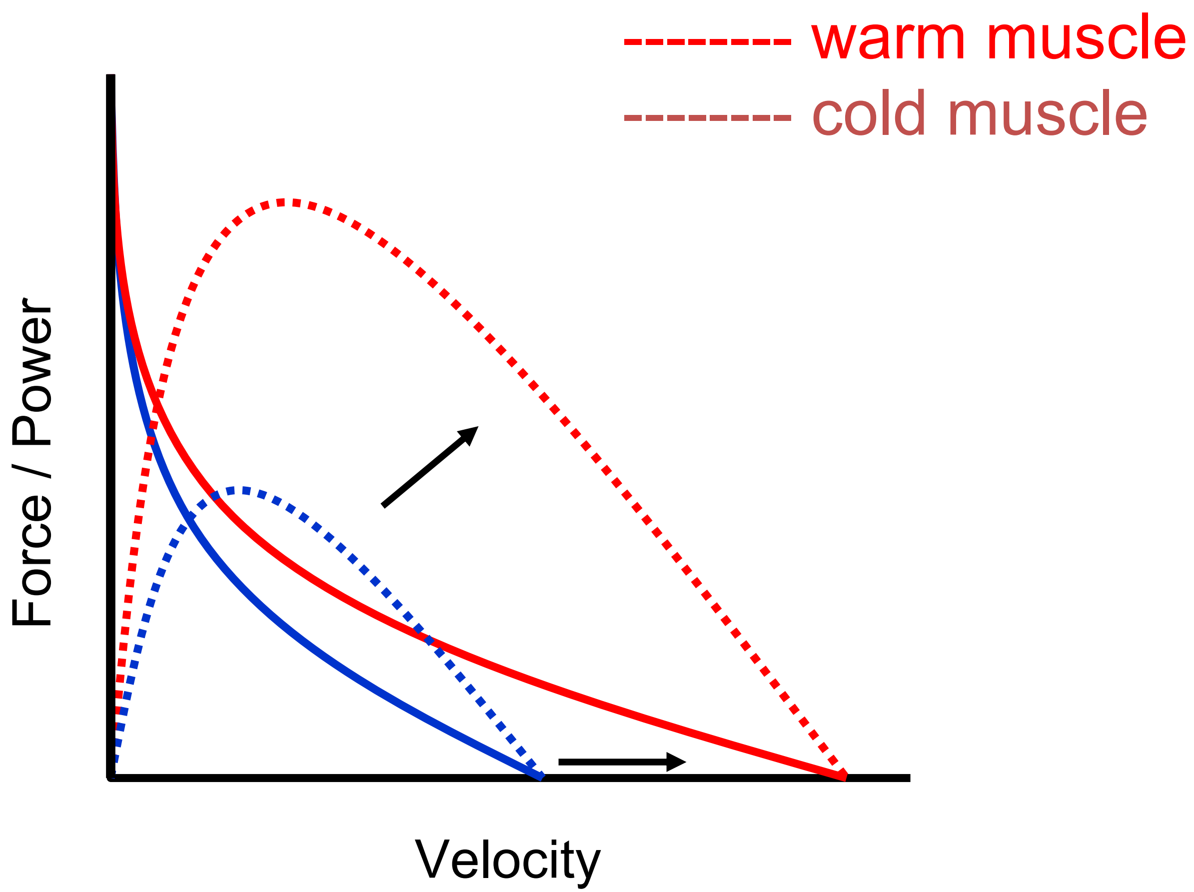


What is the Force&Length relationships for muscle A and B ?


muscle B
force
muscle A
length


muscle B
force
muscle A
velocity

Temperature



Muscle Temperature

Warming up changes muscle behaviour.
Decreased viscosity of blood and increased heart rate enables faster delivery of oxygen.

Increased muscle temperature:

- encourages the dissociation of oxygen from hemoglobin
- facilitates enzyme activity
- decreases muscle viscosity
- provides greater extensibility and elasticity of muscle fibers and connective tissue
- increases force and speed of contraction

Adaptations to Resistance Training

- **Hyperplasia** is the growth of an organ due to an increase in the number of cells.
- The breast tissue undergoes hyperplasia in a lactating mother.
- The tonsils grow by hyperplasia to enhance the immune response in a child with a throat infection.
- As it relates to skeletal muscle, hyperplasia defines muscle growth due to an increase in the number of muscle fibers.

Adaptations to Resistance Training

- In contrast, **hypertrophy** (opposite is atrophy) defines an increase in the size of existing cells or fibers rather than an increased number of cells.

Adaptations to Resistance Training

- How do muscles get bigger ?
- Do muscles get bigger due to an increase in existing fibre size or an increase in the number of fibres?

- While fibre hypertrophy is well accepted and documented, very few studies have measured fibre hyperplasia in humans.
- Studies on animals have shown conflicting results.
- There is no strong research evidence showing hyperplasia can occur in adult humans.

- *For details refer to http://www.sport-fitness-advisor.com/hyperplasia.html*

Factors influencing the production of muscle force

- muscle cross-sectional area
- muscle activation level
- muscle length (sarcomere length, stored elastic energy)
- velocity of shortening
- activation history
- muscle temperature
- electromechanical delay
- muscle fibre type
- angle of pennation
- History-Dependent Properties of Skeletal Muscle

HISTORY DEPENDENCE OF MUSCLE CONTRACTION
Force depression after shortening

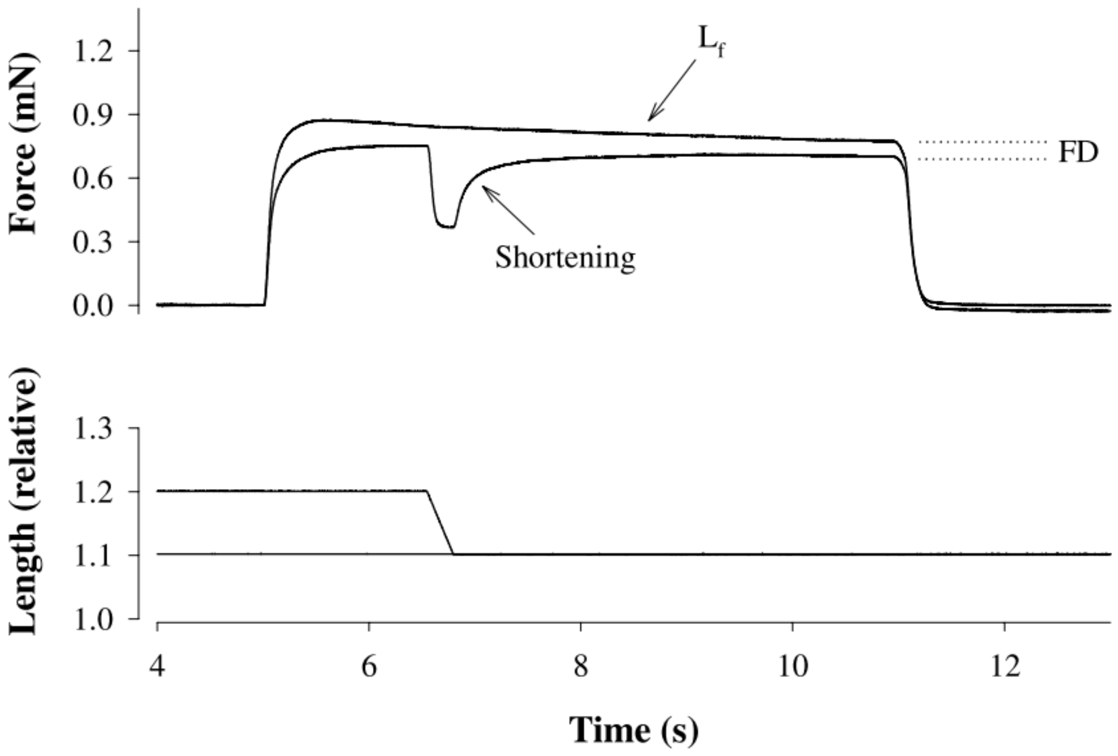


Fig. 1. Force depression (FD) after shortening of a single fiber from the lumbrical muscle of frog. In the length traces, 1.0 corresponds to the optimal length for force production (L_o). Starting from a length of 20% greater than L_o, the fiber was shortened by 10% fiber length along the descending limb of the force-length relationship, at a speed of 40% fiber length/s. An isometric reference contraction performed at the corresponding final length (L_f) is also shown.

HISTORY DEPENDENCE OF MUSCLE CONTRACTION
Force enhancement after stretching

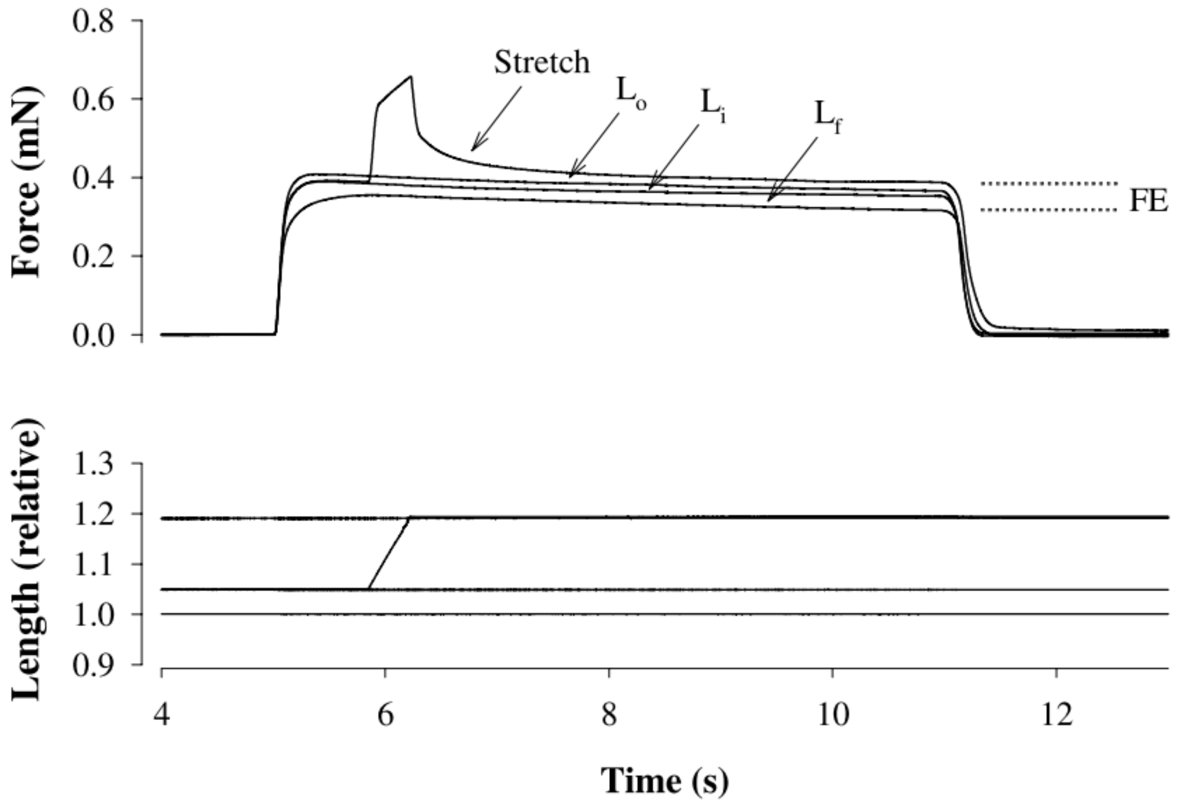
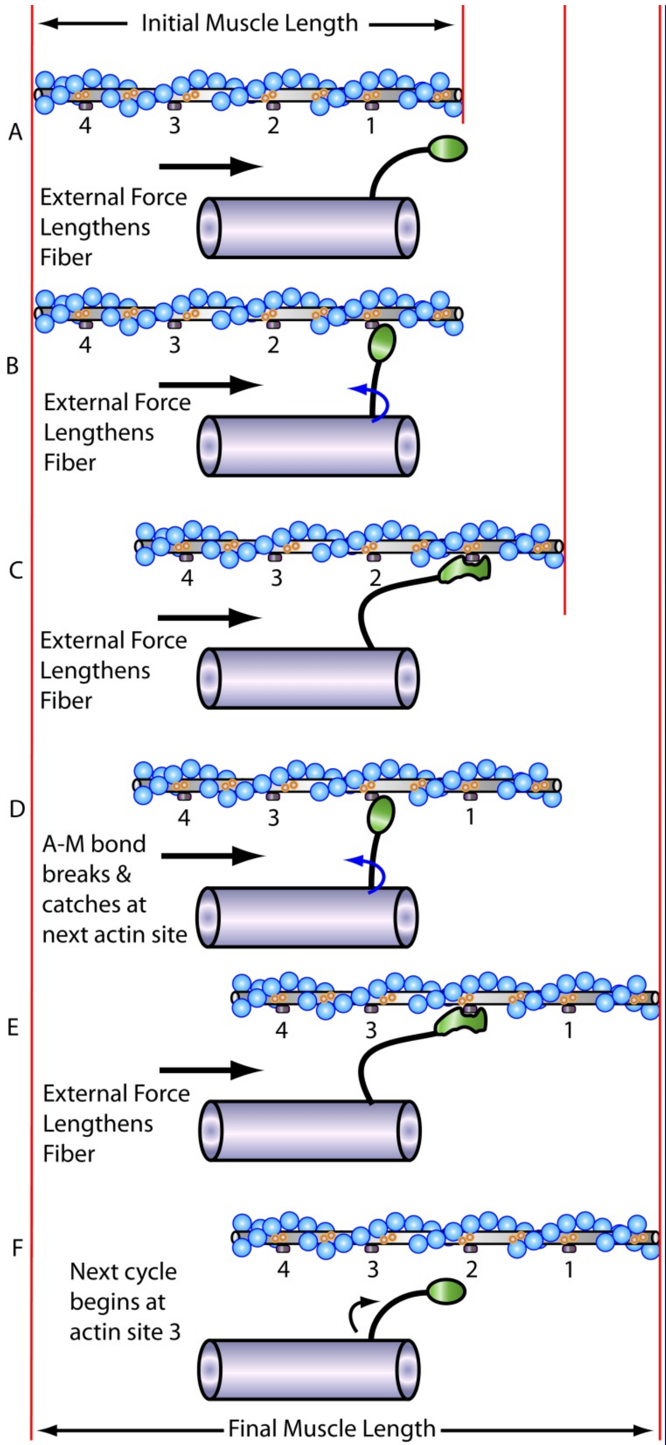


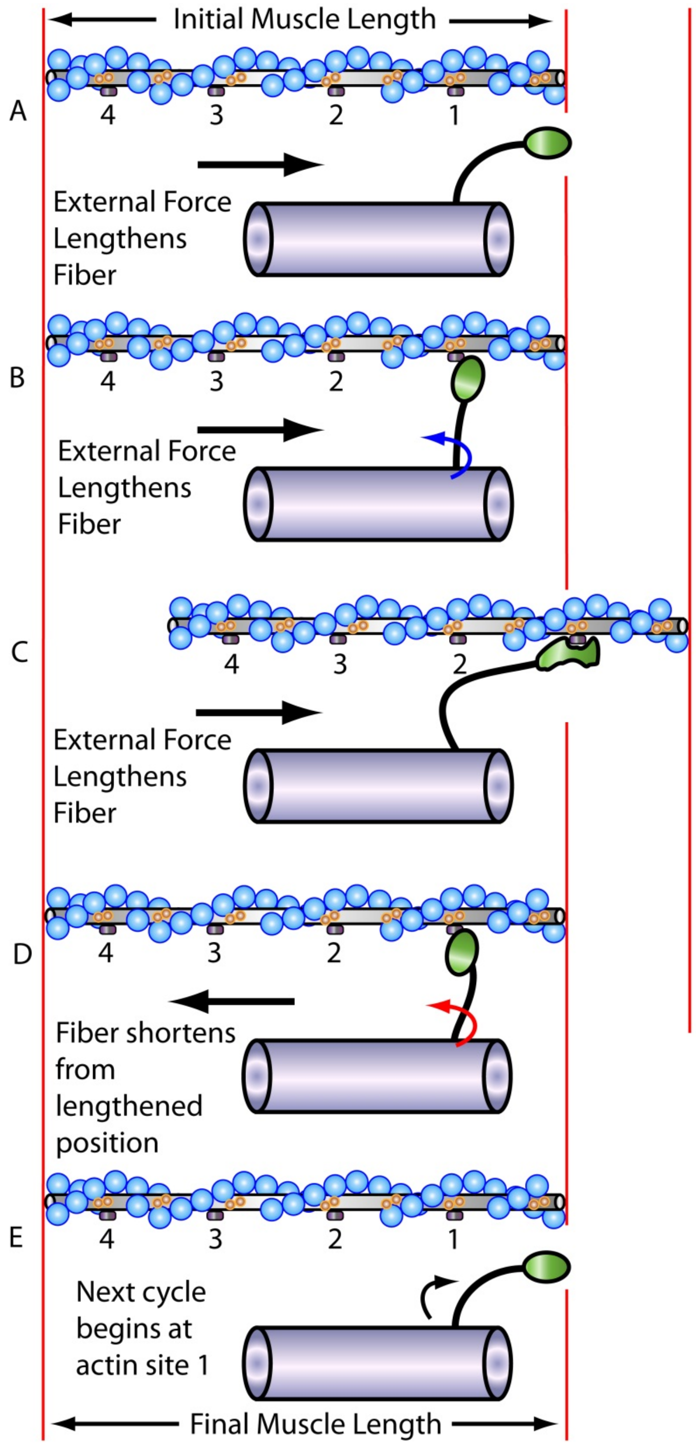
Fig. 4. Force enhancement (FE) after stretch of a single muscle fiber isolated from the lumbrical muscle of frog. In the length traces, 1.0 corresponds to L_o. Starting at a length of 5% greater than L_o, the fiber was stretched by 15% of the fiber length along the descending limb of the force-length relationship, at a speed of 40% fiber length/s. Isometric contractions, performed at L_o and at the corresponding initial length (L_i) and L_f, are also shown.

Appendix



Eccentric Cross-bridge Cycle

- Ca^{++} released from SR
- Ca^{++} binds with troponin
- Tropomyosin moves away from binding site.
- An Actin-Myosin cross-bridge is formed.
- ATP downgraded to ADP + Pi.
- Myosin attempts to rotate and shorten fiber.
- External force causes the fiber to lengthen, storing elastic energy in myosin arm.
- The cross-bridge is broken (1-4 pN) while it is still in the actively charged state, it immediately forms another cross-bridge at the next available Actin site without the need for any additional ATP.
- This “break & make” cross-bridges will continue until the length of the active state is exceeded.



Isometric Cross-bridge Cycle

- Ca^{++} released from SR
- Ca^{++} binds with troponin
- Tropomyosin moves away from binding site.
- An Actin-Myosin cross-bridge is formed.
- ATP downgraded to ADP + Pi.
- Myosin attempts to rotate and shorten fiber.
- External force causes the fiber to lengthen, storing elastic energy in myosin arm.
- From this lengthened position the myosin arm rotates and shortens the fiber.