MUSCLE PHYSIOLOGY

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Outlines

1. Background
2. Skeletal Muscle
    - Architecture & Structure
    - Sliding Filament Model of M. Contraction
    - Process of Skeletal M. Contraction
    - Mechanics of Skeletal M. Contraction
    - Energetics of Skeletal M. Contraction
3. Smooth Muscle
    - Structural Characteristics
    - Smooth Muscle Contraction
    - Classification of Smooth Muscle
4. Cardiac Muscle

Characteristics & Functions of Muscle

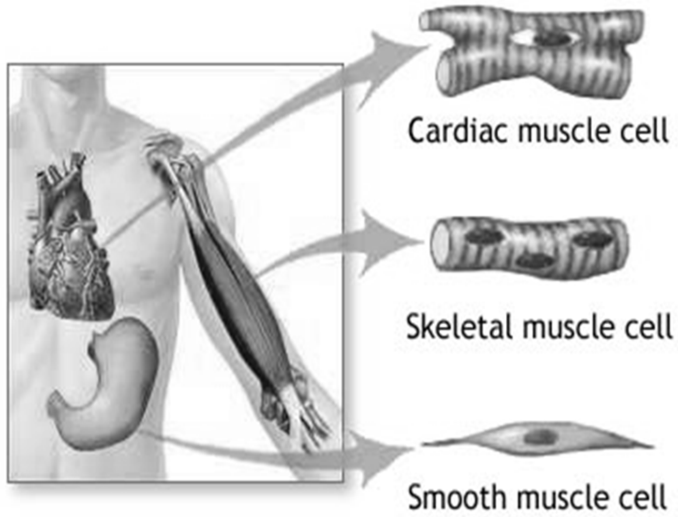
- **Characteristics**
  - Excitability: ability to receive and respond to stimuli
  - Contractility: ability to shorten and thicken
  - Extensibility: ability to be stretched (extended)
  - Elasticity: ability to return to original shape after contraction or extension

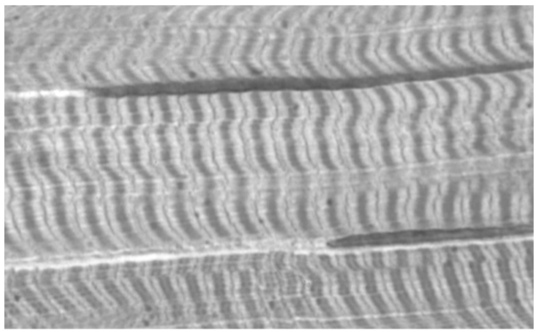
Characteristics & Functions of Muscle

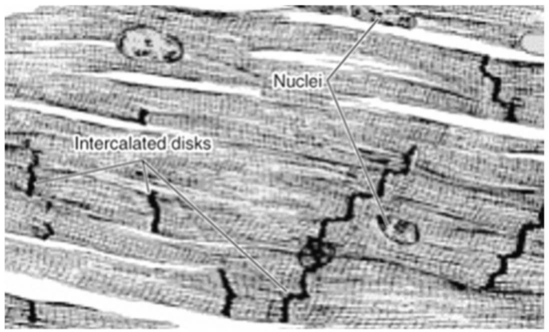
- **Functions**
  - Motion
    - Obvious: whole body walking, or grabbing
    - Less obvious: heart, stomach, intestines, urinary bladder
  - Maintenance of posture: muscle tone
  - Stabilization of joints
  - Heat production: 85% of all body heat is generated by muscles

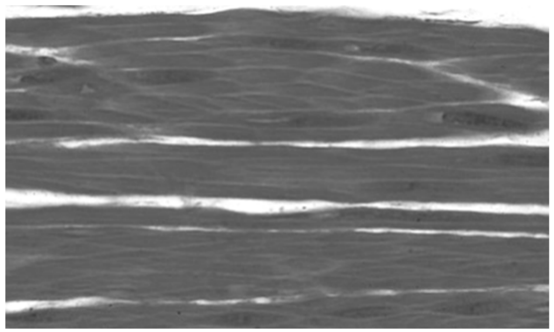
Morphological Classification of Muscle

- Striated m.
  - Voluntary m.: Skeletal m.
    - White m.
    - Red m.
  - Involuntary m.: Cardiac m.
- Smooth m.
  - Involuntary m.:
    - Single unit smooth m.
    - Multiunit smooth m.









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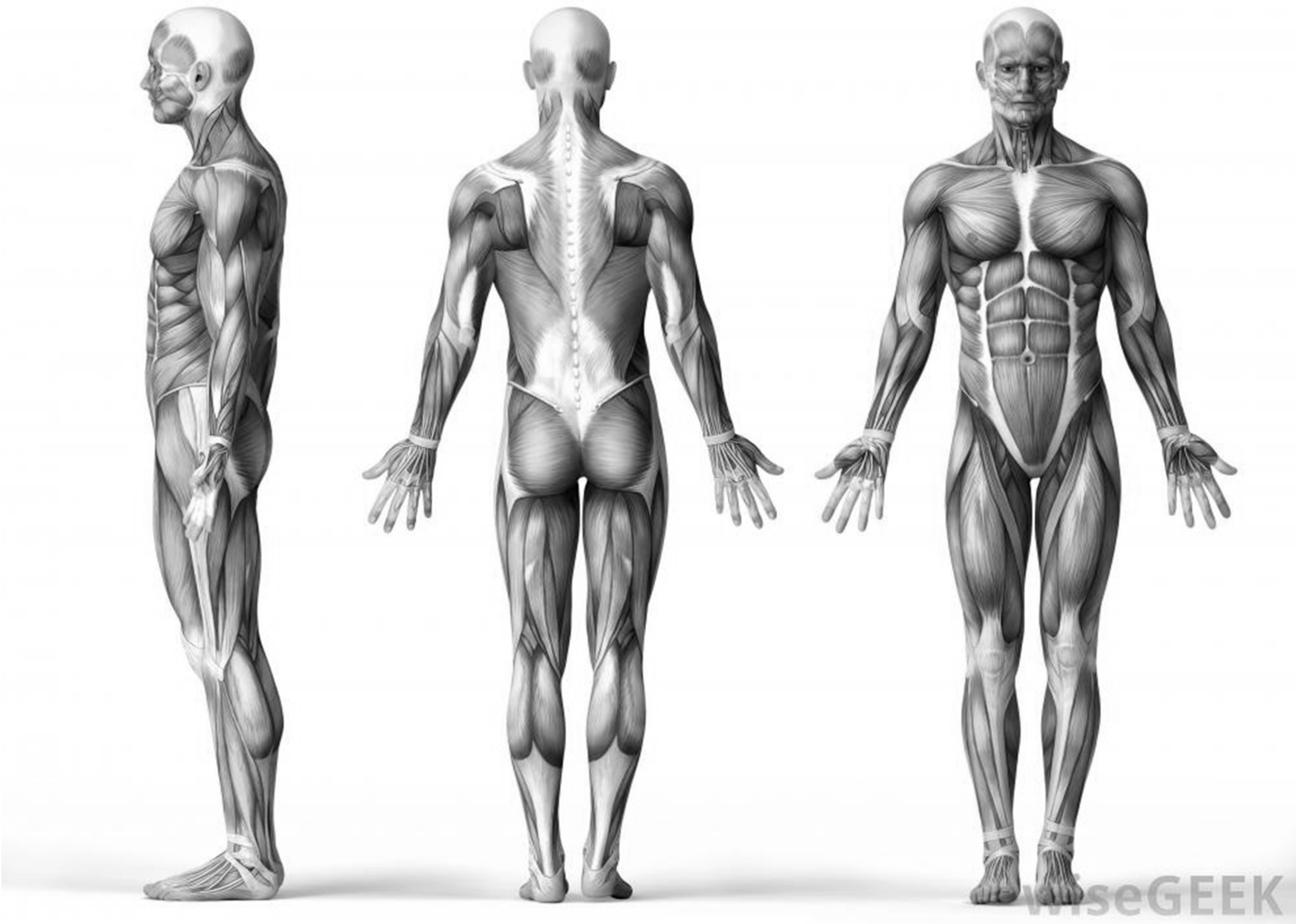

Skeletal Muscle Action

- A skeletal muscle connects two bones. When a muscle contracts, it shortens. (Ligament（韌帶）: connects two bones directly)
  - This places tension on tendons（肌腱）connecting it to a bone
  - This moves the bone at a joint
  - The bone that moves is attached at the muscle insertion
  - The bone that does not move is attached at the muscle origin.

Category	Action
Extensor	Increases the angle at a joint
Flexor	Decreases the angle at a joint
Abductor	Moves limb away from the midline of the body
Adductor	Moves limb toward the midline of the body
Levator	Moves insertion upward
Depressor	Moves insertion downward
Rotator	Rotates a bone along its axis
Sphincter	Constricts an opening

The main muscles responsible for movement
→ in the same direction are the agonists（協同肌）
→ in an opposite direction are the antagonists（拮抗肌）

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Quiz_1

Are skeletal muscles an organ?

(A) Yes

(B) No

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Quiz_2

Are muscle fibers connective tissues?

(A) Yes

(B) No

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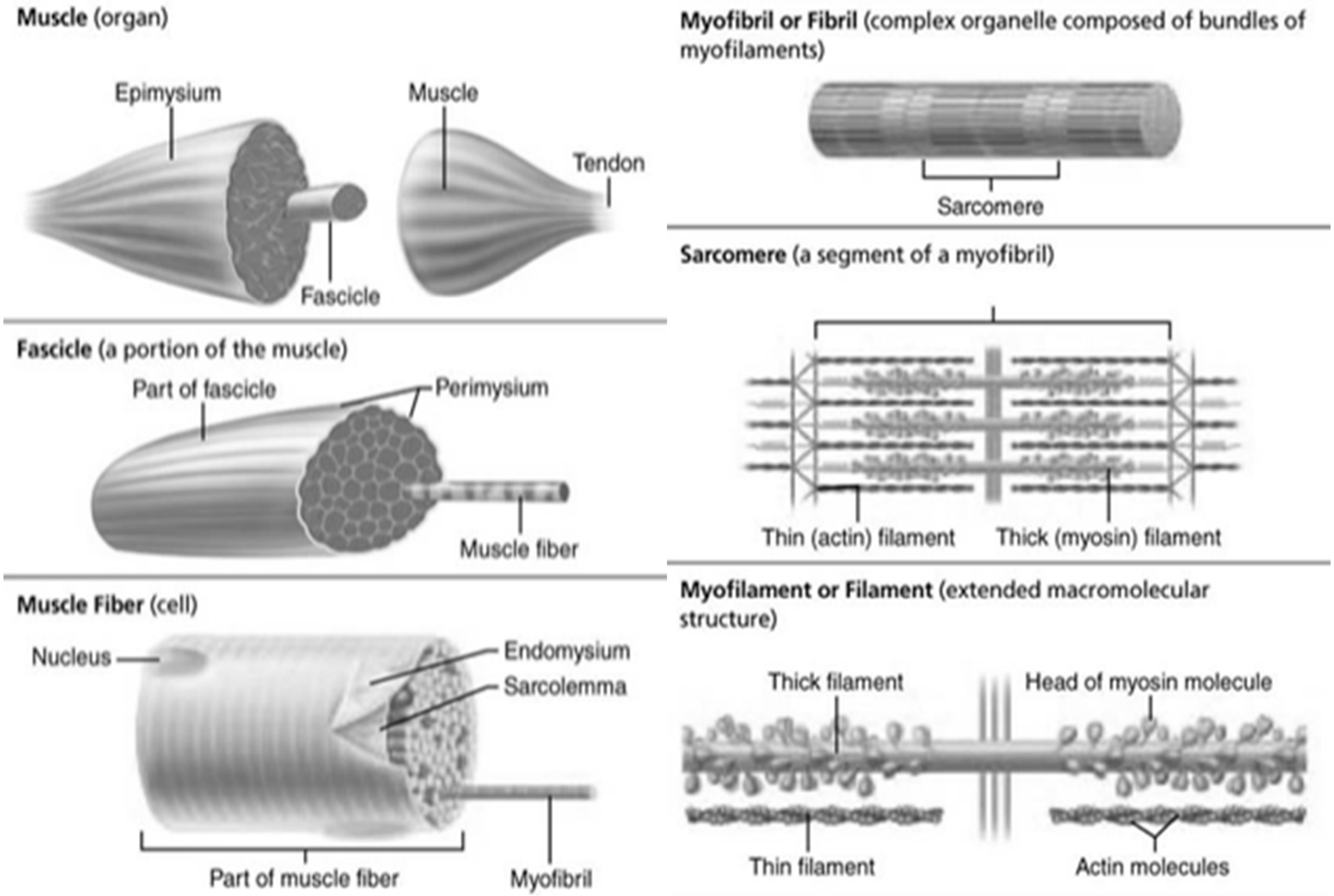
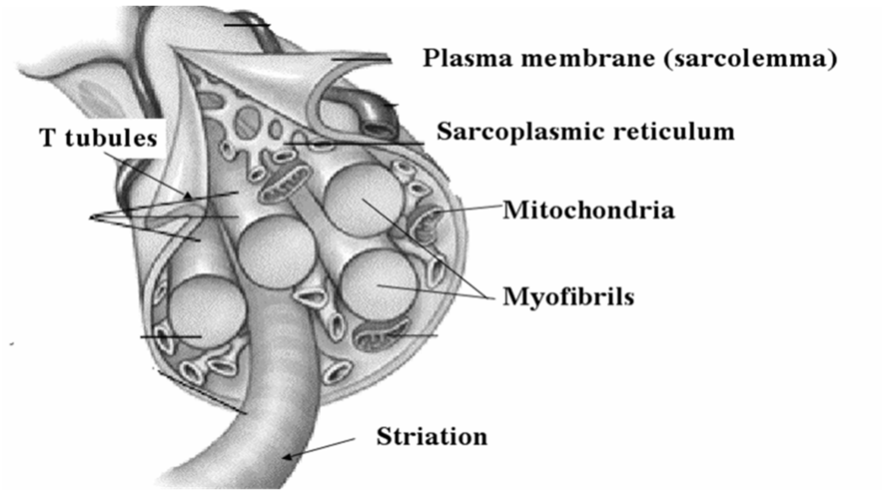
Architecture of Skeletal Muscle



Structure of Skeletal Myofiber$_1$

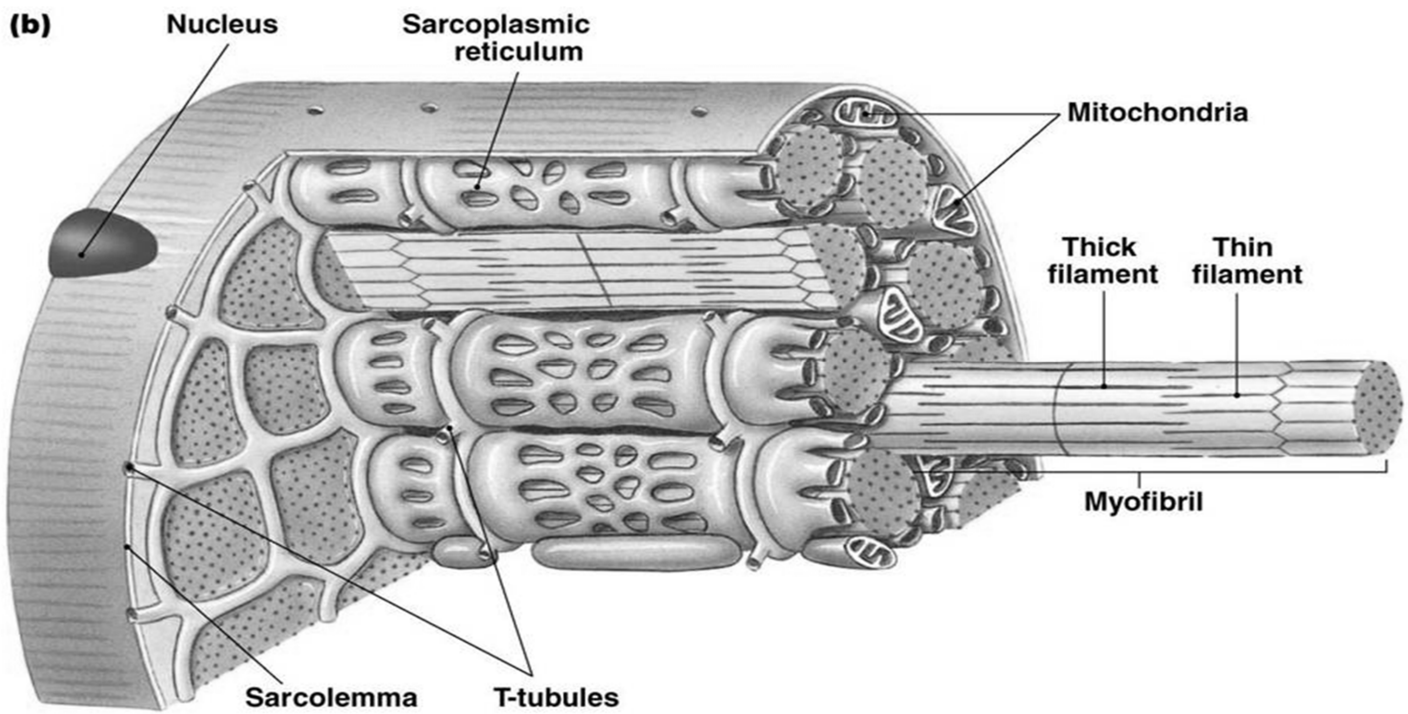
Myofiber (myocyte): a muscle cell surrounded by endomysium

- Myofibril: muscle filaments (thick & thin filaments) in the muscle cell
- Sarcolemma: the plasma membrane of a muscle cell
  - Endomysium: a connective tissue that bounds around the sarcolemma
- Sarcoplasm: the cytoplasm of the muscle cell
- Sarcoplasmic reticulum: the endoplasmic reticulum of a muscle cell



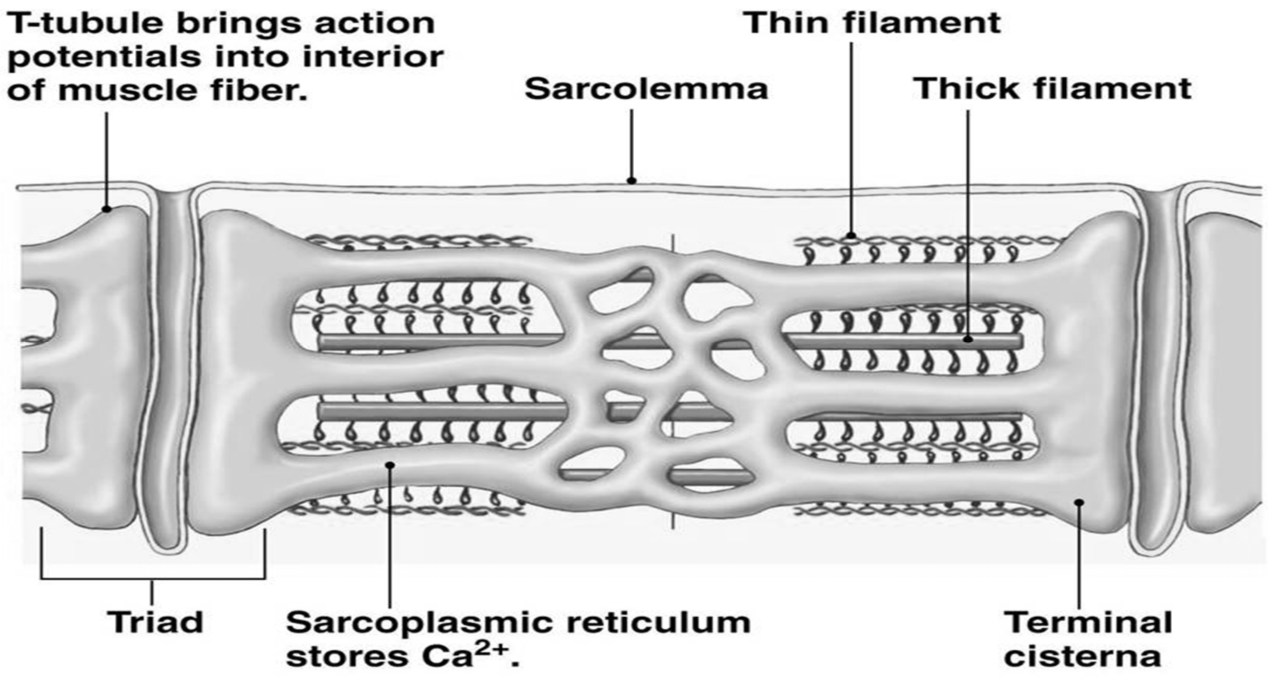
Structure of Skeletal Myofiber$_2$

- T tubule (Transverse tube, 橫管): run perpendicular to and extend from reticulum to outside
  - Have same properties as sarcolemma
  - Transmit action potential through cell
  - Allow entire muscle fiber to contract simultaneously



Structure of Skeletal Myofiber$_3$

- Cisterna（池）
  - Concentrate Ca^{2+} (*via* ion pumps)
  - Release Ca^{2+} into sarcomeres to begin m. contraction
- Triad: formed by 1 T tubule & 2 terminal cisternae
  - A transverse tubule and segments of sarcoplasmic reticulum on either side



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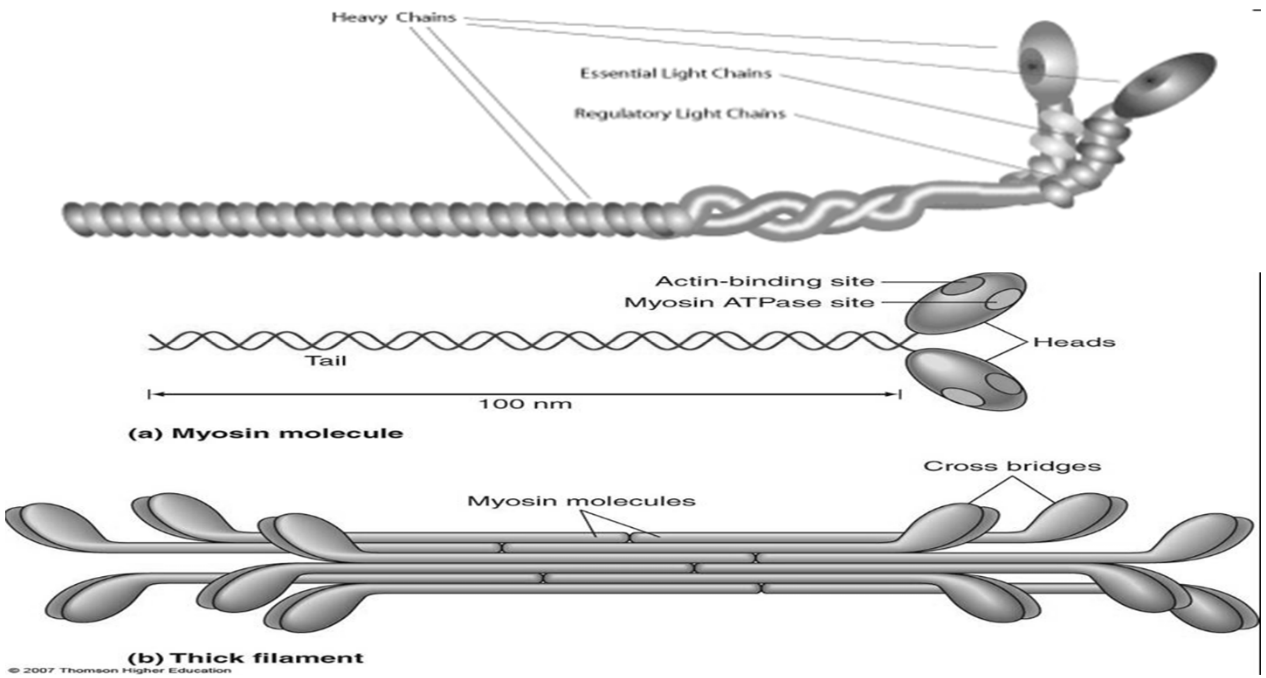
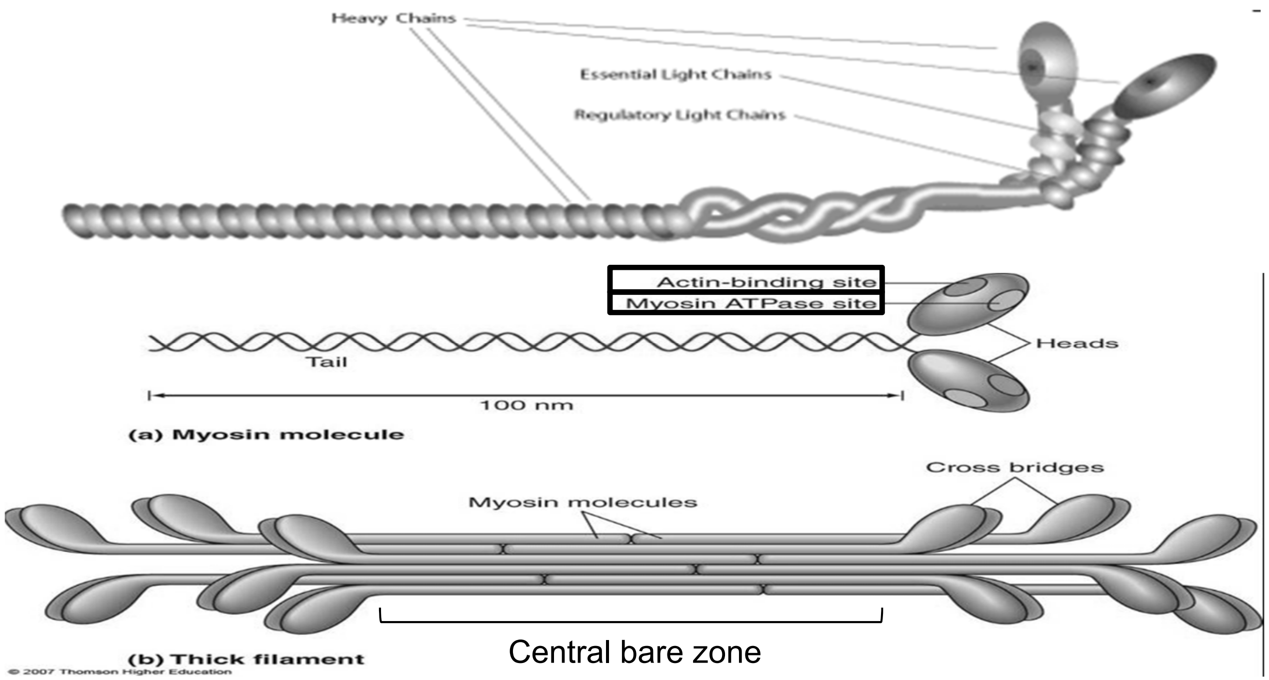
Thick Filament$_1$

- The thick filament system is composed of myosin protein
  - 6 polypeptides: 2 heavy chains, 4 light chains
  - Myosin heavy chains
    - Tail: binds to other myosin molecules
    - Head (crossbridge): made of 2 globular protein subunits & reaches the nearest thin filament



Thick Filament$_2$

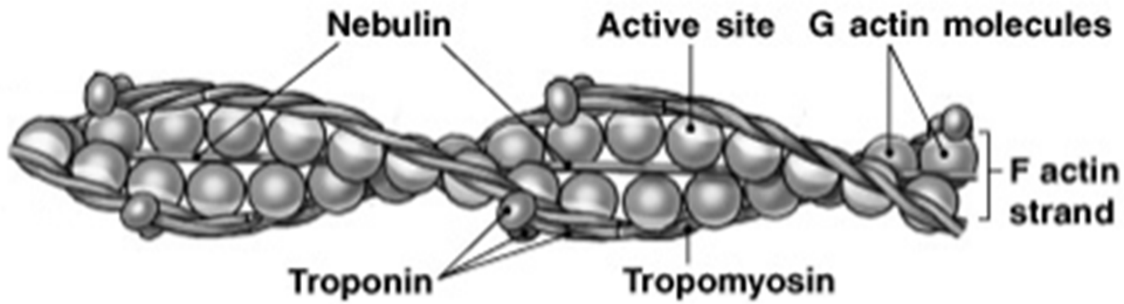
- Myosin heavy chains
  - Head (crossbridge):
    - Actin-binding site
    - Myosin ATPase site: molecular motors
      - Use ATP as a source of energy and convert ATP hydrolysis into a physical force
  - Tail: central bare zone



Thin Filament$_1$

Thin filaments contain 4 proteins: actin (肌動蛋白), nebulin, tropomyosin (原肌凝蛋白), & troponin (肌鈣蛋白)

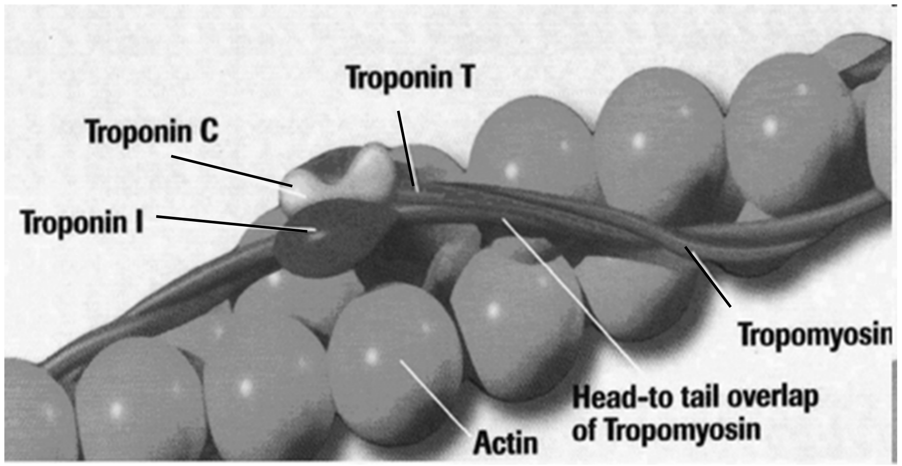
- Actin:
  - Globular actin (G-actin): individual subunits of actin
  - F-actin: G-actin subunits assemble into long filamentous polymers
- Nebulin - holds F actin strands together
- Tropomyosin: a dimer which coils itself around the F-actin of the thin filament



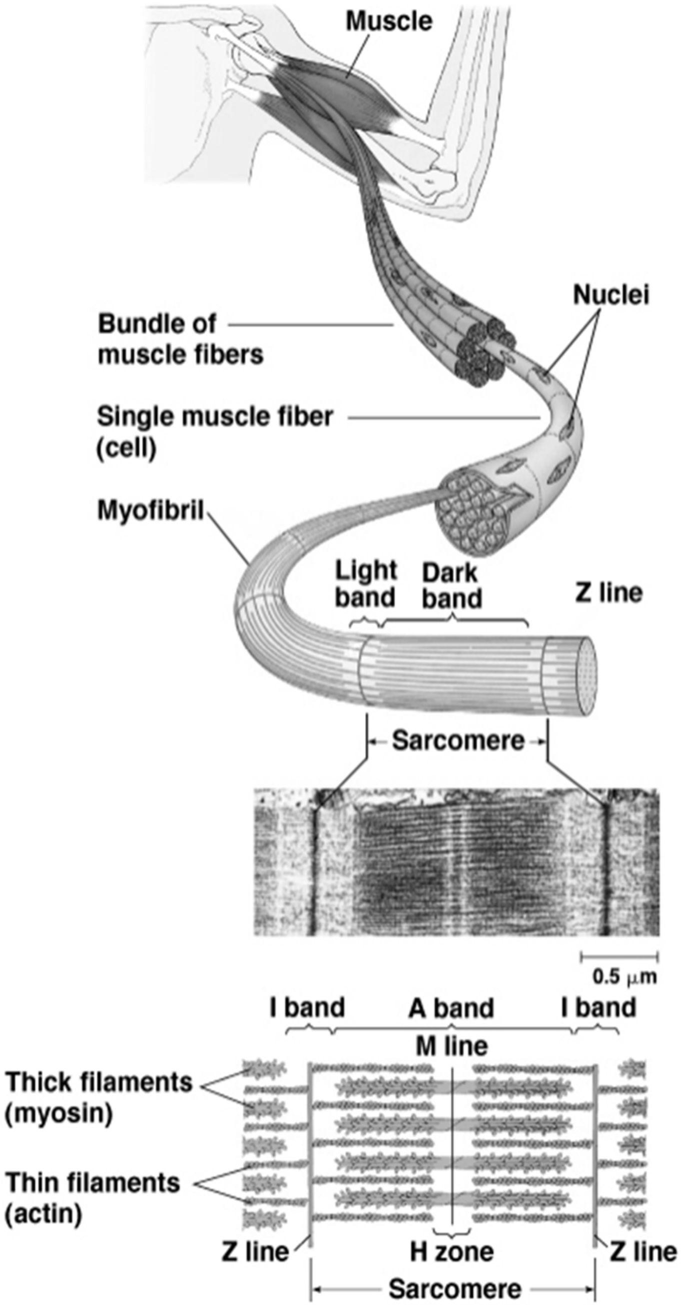
(b) Thin filament

Thin Filament$_2$

- Troponin: a complex of 3 proteins (TnC, TnI, and TnT) that is integral to m. contraction in skeletal and cardiac muscle, but NOT in smooth muscle
  - Troponin C (TnC, calcium) binds to Ca^{2+} to produce a conformational change in TnI
  - Troponin I (TnI, inhibition) binds to actin in thin filaments to hold the troponin-tropomyosin complex in place
  - Troponin T (TnT, tropomyosin) binds to tropomyosin, interlocking them to form a troponin-tropomyosin complex



Acute myocardial infarction (AMI) → Hypoxia → cell death → cardiac TnI or TnT released in blood



Structure of Sarcomere$_1$

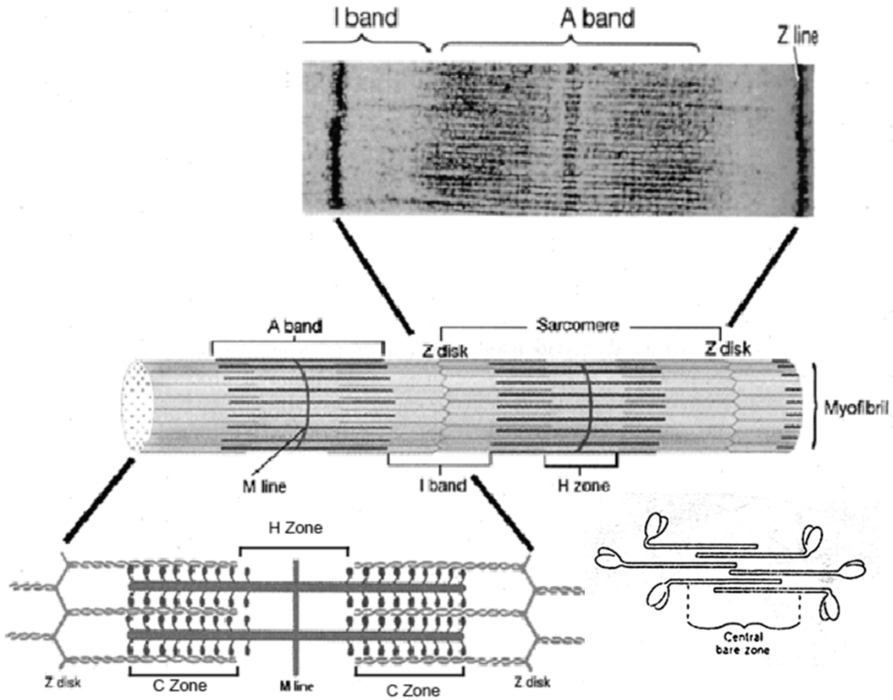
- Sarcomere: basic contractile unit of a striated myofibril
  - Between Z lines
- Striation pattern (in skeletal and cardiac muscle)
  - Z line (disk): connects adjacent sarcomeres & anchors thin filaments
  - I band: composed of thin filaments only
    - Across two sarcomeres

Structure of Sarcomere$_2$

- Striation pattern (in skeletal and cardiac muscle)
  - A band: composed of thick and overlapping thin filaments
    - Each sarcomere has **TWO T tubules** at the junction of A band and I band
  - H zone: a paler region within the A-band & composed of thick filaments only
  - M line: inside the H-band (middle of the sarcomere); central bare zone
  - C zone: overlapped area between thick (cross bridge) and thin filaments

Length of thick filament?
→ A band width
or (Sarcromere – I band)

Length of thin filament?
→ (Sarcomere – H zone) / 2



Quiz_4

If we did cross-section of skeletal muscles, which area can be seen the thick filaments only:

(A) H zone

(B) I band

(C) C zone

(D) A band

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Quiz_5

If we did cross-section of skeletal muscles, which area can be seen the thin filaments only:

(A) H zone

(B) I band

(C) C zone

(D) A band

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Quiz_6

If we did cross-section of skeletal muscles, which area can be seen both thick and thin filaments:

(A) H zone

(B) I band

(C) C zone

(D) A band

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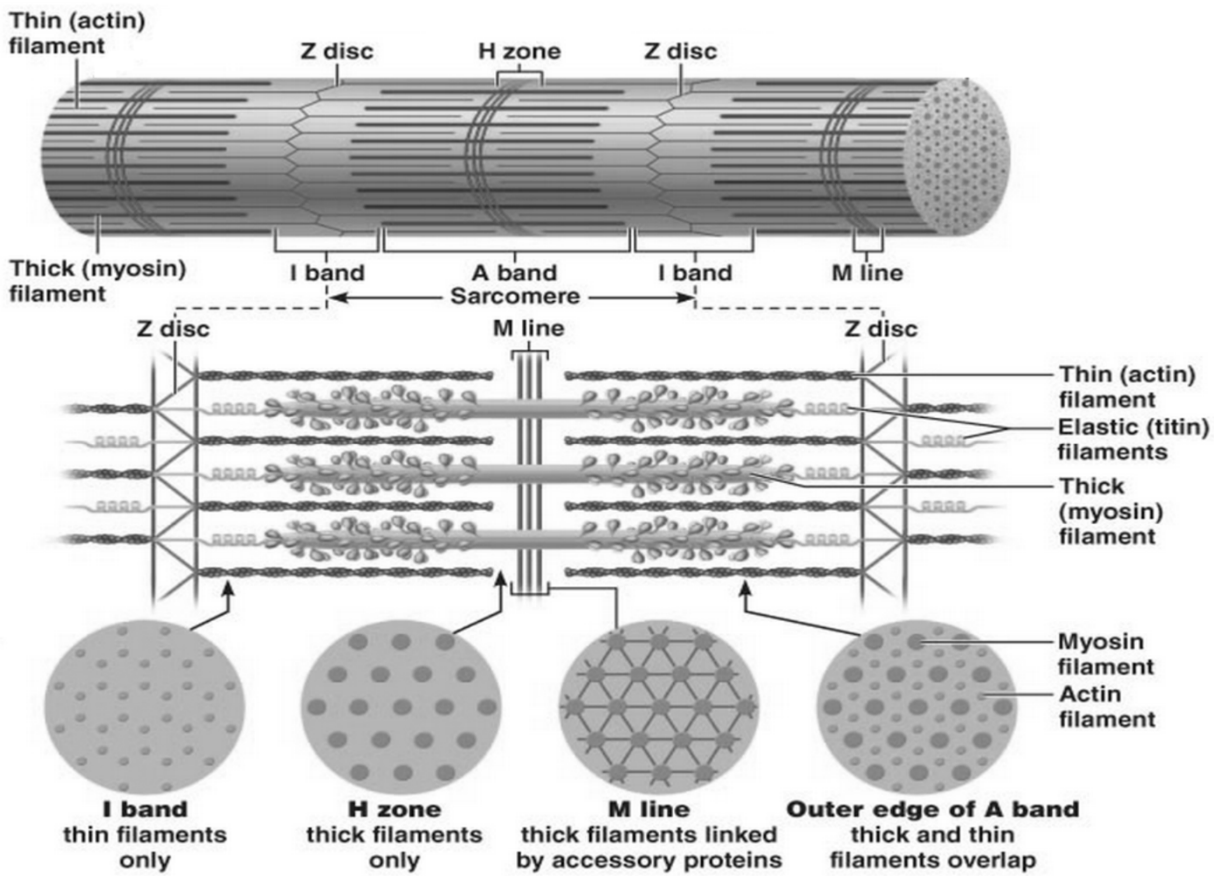
Architecture of Skeletal Muscle

Cross section of myofibril

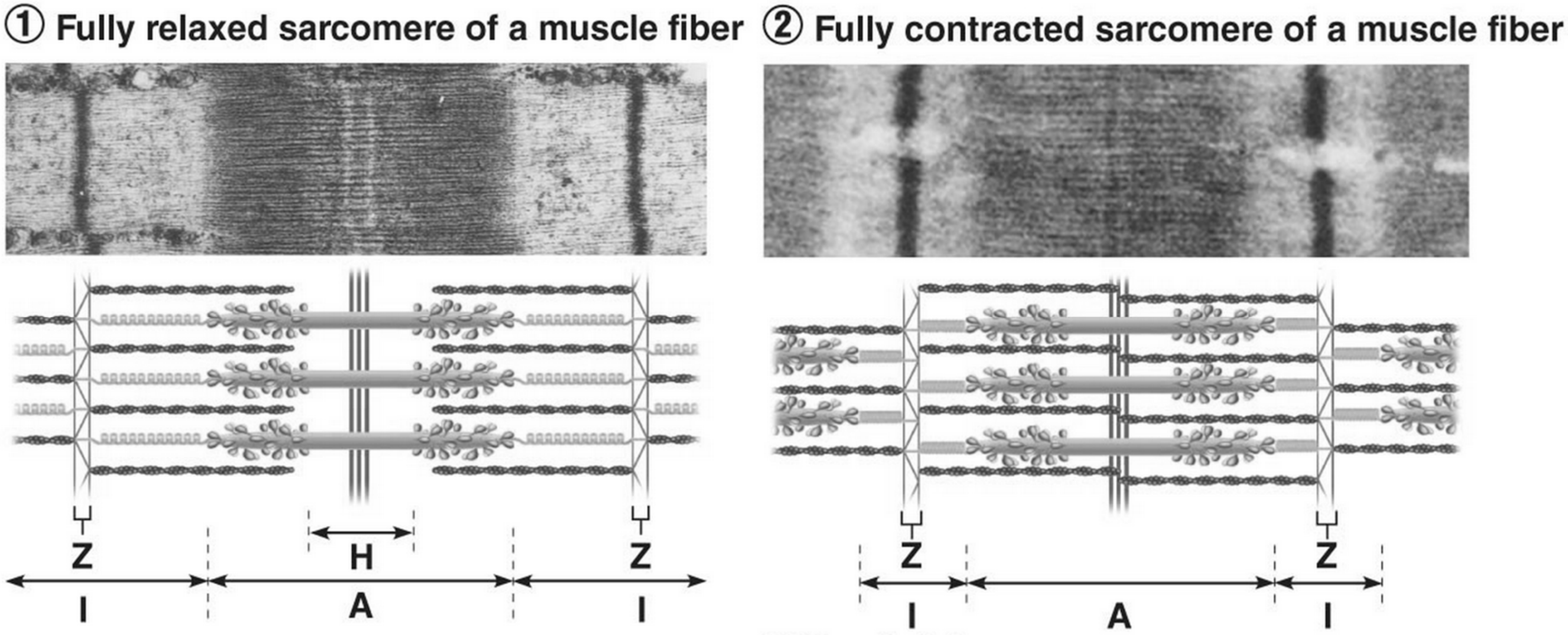
- Each thick filament is surrounded by 6 thin filaments
- Each thin filament is surrounded by 3 thick filaments



Sliding Filaments

As a muscle shortens, the following is observed:

- Sarcomeres shorten
- I band length becomes shorten
- H zone reduced
- Myofilament length remains constant
- A band length remains constant



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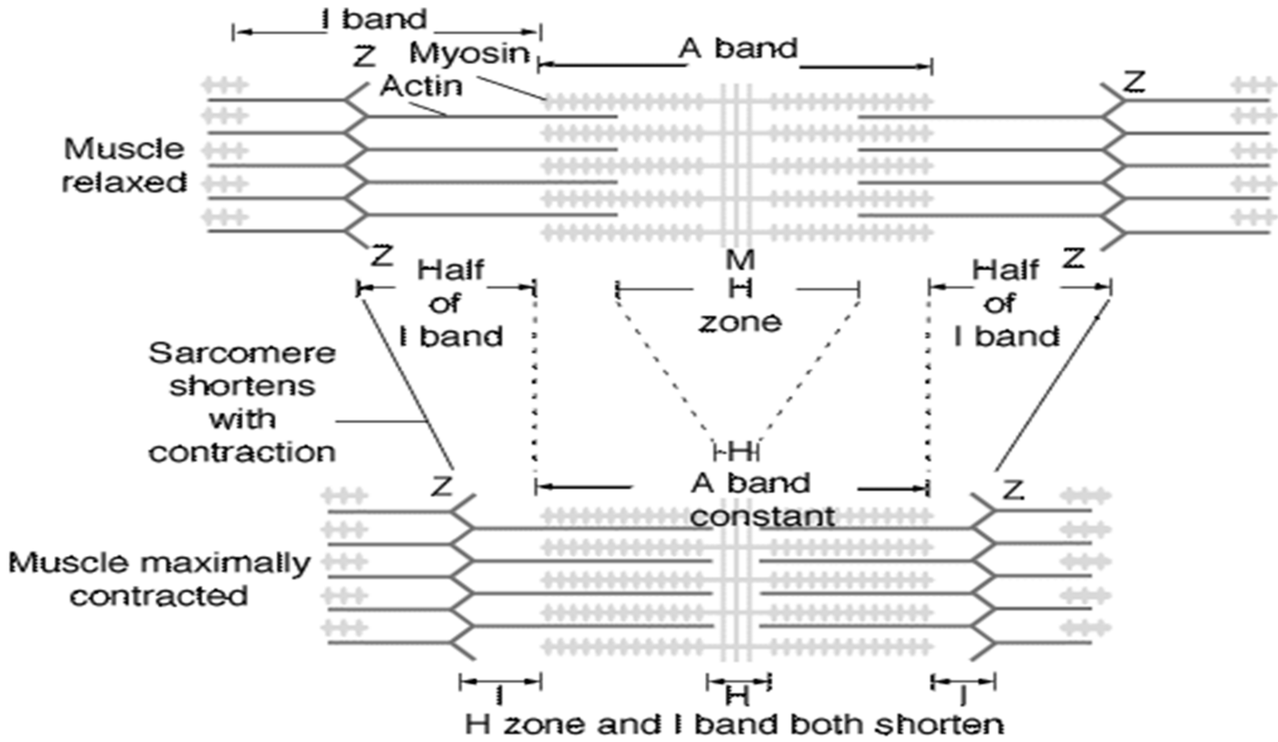

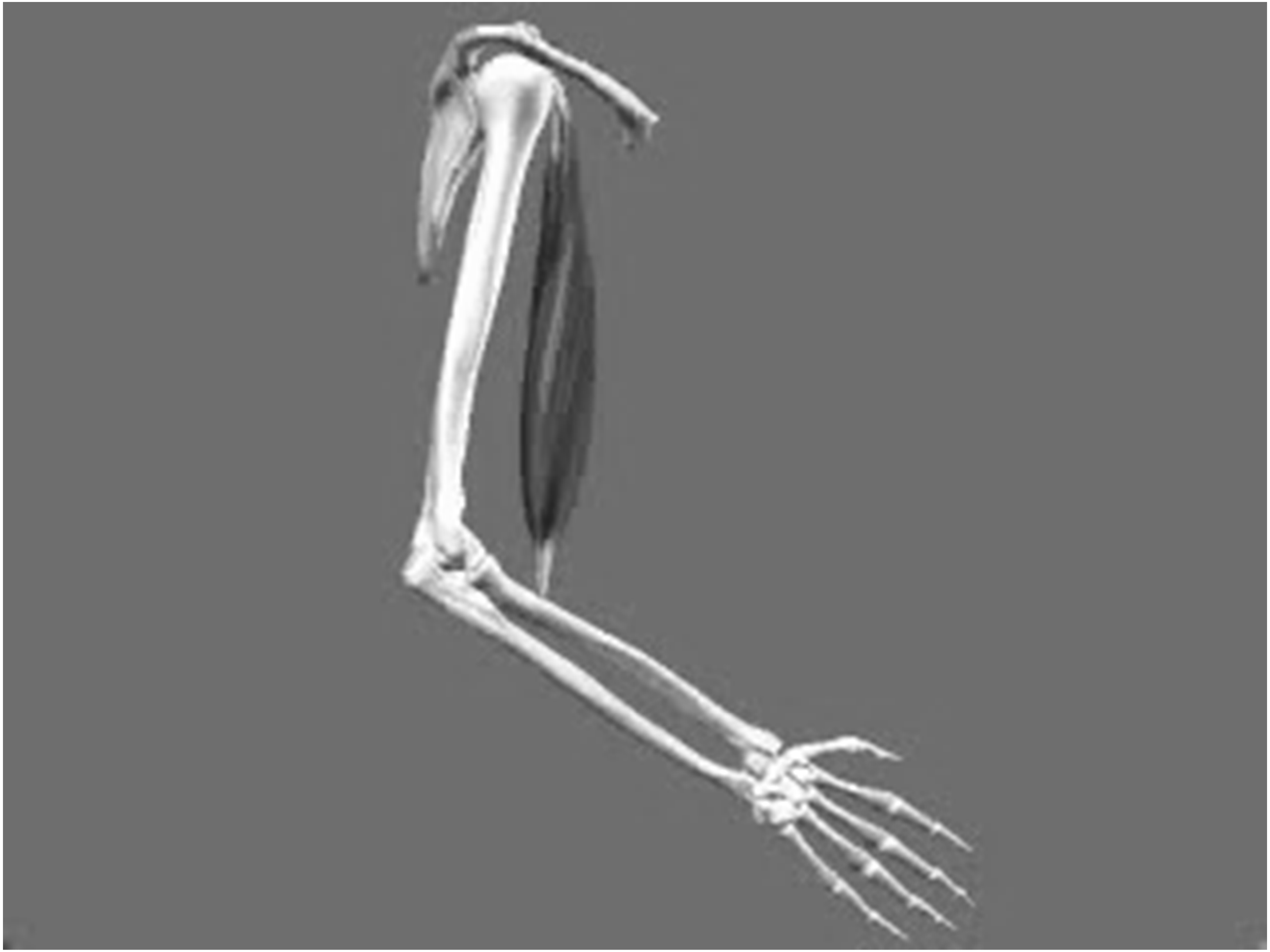

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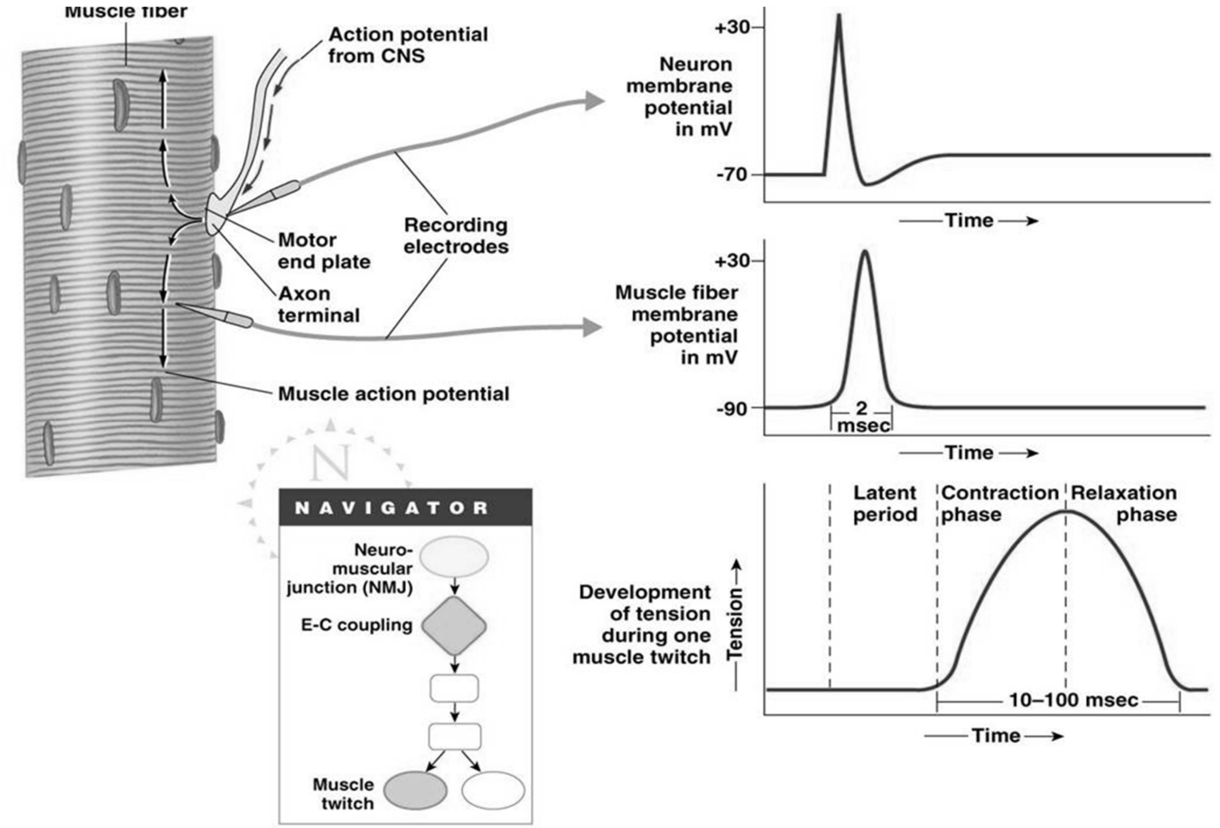
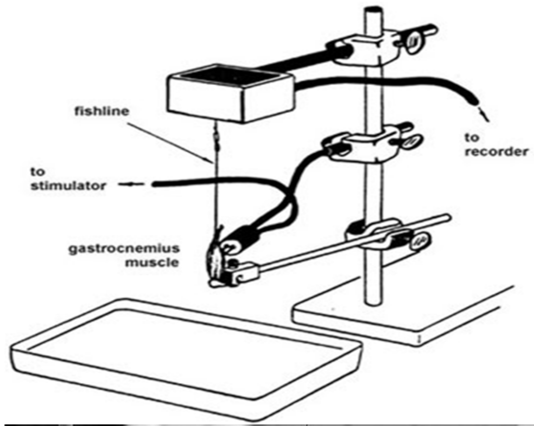
When an action potential travels to a muscle fiber,
Icecream
APPS

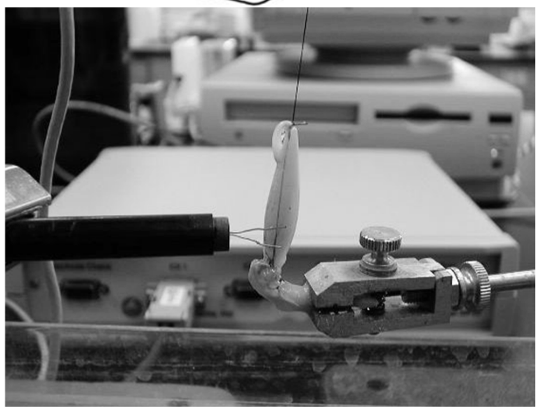
Phases of M. Contraction

Three phases of m. contraction (twitch):

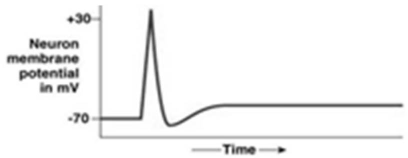
1. Latent period
2. Period of contraction
3. Period of relaxation







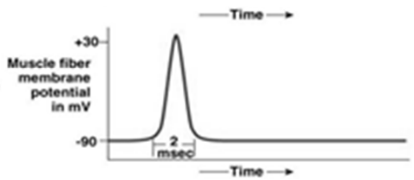
Process of Skeletal Muscle Contraction



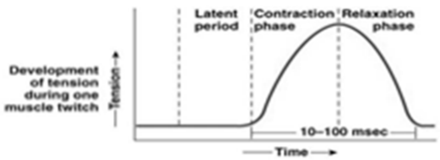
Phase 1
Motor neuron stimulates muscle fiber

- Action potential (AP) arrives at axon terminal at neuromuscular junction
- ↓ ACh released; binds to receptors on sarcolemma
- ↓ Ion permeability of sarcolemma changes
- ↓ Local change in membrane voltage (depolarization) occurs
- ↓ Local depolarization (end plate potential) ignites AP in sarcolemma

↓

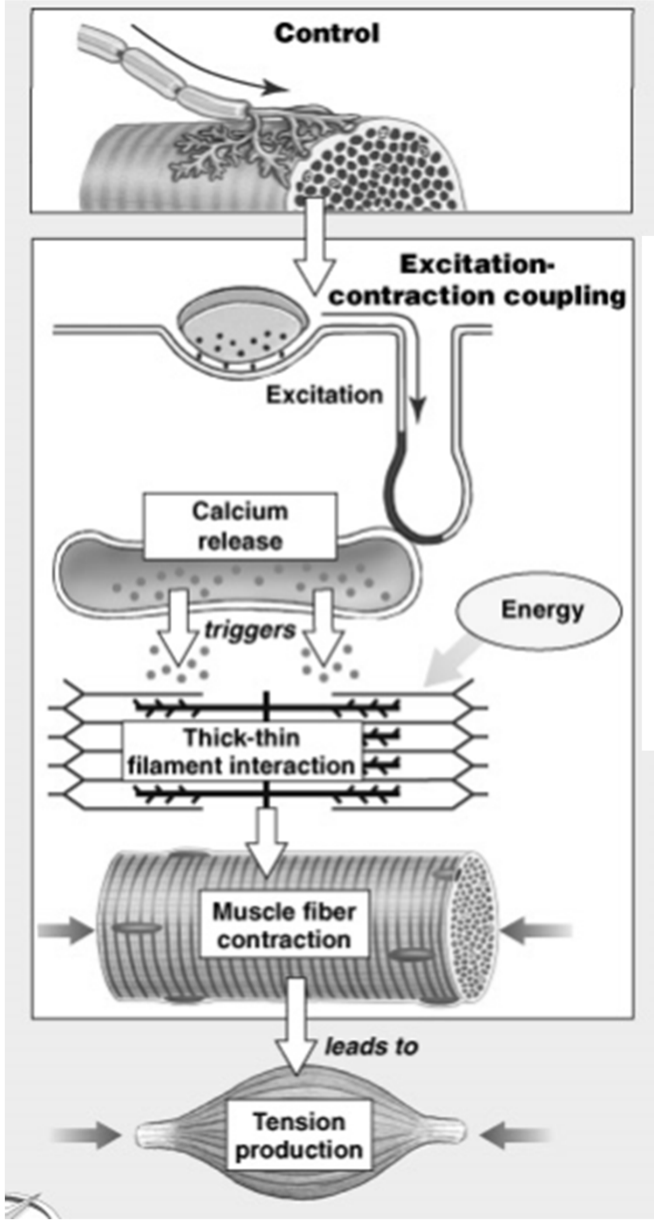


Phase 2:
Excitation-contraction coupling occurs



- AP travels across the entire sarcolemma
- ↓ AP travels along T tubules
- ↓ SR releases Ca^{2+}; Ca^{2+} binds to troponin; myosin-binding sites (active sites) on actin exposed
- ↓ Myosin heads bind to actin; contraction begins

Process of Skeletal Muscle Contraction



Phase 1: Motor neuron stimulates muscle fiber

(1) Discharge of motor neuron.

(2) Release of transmitter (acetylcholine) at motor end-plate.

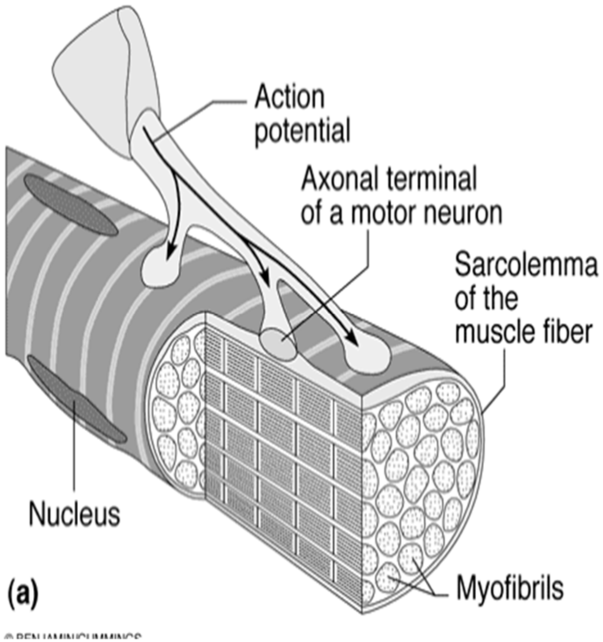
(3) Binding of acetylcholine to nicotinic acetylcholine receptors.

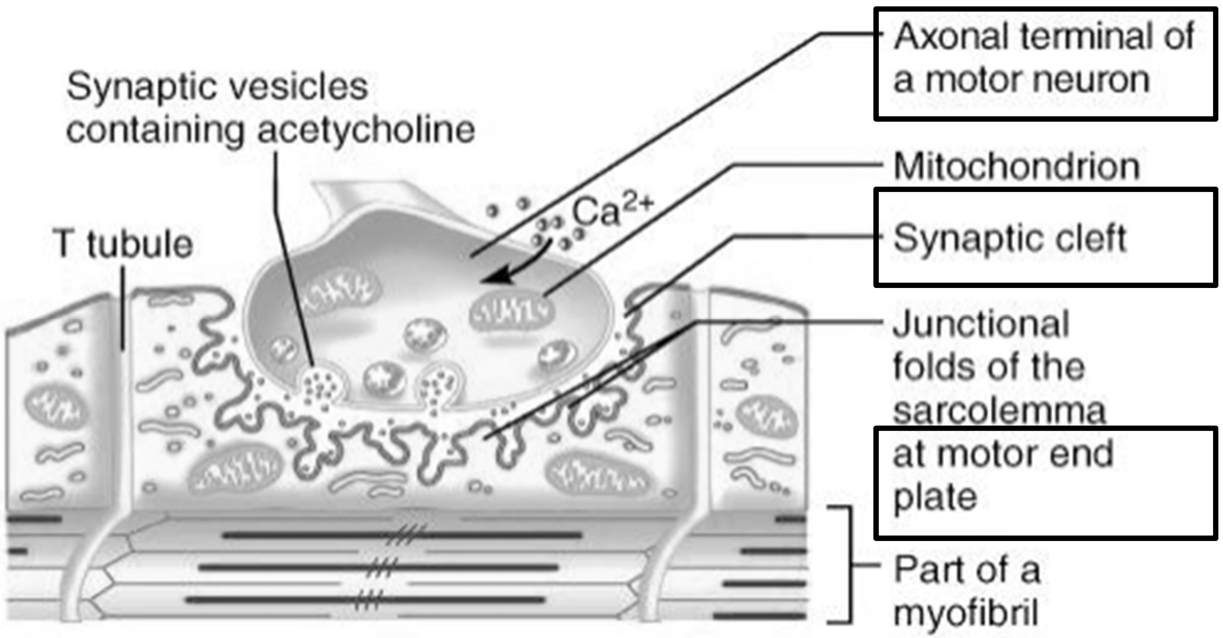
(4) Increased Na^+ and K^+ conductance in end-plate membrane.

(5) Generation of end-plate potential.

Neuromuscular Junction$_1$

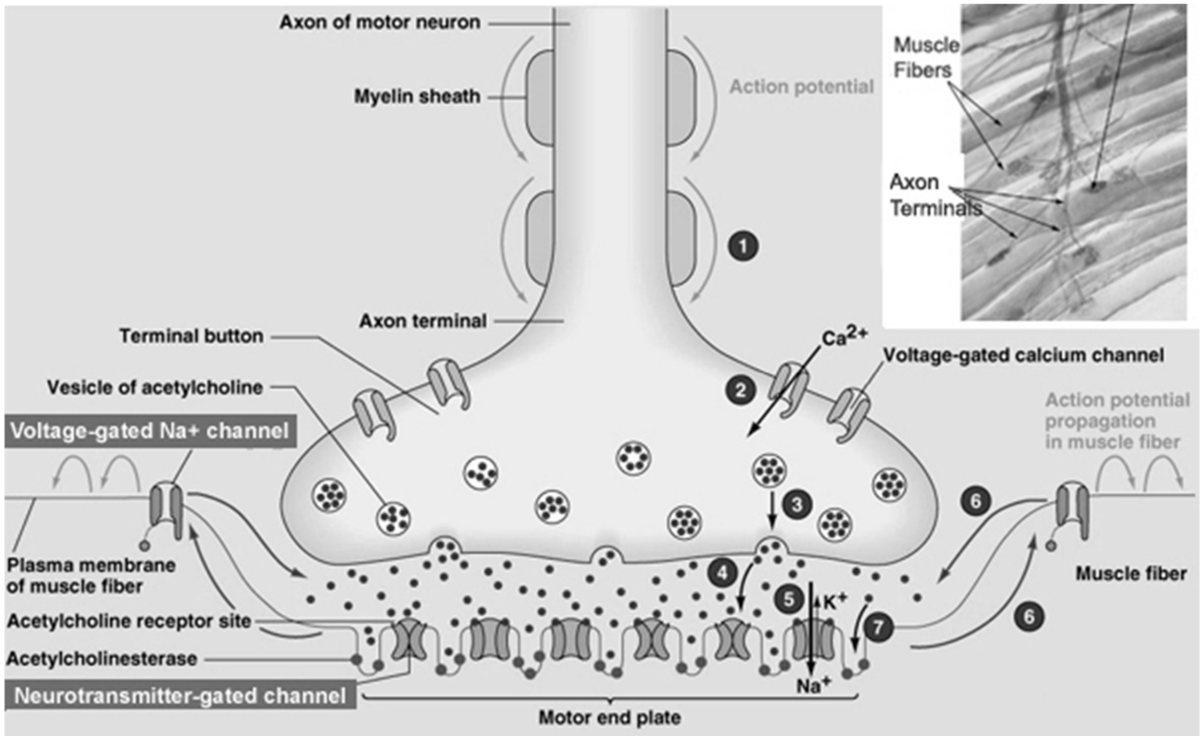
- The nerve impulse reaches the neuromuscular junction, which consists of
  - Axonal terminal of a somatic motor neuron
  - Synaptic cleft
  - Motor end plate





Neuromuscular Junction$_2$

- When an impulse reaches the axonal terminal, Ca^{2+} enters voltage-gated channel
- Acetylcholine (Ach) is released from the active zone of motor neuron via exocytosis of synaptic vesicles (quantal release)



Quiz_9

Why injection of Botulinum toxin (肉毒桿菌素) can reduce facial wrinkles?

(A) It inhibits the release of Ach

(B) It stimulates the release of Ach

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Cosmetic Aesthetic Medicine

- Botulinum toxin (肉毒桿菌素) can inhibit the release of Ach
- Botulinum toxin injection: wrinkle reduction is noticeable in 3-5 days with full effects being achieved by 2 weeks
- Results last about 3 months

Quiz_10

What is the purpose of converting electrical signal to chemical signal?

(A) amplify electrical signal

(B) reduce electrical signal

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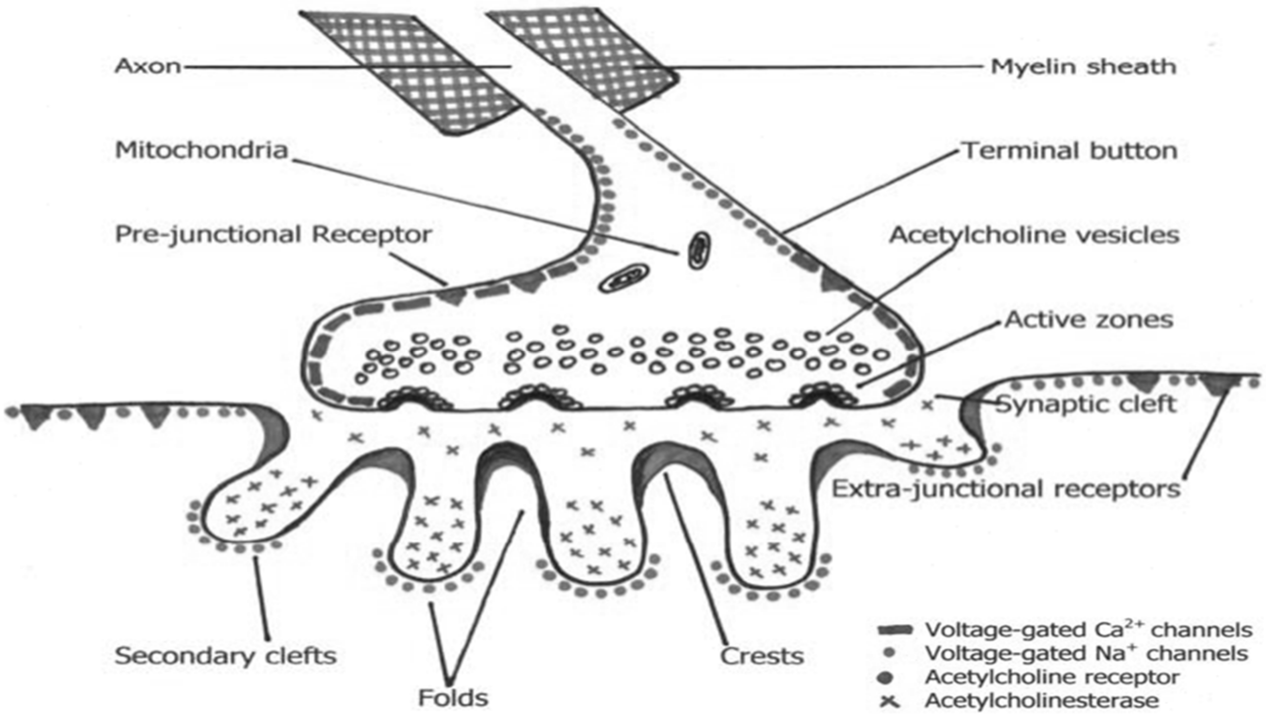
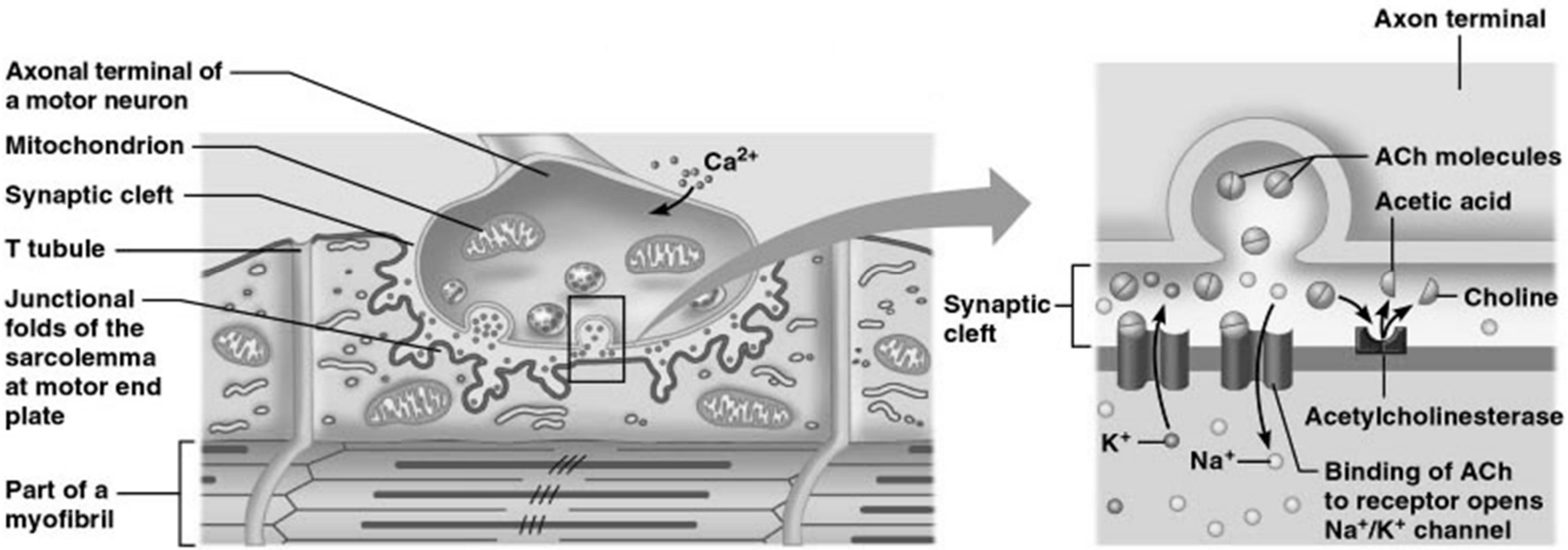
Neuromuscular Junction$_3$

- Motor neurons communicate with skeletal m. fiber through the neurotransmitter acetylcholine (Ach) → amplify signal
- Ach is synthesized from acetyl-coenzyme A and choline, and stored in synaptic vesicles at the distal end of the axon



Neuromuscular Junction$_4$

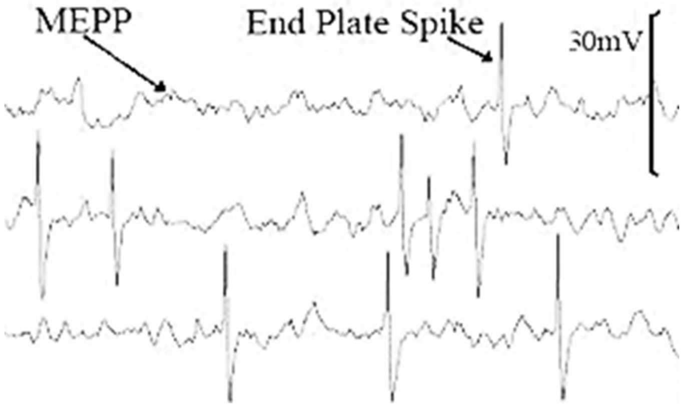
- The post-junctional membrane receptors of the motor endplate are nicotinic acetylcholine receptors
  - Ligand-gated channel
  - Non-selective cationic channel

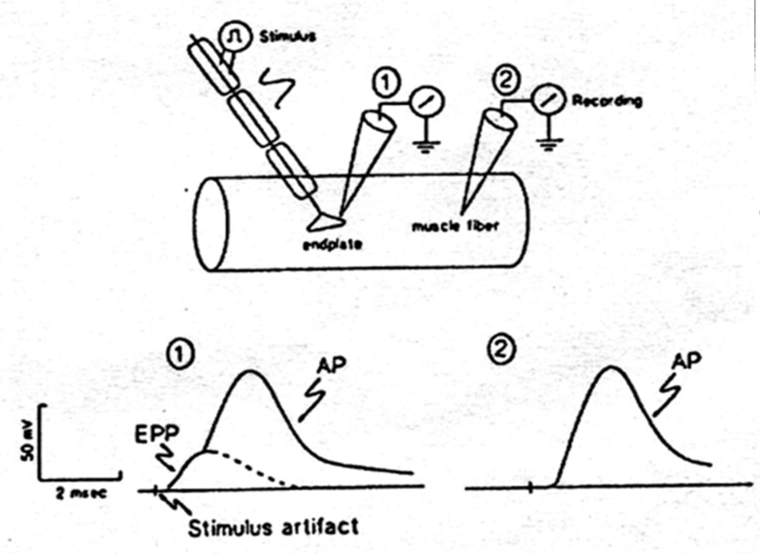


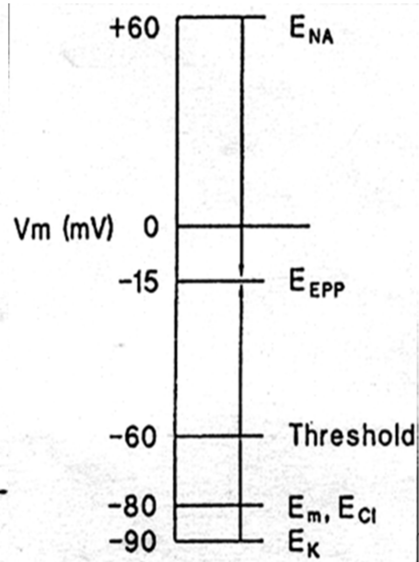
Neuromuscular Junction$_5$

- The influx of sodium ions reduces the charge, creating an End Plate Potential (EPP)
- If the end plate potential reaches the threshold voltage → an Action Potential (AP)
- The release of acetylcholine into the synaptic cleft may be spontaneous or in response to a nerve impulse

→ Spontaneous release of single vesicles of acetylcholine occurs randomly and results in Miniature EndPlate Potentials (MEPP)

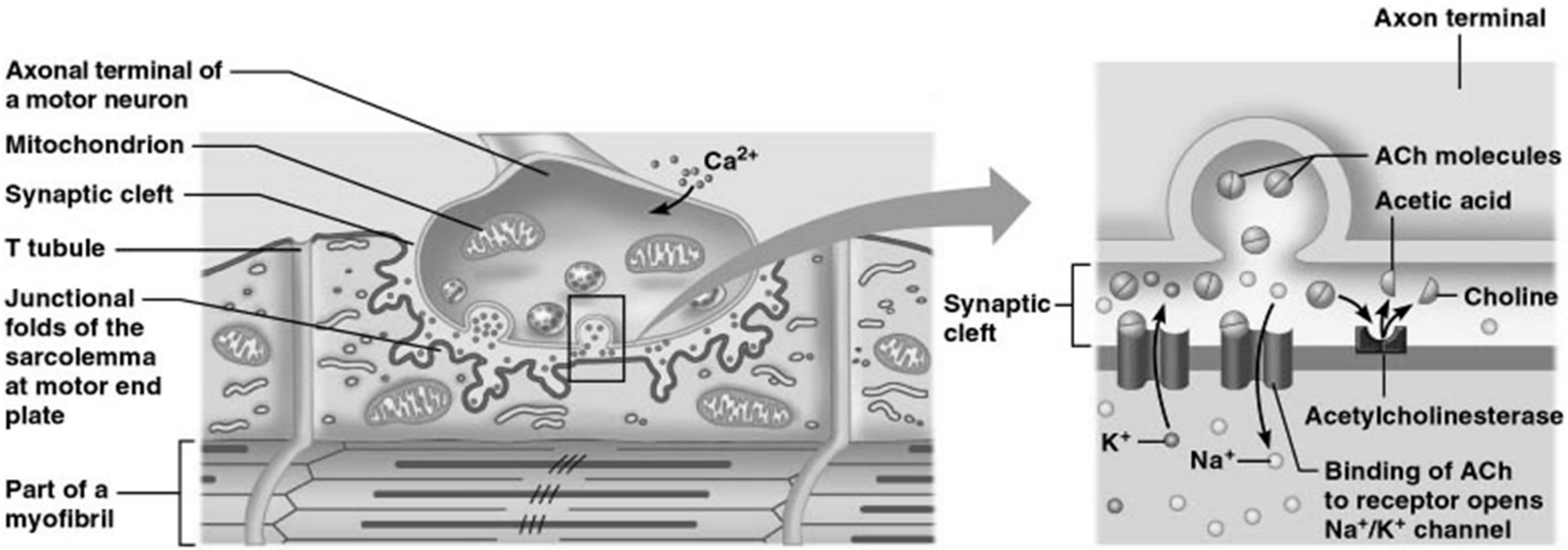






Neuromuscular Junction$_6$

- Ach is hydrolyzed to choline and acetic acid by acetylcholinesterase (AChE)
- The choline produced by the action of AChE is recycled — it is transported, through reuptake, back into nerve terminals where it is used to synthesize new acetylcholine molecules



Quiz_11

How to prolong the function of acetylcholine at neuromuscular junction?

(A) add cholinesterase

(B) add cholinesterase inhibitor

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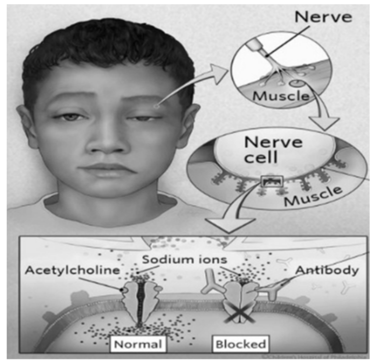
Neuromuscular Junction Disease

Curare

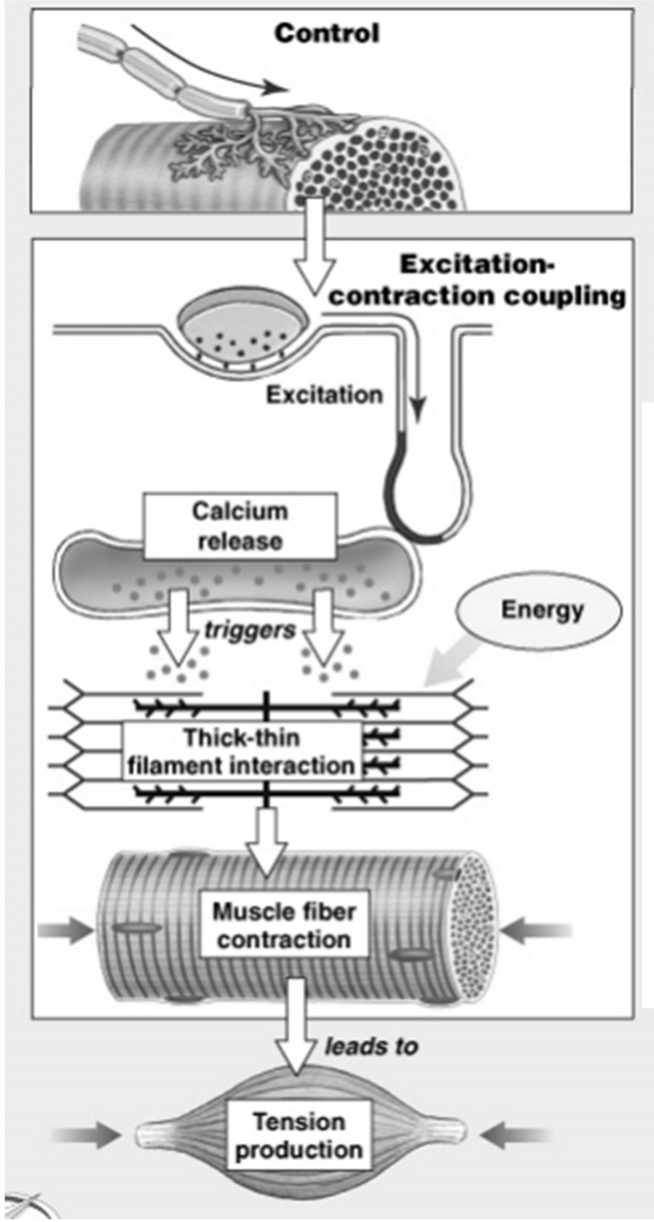
- A toxic alkaloid found in certain tropical south American trees
- A non-depolarizing muscle relaxant which blocks the nicotinic acetylcholine receptor
- Competitive against acetylcholine
- The antidote is cholinesterase inhibitor

Myasthenia gravis (literally "serious muscle-weakness“)

- A neuromuscular disease leading to fluctuating muscle weakness and fatigue
- An autoimmune disorder, in which weakness is caused by antibodies from thymus, which block acetylcholine receptors
- Treated with cholinesterase inhibitors or immunosuppressants



Process of Skeletal Muscle Contraction



Phase 2: Excitation-contraction coupling occurs

Excitation Contraction Coupling

(6) Generation of action potential in muscle fibers.

(7) Inward spread of depolarization along T tubules.

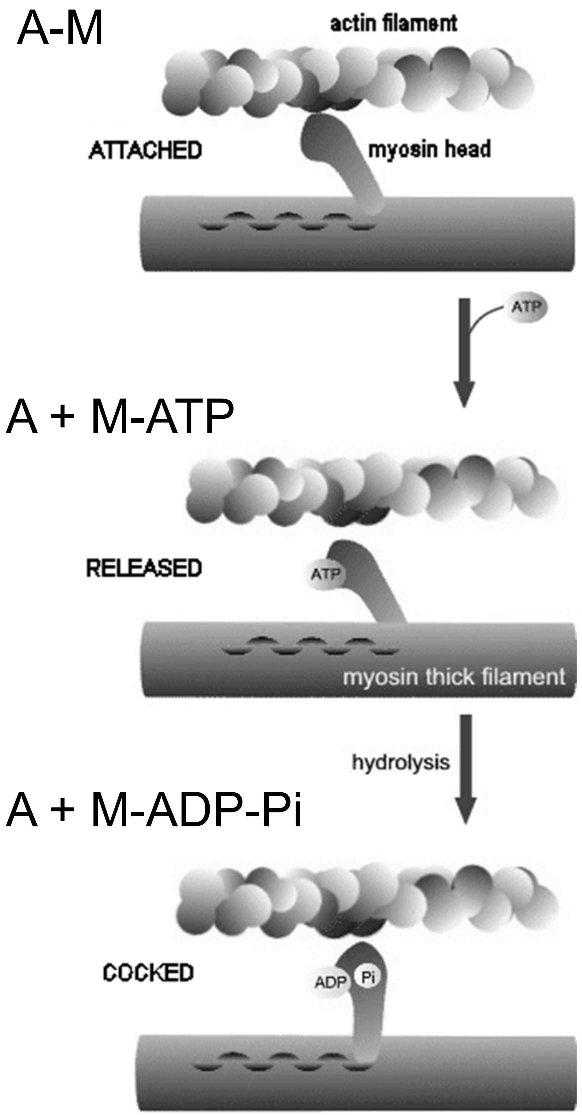
(8) Release of Ca^{2+} from terminal cisterns of sarcoplasmic reticulum and diffusion to thick and thin filaments.

(9) Binding of Ca^{2+} to troponin C, uncovering myosin-binding sites on actin.

(10) Formation of cross-linkages between actin and myosin and sliding of thin on thick filaments, producing shortening.

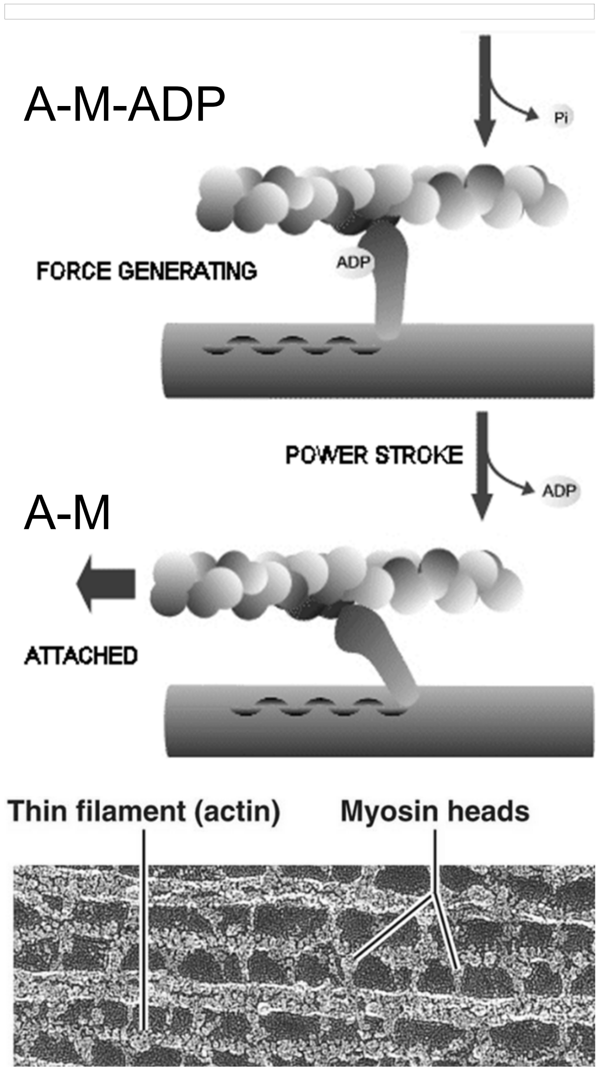
Effect of n. stimulation on skeletal m.: excitation only

Crossbridge Cycle$_1$



- A contractile cycle begins when a myosin filament is tightly bound to an actin filament in a *rigor* configuration
  - rigor mortis (屍僵): few ~ 12 hours after death
- This state is rapidly terminated when an ATP molecule binds to the myosin head
- ATP causes a change in the myosin head which allows the head to move in cocked position
- Hydrolysis of ATP occurs, but ADP and Pi remain bound to the myosin head

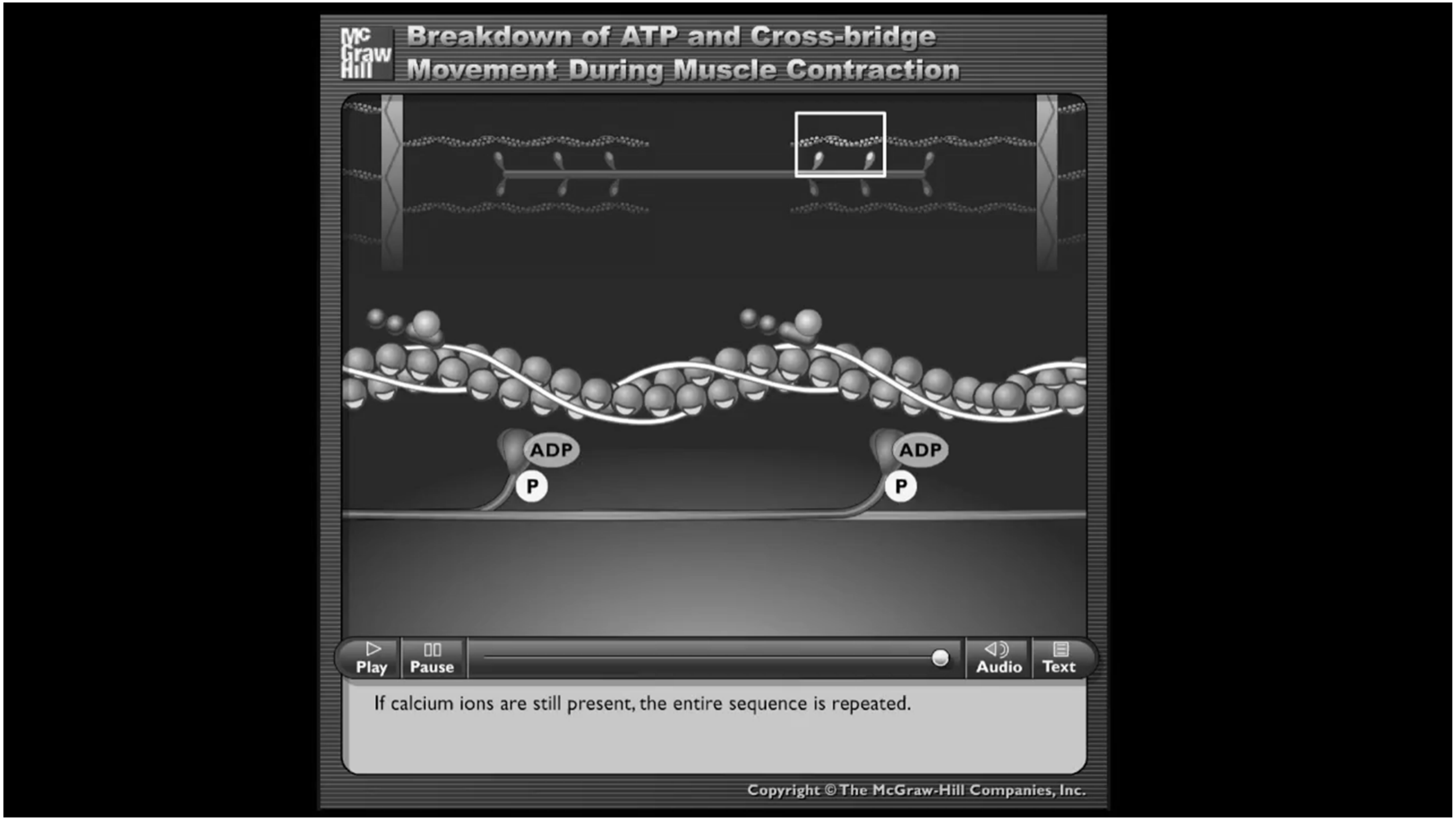
Crossbridge Cycle$_2$



• In the presence of Ca^{2+},
the myosin head binds to a new binding site on the actin filament together with release of P_i, which triggers the power stroke

• During this phase the myosin head returns to its original conformation and ADP is released

Each cycle: Move about 10 nm, consume 1 ATP


Breakdown of ATP and Cross-bridge Movement During Muscle Contraction
ADP
P
ADP
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Audio
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If calcium ions are still present, the entire sequence is repeated.
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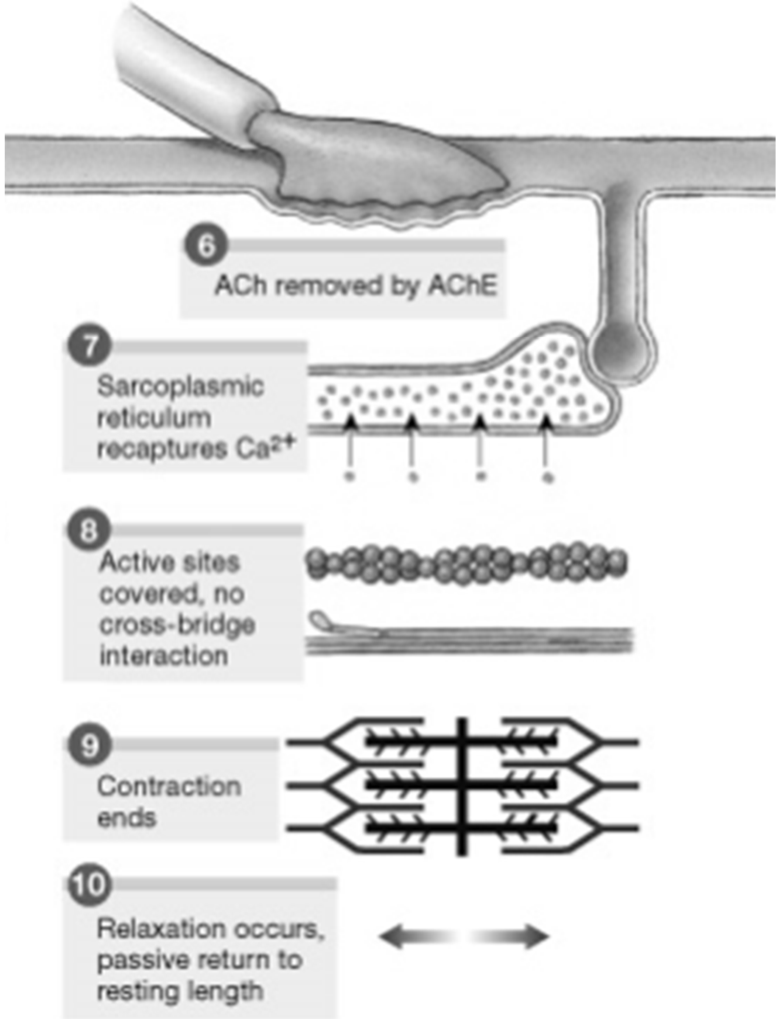
Process of Skeletal Muscle Relaxation



Steps in relaxation

(1) Ca^{2+} pumped back into sarcoplasmic reticulum.

(2) Release of Ca^{2+} from troponin.

(3) Cessation of interaction between actin and myosin.

* Ca^{2+} is actively pumped back to SR, which is required ATP

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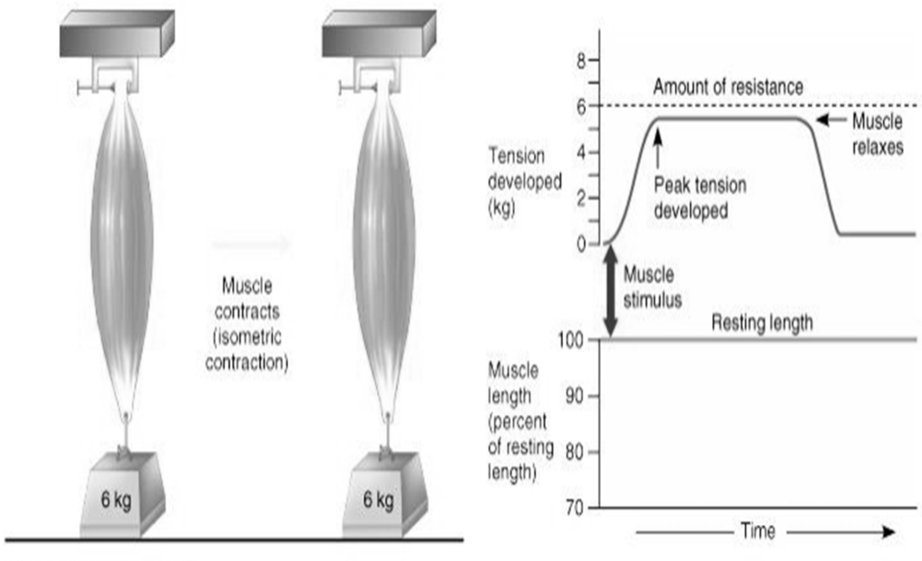
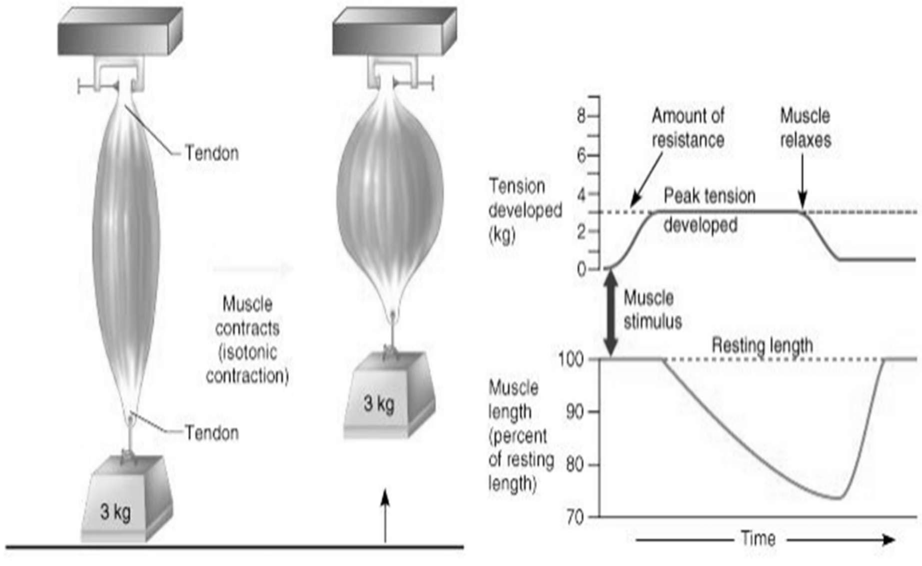
Types of Muscle Contraction

- Isometric contraction: no change in length but tension increases, e.g. postural muscles of body
  - Co-contraction of antagonist muscle
- Isotonic contraction: change in length but tension constant
  - Concentric: overcomes opposing resistance and muscle shortens
  - Eccentric: tension maintained but muscle lengthens

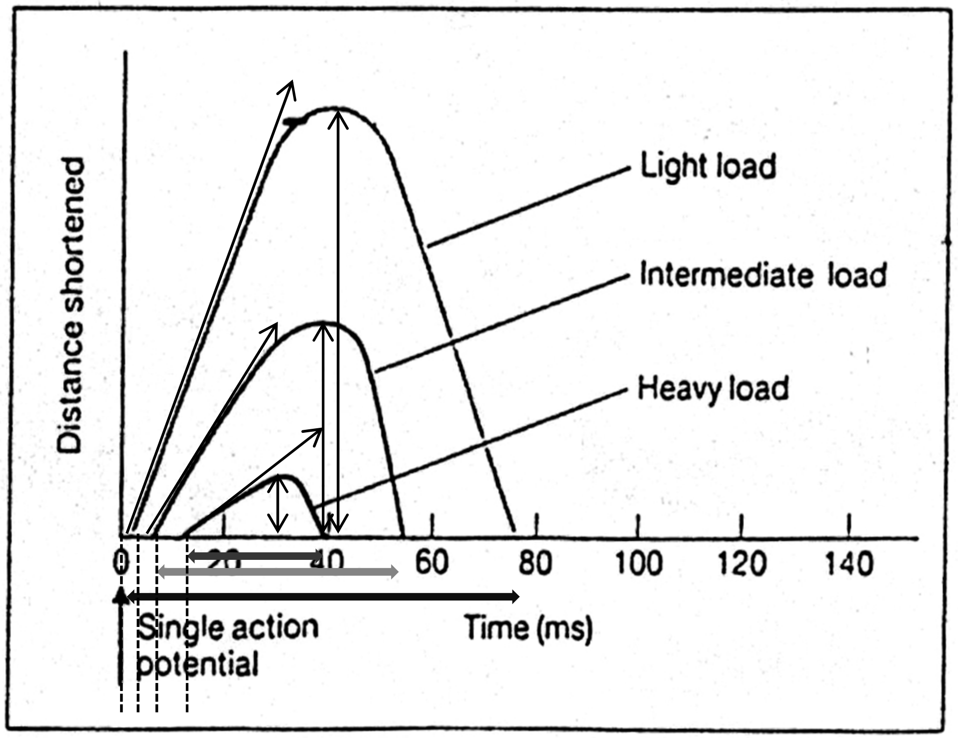


(b) Isometric contraction



(a) Isotonic (concentric) contraction

Isotonic Contraction With Different Loads



As load increases,

- Max. distance shortened ↓
- Shortening velocity ↓
- Duration of shortening ↓

BUT

- Latent period ↑

Quiz_13

We exert different levels of muscle force.

(A) True

(B) False

https://forms.gle/V2LGgkVpBunV6KKb6

Quiz_14

Are all-or-none law applied for muscle fibers?

(A) Yes

(B) No

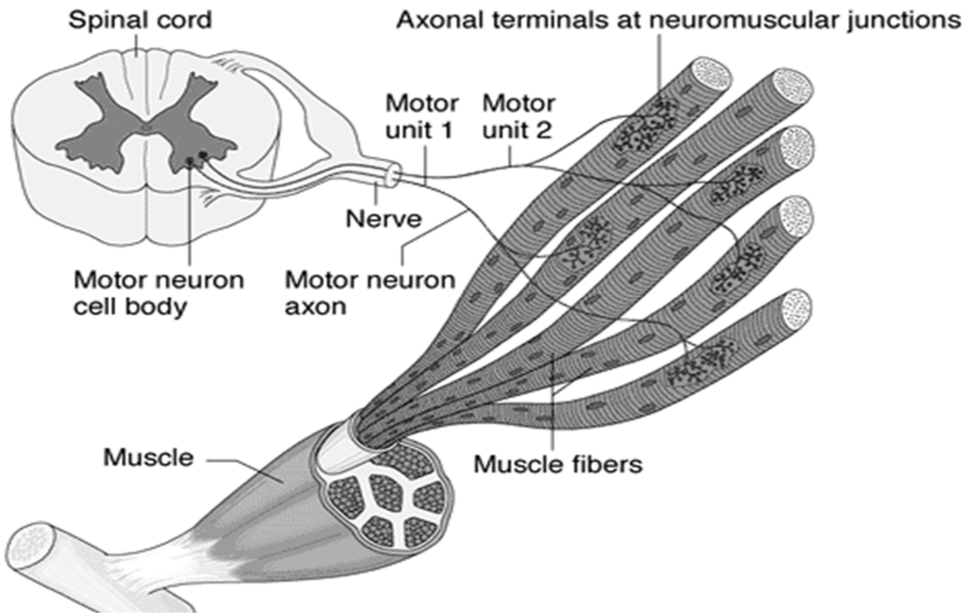
https://forms.gle/brr6qGDAyrHemSM98

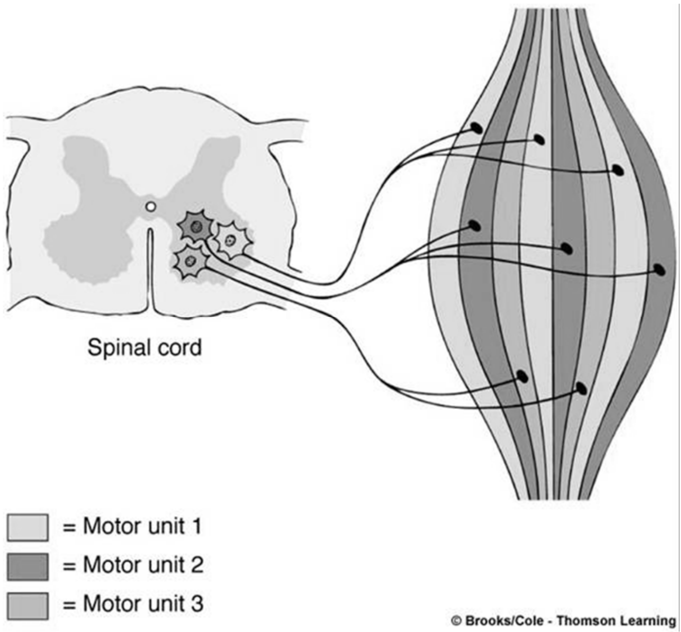
Different Response of M. Fiber vs. Whole Muscle

- All-or-none law for muscle fibers: contraction of equal force in response to each action potential
- Graded for whole muscles: strength of contractions range from weak to strong depending on several factors
  - Numbers of myofibrils working in parallel
    - Thicker m. have greater strength than thinner ones
    - Exercise adds myofibrils (hypertrophy) by adding more actin and myosin
  - Recruitment of motor units (groups of muscle fibers)
  - Frequency of stimulation
  - Muscle length
  - Fatigue

Motor Unit$_1$

- Lower motor neurons: cell bodies in ventral horn of spinal cord
  - Influenced by
    - Sensory feedback from muscles and tendons
    - Stimulation or inhibition from upper motor neurons
- Motor unit: a motor neuron and all of the corresponding muscle fibers it innervates
  - When a motor unit is activated, all of its fibers contract





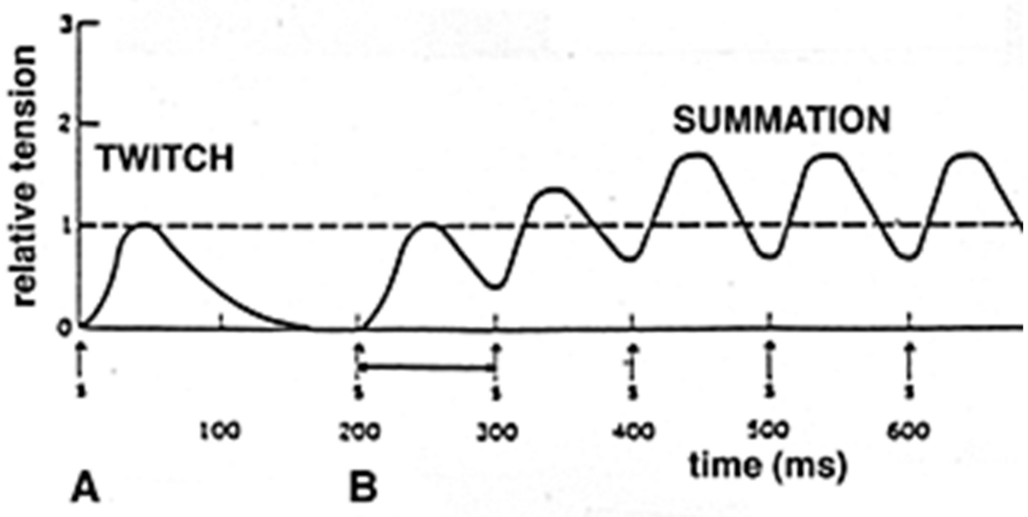
Motor Unit$_2$

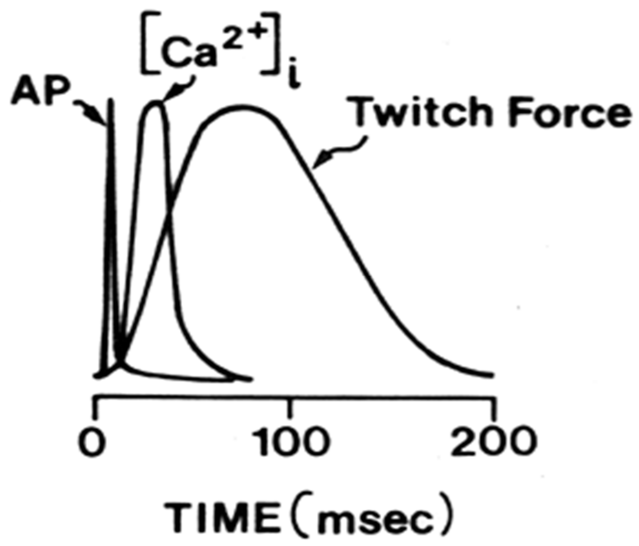
- The number of muscle fibers within each unit can vary
  - The smaller the motor unit, the more precise the action of the muscle
  - back m. (1:100); finger m. (1:10); eye m. (1:1)
- The strength of entire muscle increases by recruiting more motor units
- Size principle: Large motor units require the greater amplitude of stimulus to become active
  - Smaller motor units are more excitable than larger motor units
  - Smaller motor units are activated first

Frequency-Tension Relation$_1$

- Summation: increase in contractile response to a second action potential that occurs during the contractile response produced by the previous action potential
  - Due to insufficient time to pump Ca^{2+} back to sarcoplasmic reticulum (SR)

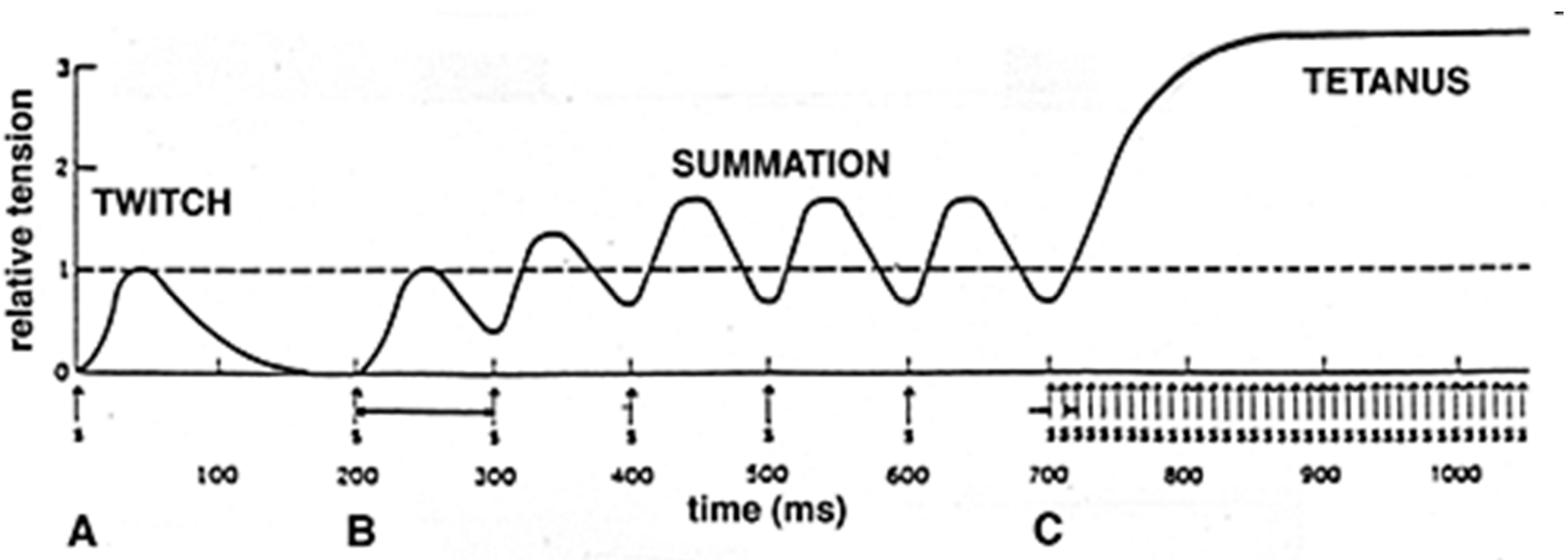
  → an increase in the amount of Ca^{2+} in the sarcoplasm





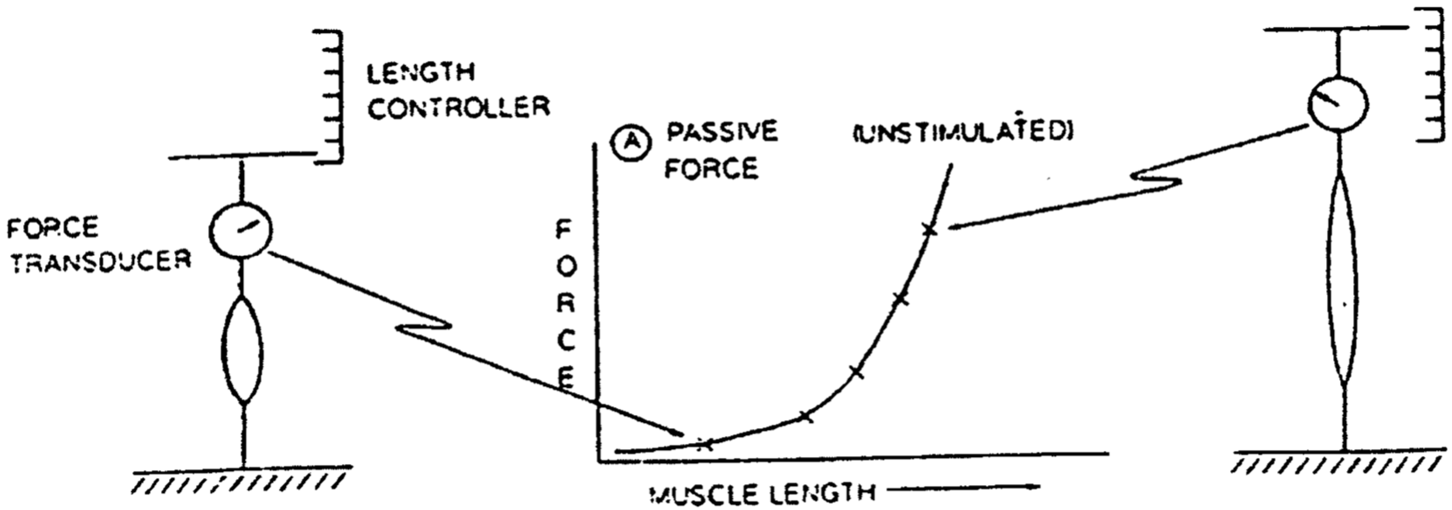
Frequency-Tension Relation$_2$

- Tetanus: response to multiple stimuli delivered at a rate sufficient to produce a fused contraction
  - Because all of the myofilaments are forming bonds (a maximum of Ca^{2+} in the myofibril)



Muscle Force$_1$

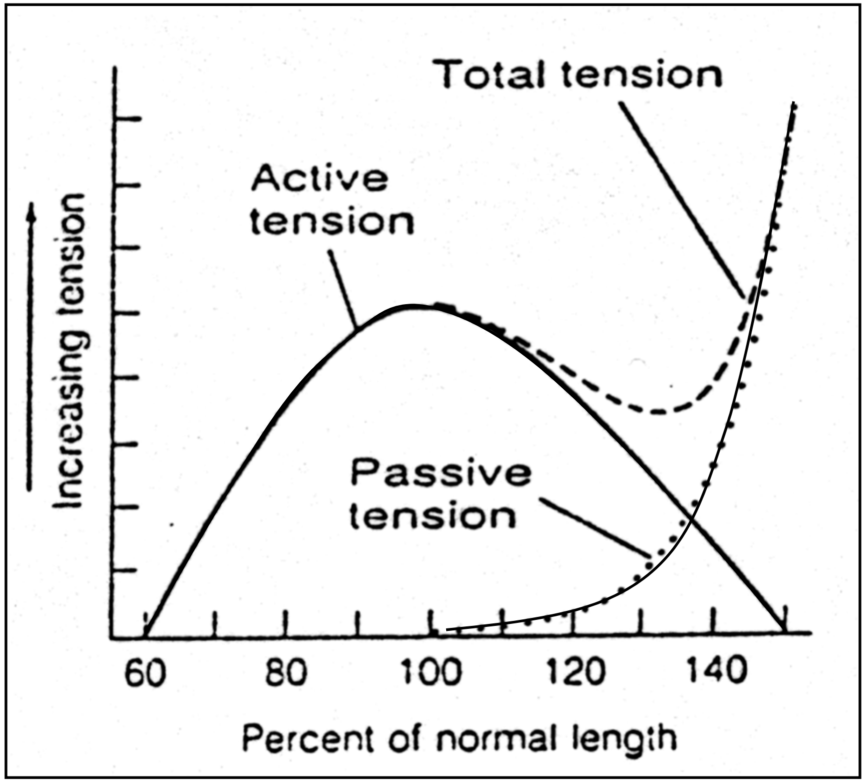
- Passive force: the force required to stretch a relaxed muscle to a given length



- Active force: the force generated by the attachment of cross bridges

Muscle Force$_2$

- Total force: the final force that a muscle attains following stimulation
  - the passive force that existed prior to stimulation
  - the component of force that was generated in response to the stimulus

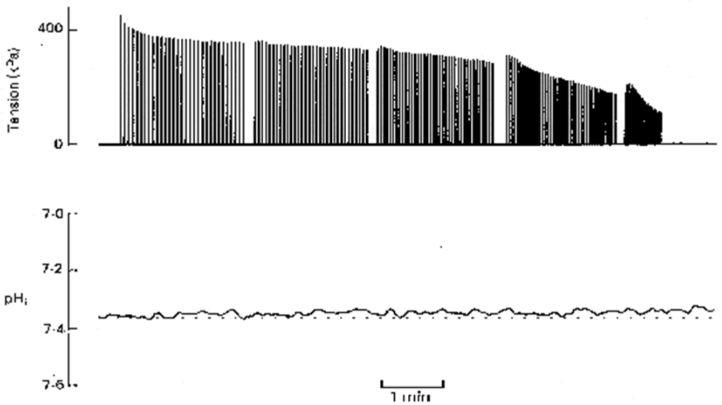


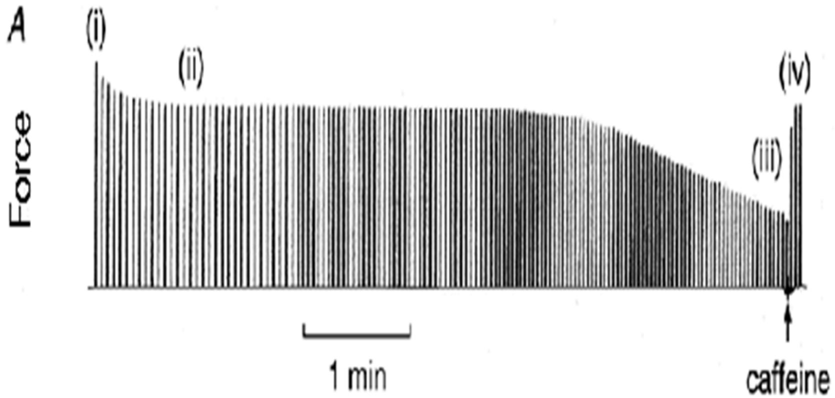
Muscle Fatigue

- When muscle can no longer respond to stimulation with same degree of contractile activity
- Types of muscle fatigue:
  - Muscular fatigue: due to ATP depletion, and failure of SR Ca^{2+} release, NOT due to lactic acid accumulation
  - Neuromuscular fatigue: motor neurons can not make Ach fast enough
  - Psychological fatigue: depends on emotional state of individual

Causes of Muscular Fatigue

- pH has minimal role in muscle fatigue
- Depletion of stored glycogen; lack of ATP; buildup of ADP
- Muscle fatigue is partly caused by failure of SR Ca^{2+} release
  - $Ca\text{-}P_i$ precipitation in the SR could decrease the Ca^{2+} available for release
  - Caffeine to increase Ca^{2+} release from the SR
- After severe exercise, remodeling of ryanodine receptor complex causes leaky Ca^{2+} channels that cause decreased exercise tolerance





Quiz_16

The response of skeletal m. is always excitatory. How to inhibit the response of skeletal muscle?

(A) Reduce the excitability of neuron

(B) Activation of antagonist

(C) Make muscle fatigue

https://forms.gle/xsrAj8BfP7fzPXqo9

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Quiz_17

What is the energic fuel of skeletal muscle contraction?

(A) ATP

(B) ADP

(C) AMP

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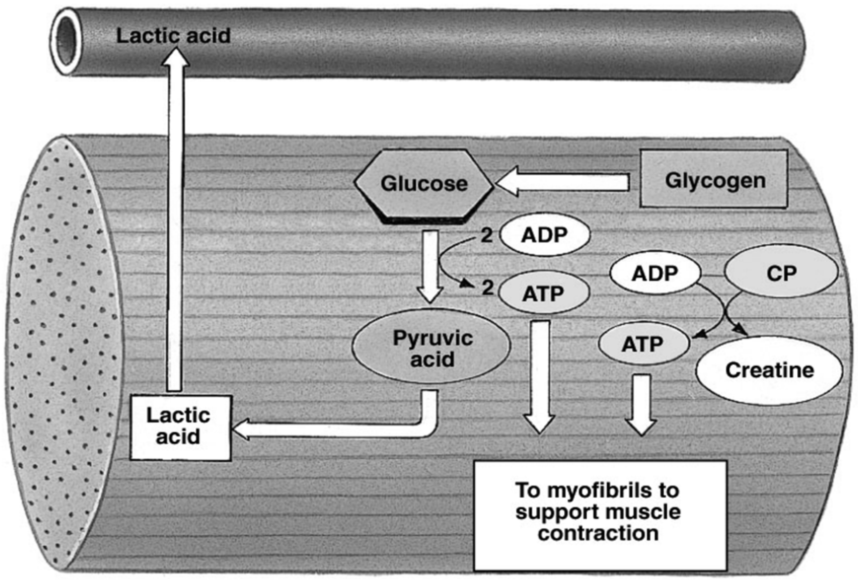
Energy for Contraction$_1$

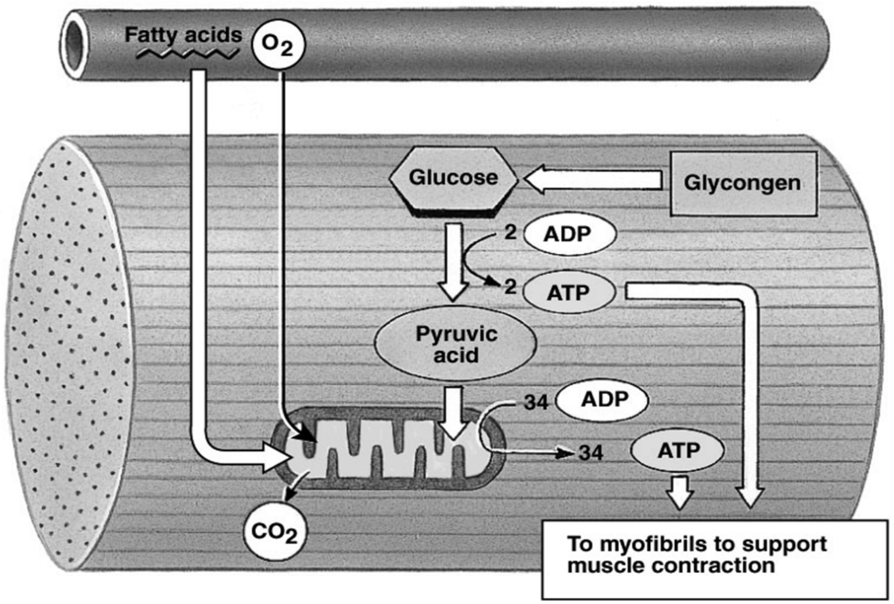
ATP provides energy for muscle contractions from following sources

- Cellular ATP
- Creatine phosphate: 1 ATP
  - During resting conditions stores energy to synthesize ATP
- Anaerobic respiration (Glycolysis) : 2 ATP
  - Occurs in absence of oxygen and results in breakdown of glucose to yield ATP and lactic acid
- Aerobic respiration (Oxidative phosphorylation) : 36 ATP
  - Requires oxygen and breaks down glucose to produce ATP, CO_2 and H_2O
  - More efficient than anaerobic

Energy for Contraction$_2$

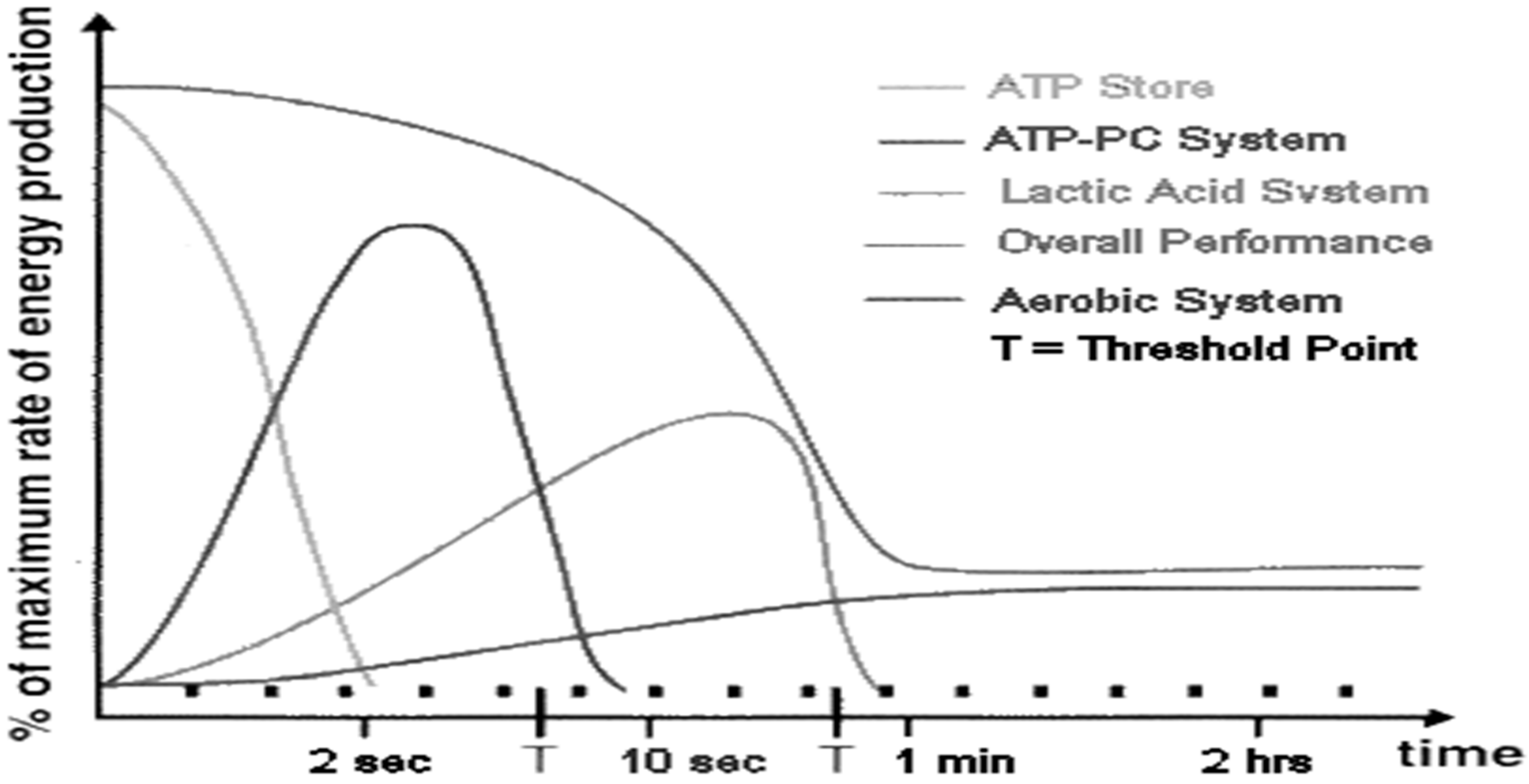
- Creatine phosphate
- Anaerobic respiration (Glycolysis)
- Aerobic respiration (Oxidative phosphorylation)





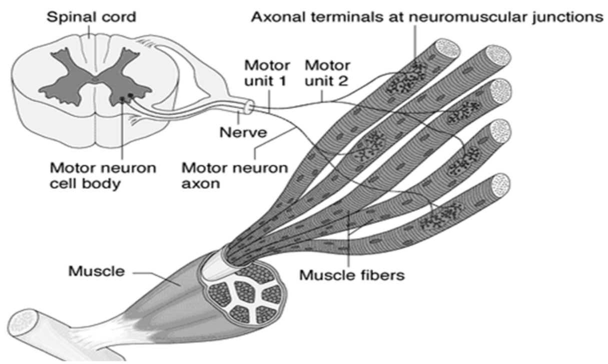
Energy Sources in Working M.

- Stored ATP → Creatine phosphate (ATP-CP) → Glycolysis (Lactic acid sys.) → Aerobic respiration



Types of Skeletal Muscle Fiber$_1$

- According to ATP-forming pathways
  - Oxidative fibers: use aerobic pathways
  - Glycolytic fibers: use anaerobic glycolysis
- These two criteria define three categories:
  - Slow Oxidative (SO) (type I) fibers
  - Fast Oxidative (FO) (type IIa) fibers
  - Fast Glycolytic (FG) (type IIb) fibers
- Most muscles have all three types of m. fibers
- A motor unit is composed of one type of fiber



Quiz_19

Why can skeletal muscles be divided into red muscles and white muscles?

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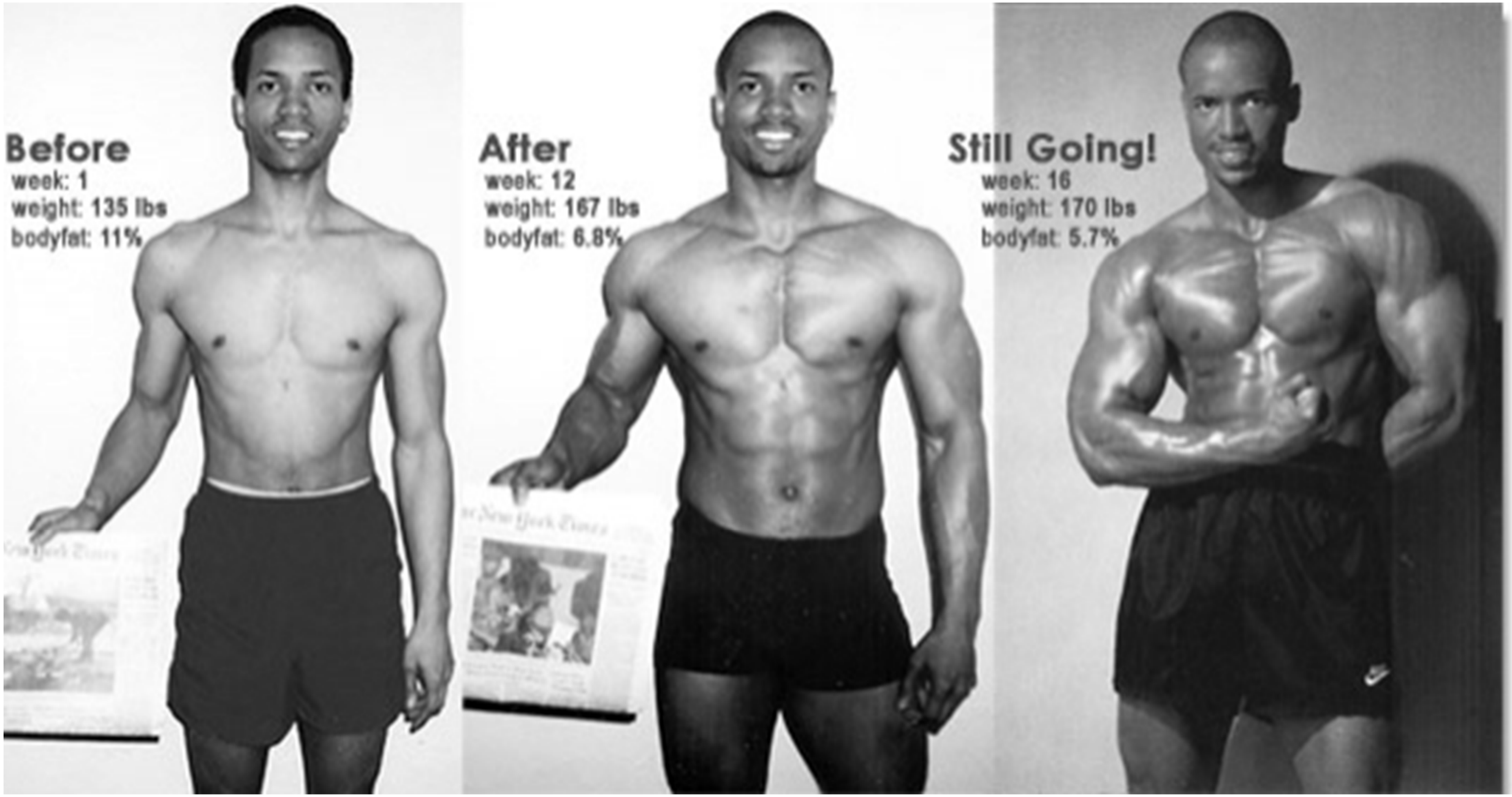
Types of Skeletal Muscle Fiber$_2$

	Slow Oxidative Fibers (I)	Fast Oxidative Fibers (IIa)	Fast Glycolytic Fibers (IIb)
Metabolic Characteristics			
Speed of contraction	Slow	Fast	Fast
Myosin ATPase activity	Slow	Fast	Fast
Primary pathway for ATP synthesis	Aerobic	Aerobic	Anaerobic
Myoglobin content	High	High	Low
Glycogen stores	Low	Intermediate	High
Recruitment order	First	Second	Third
Rate of fatigue	Slow	Intermediate	Fast
Activities Best Suited For	Endurance-type activities; e.g., running a marathon; maintaining posture	Sprinting, walking	Short-term intense or powerful movements, e.g., hitting a baseball
Structural Characteristics			
Color	Red	Red to pink	White
Fiber diameter	Small	Intermediate	Large
Mitochondria	Many	Many	Few
Capillaries	Many	Many	Few

Exercise Training on Adaptation of Muscle Fibers



Exercise Training on Adaptation of Muscle Fibers

- Regular endurance exercise
  - improves oxidative capacity in oxidative fibers
    - increase capillaries, mitochondria
- High-intensity resistance training
  - promotes hypertrophy of fast glycolytic fibers
    - increase diameter (more myofibrils)
    - Testosterone promotes myofibril synthesis
- The extent of training determines the interconversion of the two types of fast-twitch fibers
  - E.g., weight training can convert fast-oxidative fibers to fast-glycolytic fibers
- Fast-twitch and slow-twitch fibers are not interconvertible

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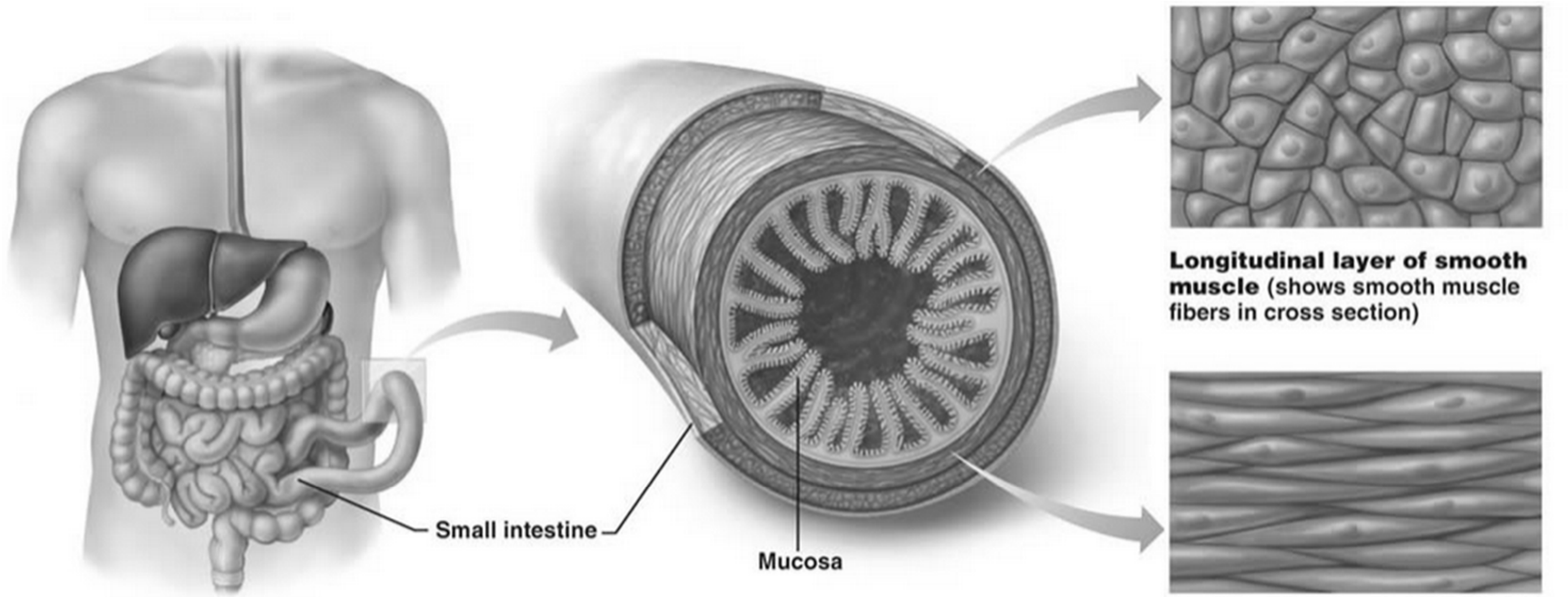
Smooth Muscle



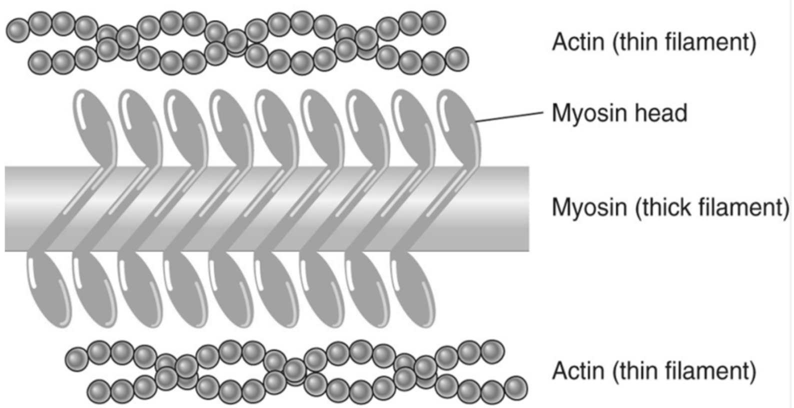
(a)

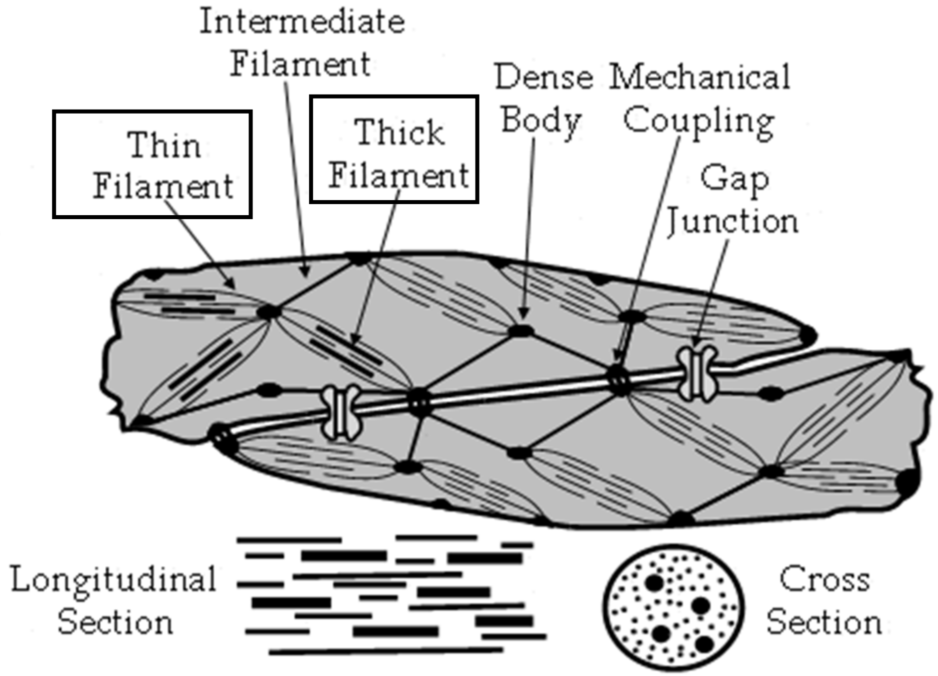
(b) Cross section of the intestine showing the smooth muscle layers (one circular and the other longitudinal) running at right angles to each other.

Structural Characteristics of Smooth M_1

<Anatomical Structure>

- No sarcomeres (hence the name smooth)
- Spindle shaped cells
- A single nucleus present in the central thick portion
- Relatively small compared to skeletal and cardiac muscle
- Fewer mitochondria as compared to the skeletal muscle





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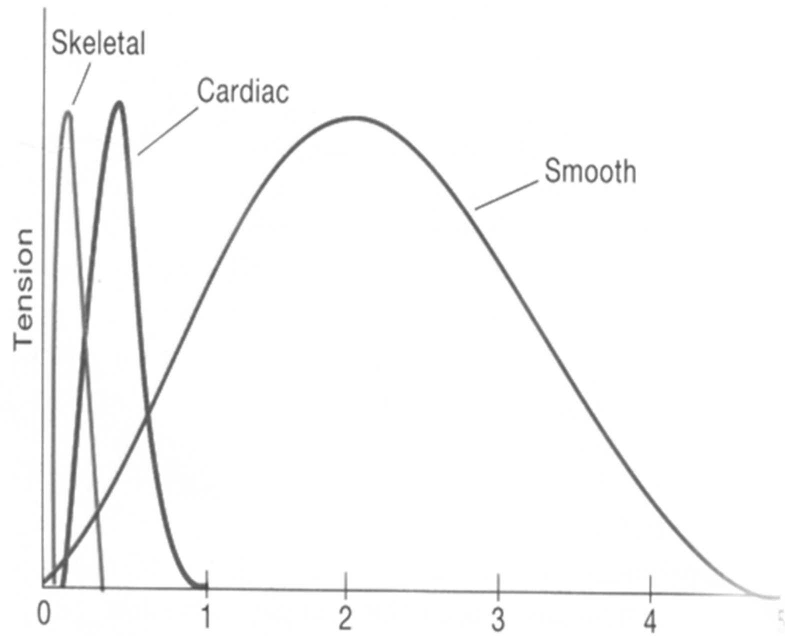
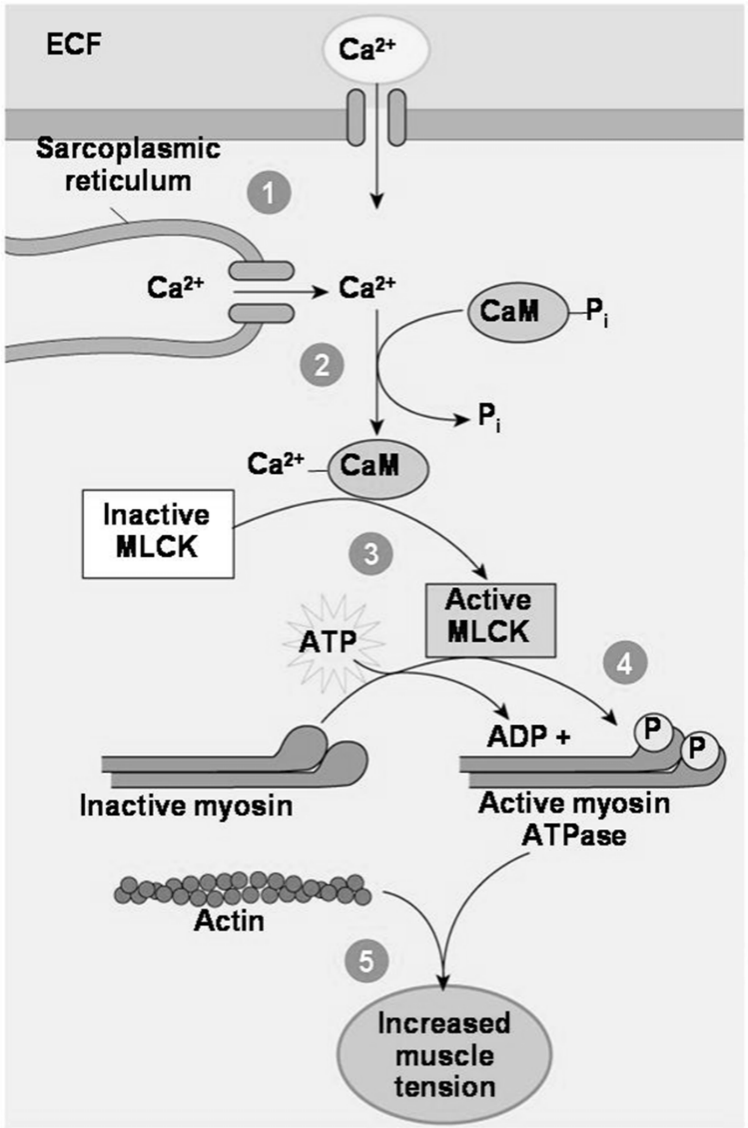
Single Muscle Twitch

- Single muscle contraction (muscle twitch) develops more slowly & relaxes even more slowly

  → longer sustained contraction without fatigue
- A typical smooth muscle contraction is about 30 times longer than single skeletal muscle contraction
- Advantage: allows the walls of organs to maintain tension with a continued load .e.g. urinary bladder filled with urine



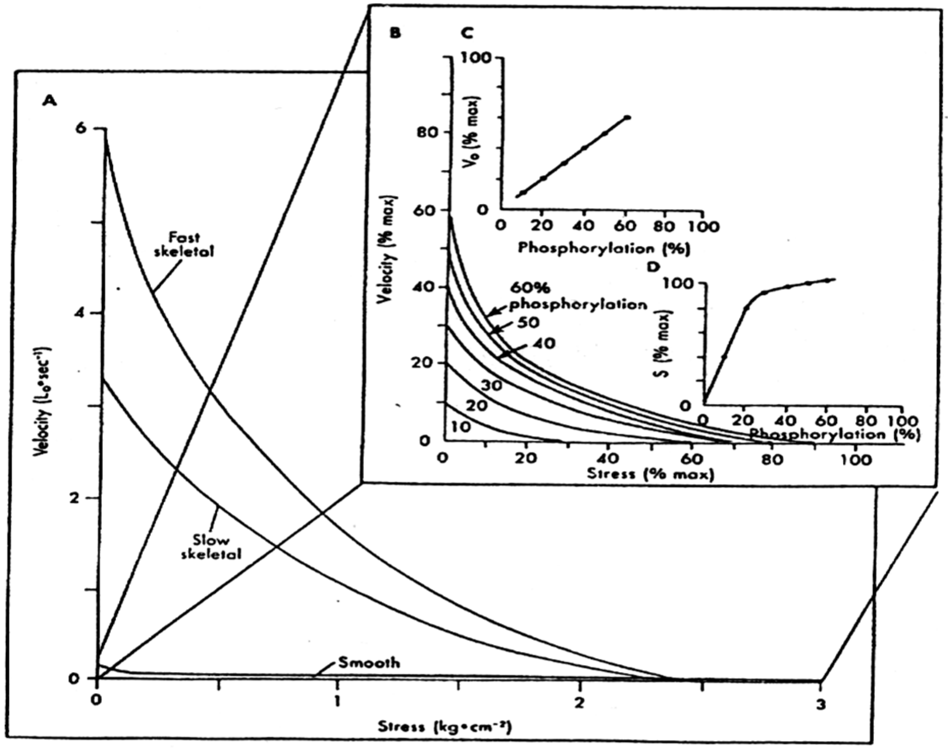
Smooth Muscle Contraction



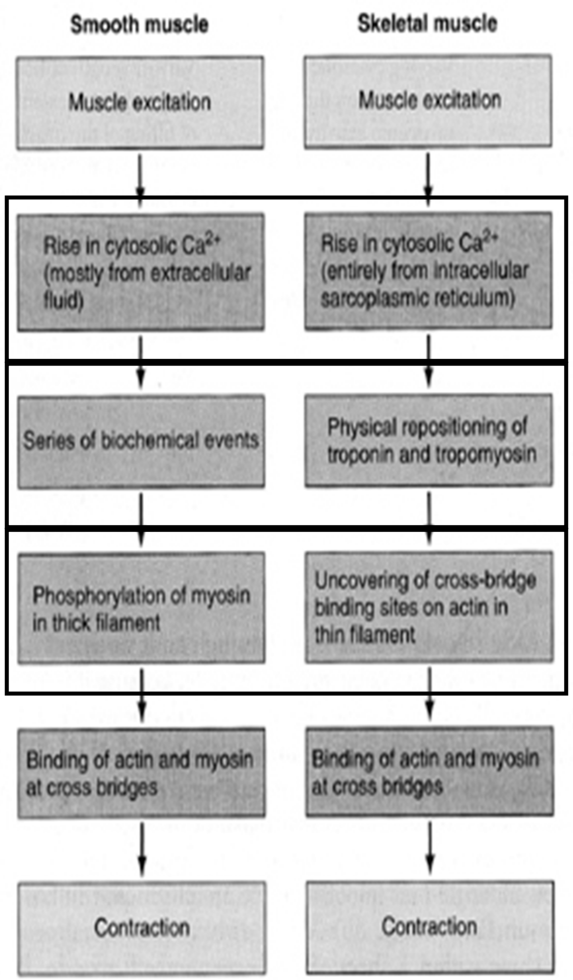
1. Excitatory stimulus leads to rise in intracellular [Ca^{2+}]
   - Entry through membrane calcium channels
   - Release of calcium from SR intracellular stores
2. Calcium binds to calmodulin (CaM; CALcium MODULated proteIN)
3. Calmodulin Complex activates the Myosin Light Chain Kinase (MLCK)
4. MLCK phosphorylates the myosin light chains
5. Myosin can begin to cycle and attach to actin

Unique Mechanical Properties

- Slow shortening velocity
  - Slow actomyosin ATPase (i.e. slow cross bridge cycle)
- Max shortening velocities and active stress are proportion of phosphorylation
- High economy of energy utilization during isometric contraction (latch state)



Difference in Contraction Mechanism Between Smooth M. & Striated M.



- Smooth m.
  - Ca^{2+} from extracellular space and SR
  - Covalent regulation: Ca-calmodulin-MLCK phosphorylates myosin
  - Thick filament regulation: myosin-based
- Striated m. (skeletal m. & cardiac m.)
  - Ca^{2+} from SR only
  - Allosteric regulation: Ca^{2+} binds TnC→ tropomyosin moves → myosin binding site is exposed
  - Thin filament regulation: actin-tropomyosin-troponin complex-based

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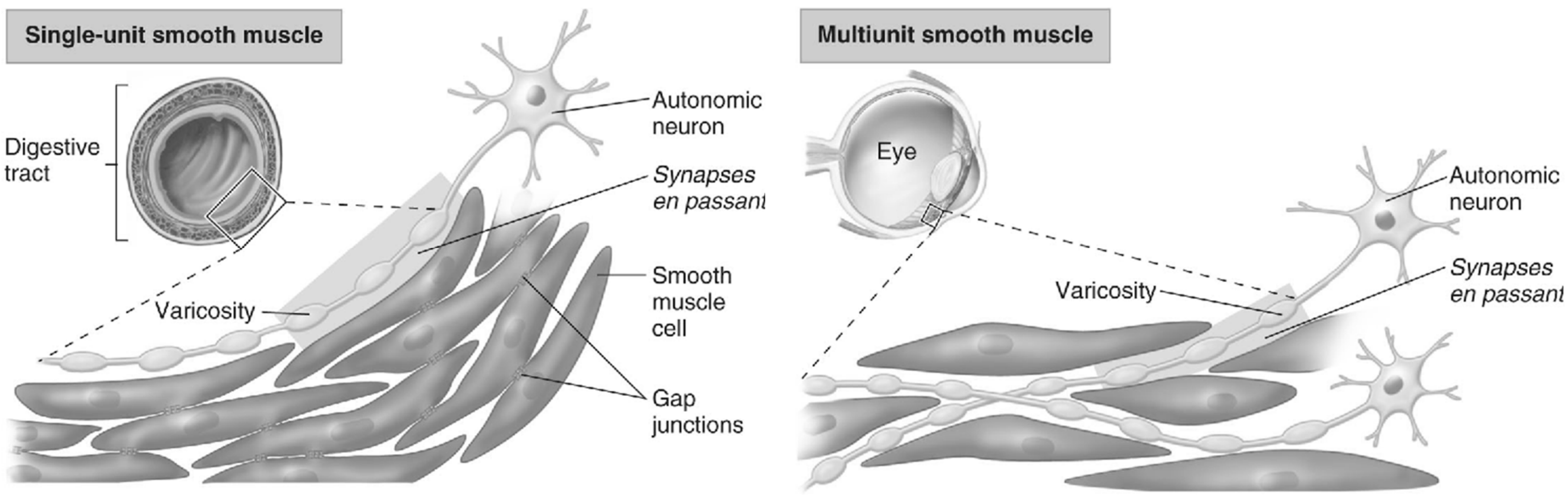
Classification of Smooth Muscle

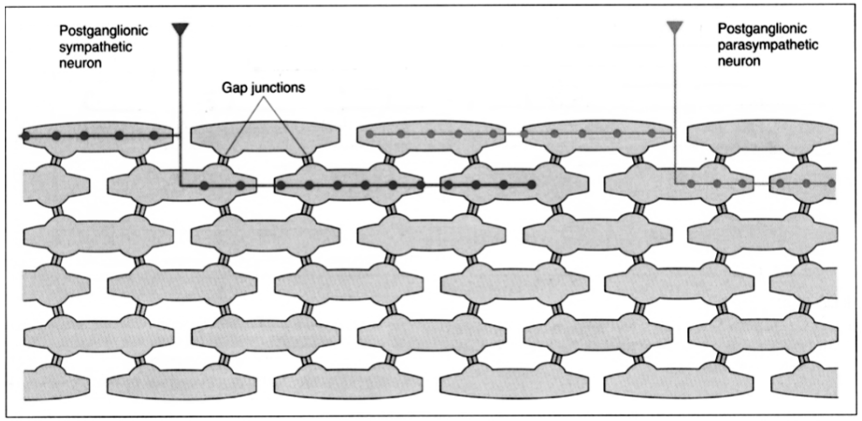
Types of smooth muscle:

- Single unit (visceral or unitary): common
  - Function as a unit
- Multiunit: rare
  - Cells or groups of cells act as independent units



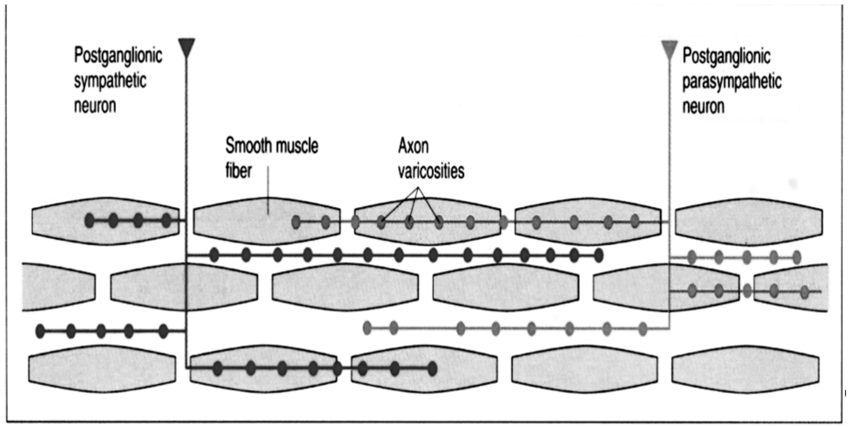
Single-Unit Smooth Muscle

- Behave in a synchronic manner, much like cardiac muscle
- Function as a single unit and contract together
  - When an AP develops in one cell, depolarization quickly spreads to other cells
- Link by gap junctions
- Example:
  - Small intestine
  - Urinary bladder
  - Uterus
  - Smaller arteriole
  - Lymph vessels



Multiunit Smooth Muscle

- Each smooth muscle cell acts independently (like skeletal muscle)
- Less gap junctions between cells
- Example:
  - Large blood vessels
  - Tracheal muscle & bronchial muscle
  - Iris muscle
  - Base of hair follicles (goose bumps)



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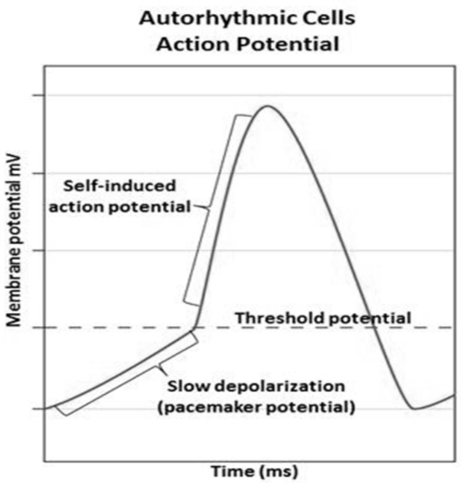
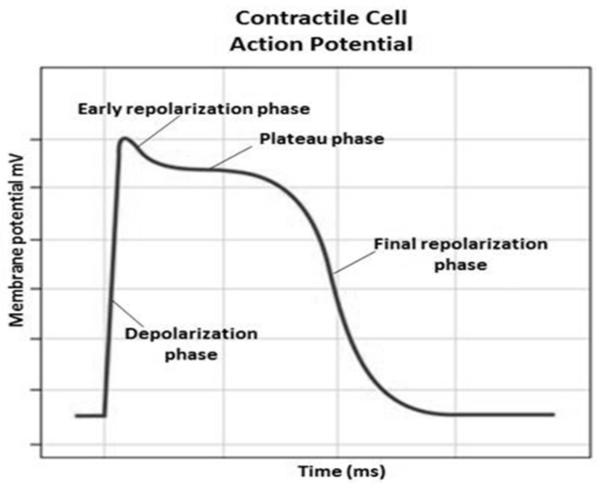
Cardiac Muscle

- Autorhythmic cells
  - Do not contract
  - Initiate and conduct action potentials
  - No resting potential; neural input not necessary to initiate an action potential
  - Pacemaker activity instead: slow depolarization, drift to threshold, then firing
- Contractile cells
  - Do not initiate their own action potentials
  - Pump heart

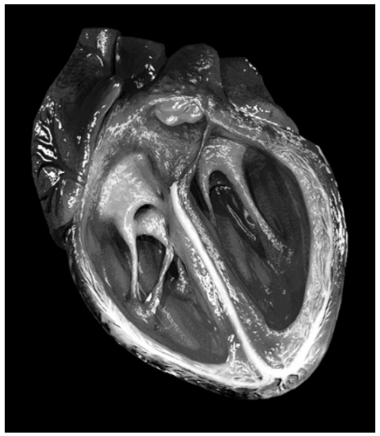


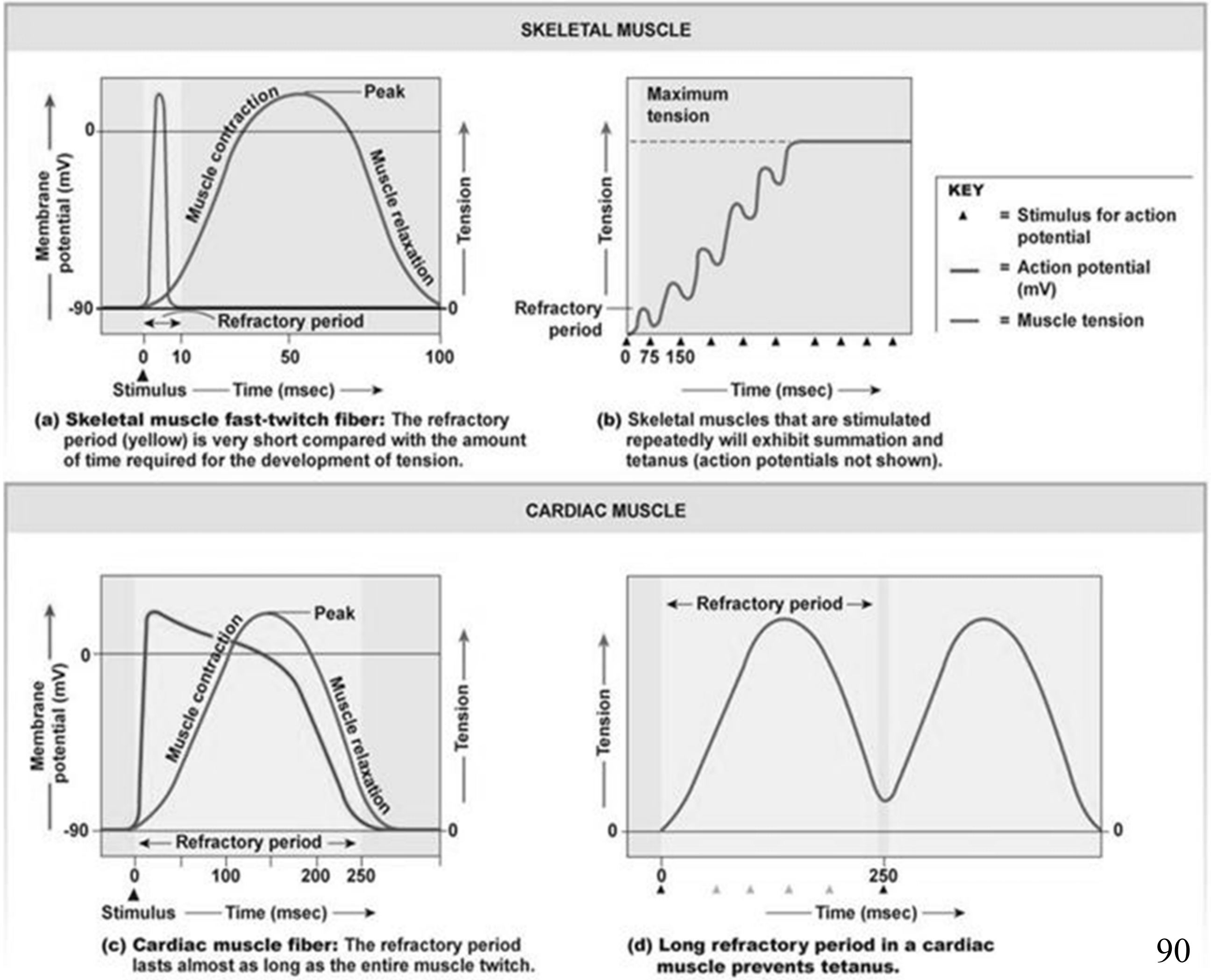


Excitability

The refractory period lasts almost as long as the entire muscle twitch

- No summation
- No tetanus





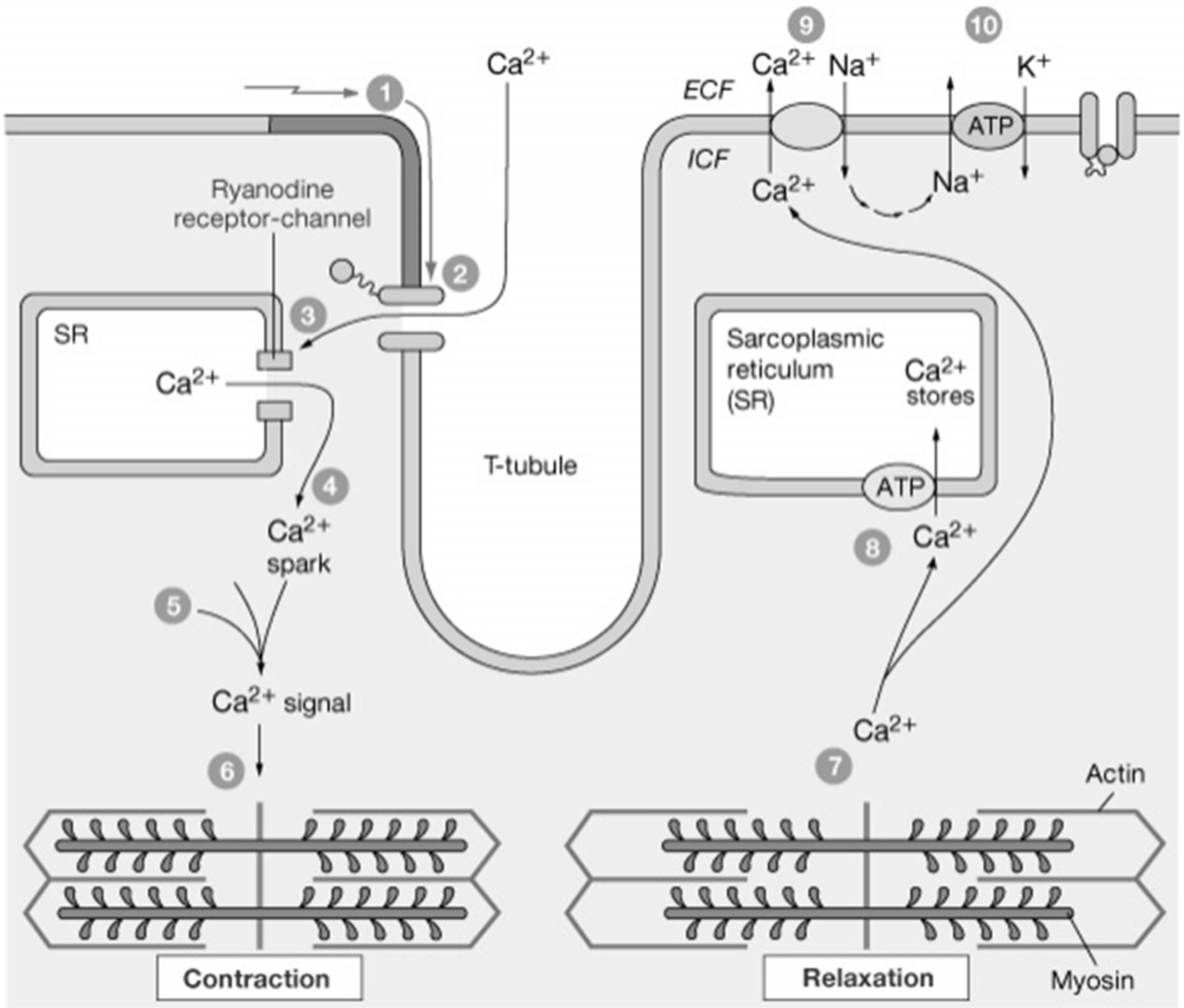
(a) **Skeletal muscle fast-twitch fiber:** The refractory period (yellow) is very short compared with the amount of time required for the development of tension.

(b) Skeletal muscles that are stimulated repeatedly will exhibit summation and tetanus (action potentials not shown).

(c) **Cardiac muscle fiber:** The refractory period lasts almost as long as the entire muscle twitch.

(d) **Long refractory period in a cardiac muscle prevents tetanus.**

Mechanism of Cardiac Muscle Excitation, Contraction, & Relaxation



1. Action potential enters from adjacent cell.
2. Voltage-gated Ca^{2+} channels open. Ca^{2+} enters cell.
3. Ca^{2+} induces Ca^{2+} release through ryanodine receptor-channels (RyR).
4. Local release causes Ca^{2+} spark.
5. Summed Ca^{2+} sparks create a Ca^{2+} signal.
6. Ca^{2+} ions bind to troponin to initiate contraction.
7. Relaxation occurs when Ca^{2+} unbinds from troponin.
8. Ca^{2+} is pumped back into the sarcoplasmic reticulum for storage.
9. Ca^{2+} is exchanged with Na^{+}.
10. Na^{+} gradient is maintained by the Na^{+}-K^{+}-ATPase.

The End!