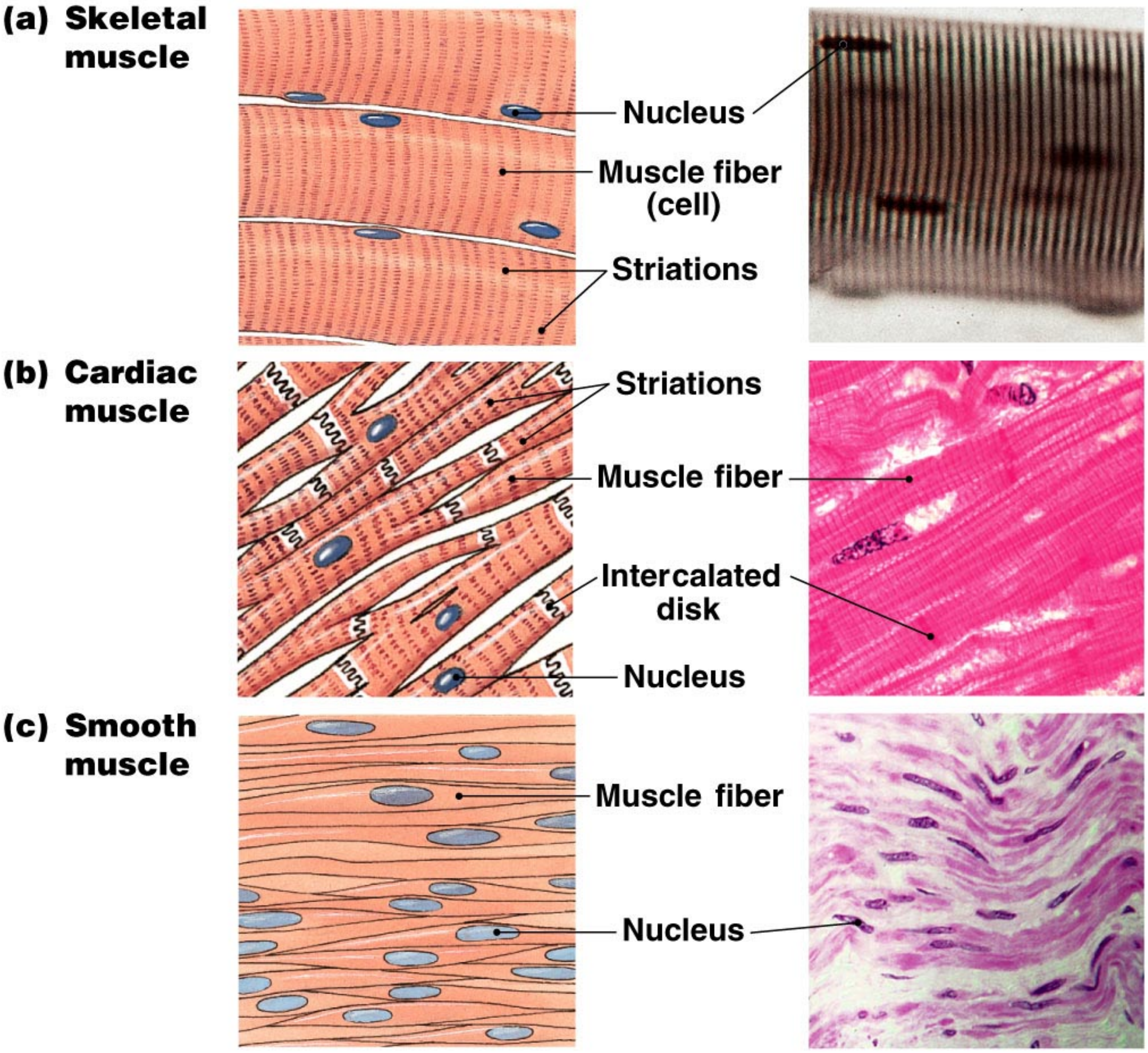
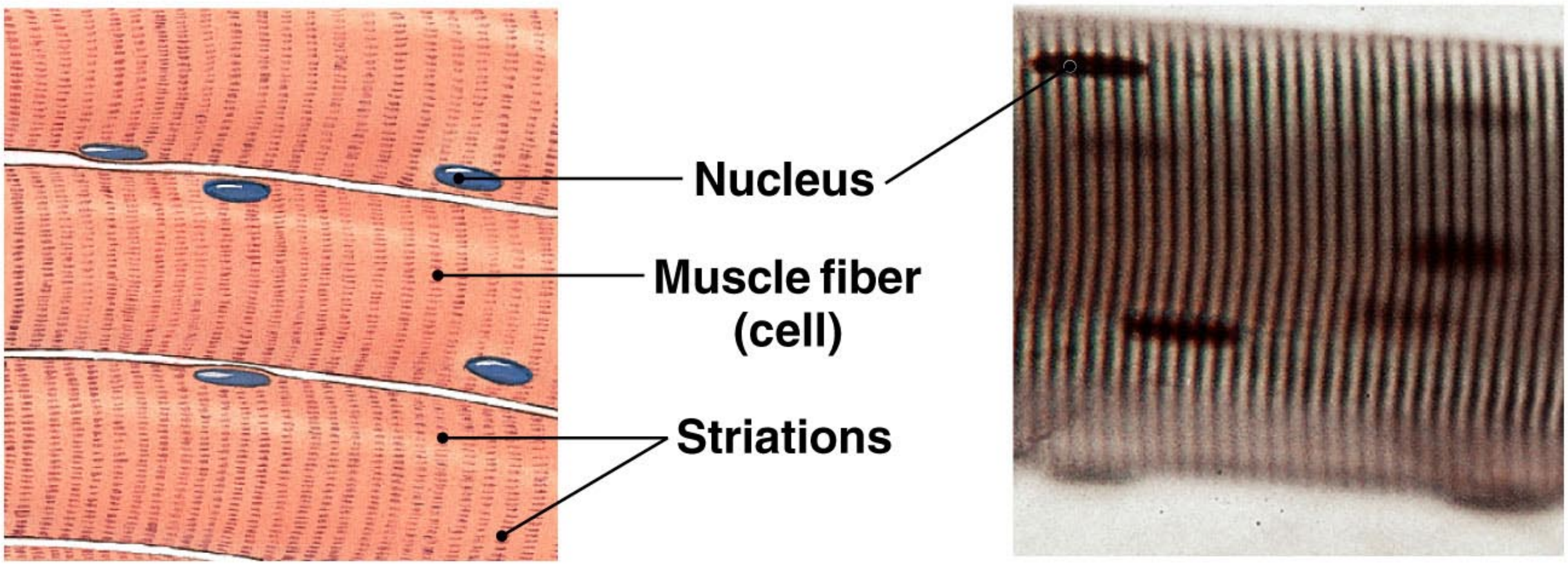


Figure 12-1 - Overview

(a) Skeletal muscle



(b) Cardiac muscle

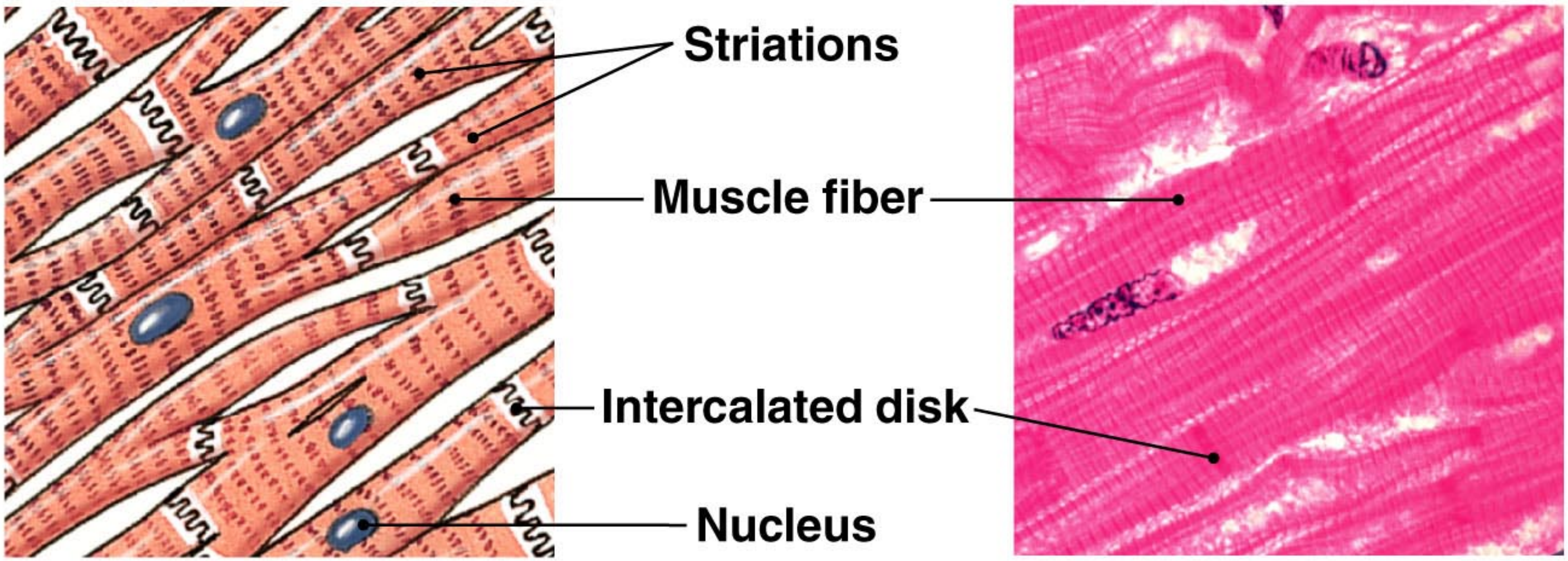


Figure 12-1b

(c) Smooth muscle

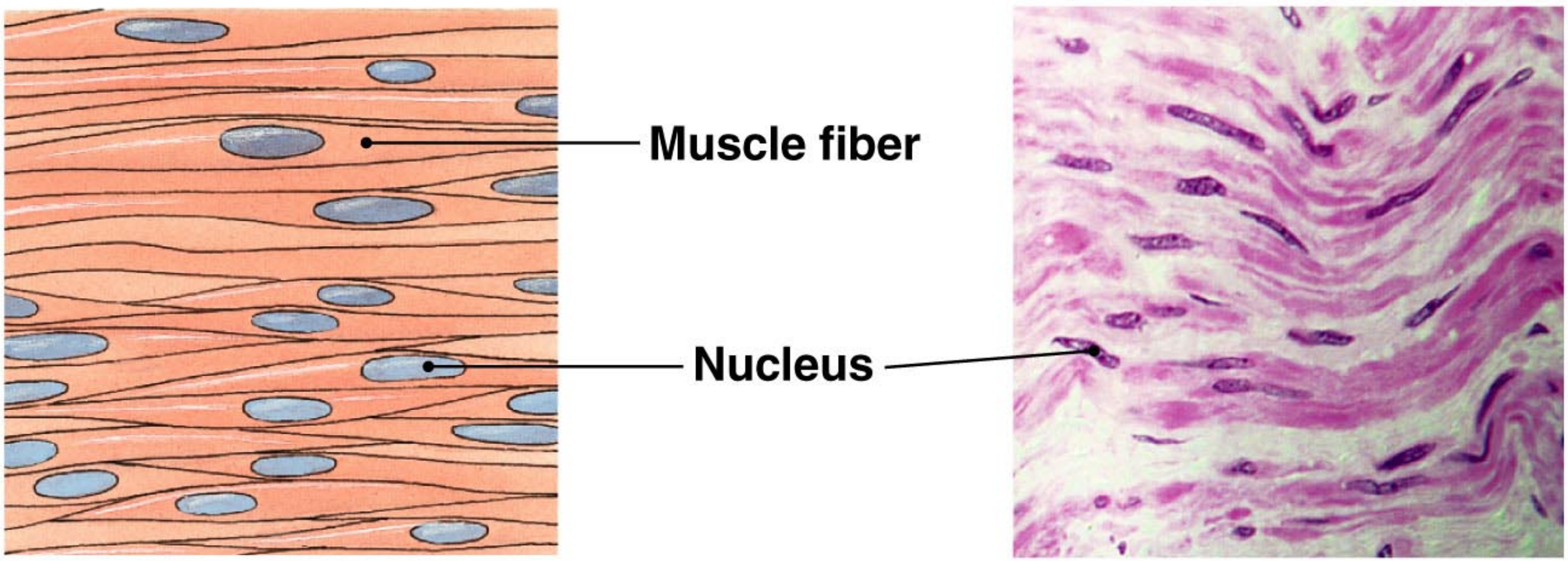


Figure 12-1c

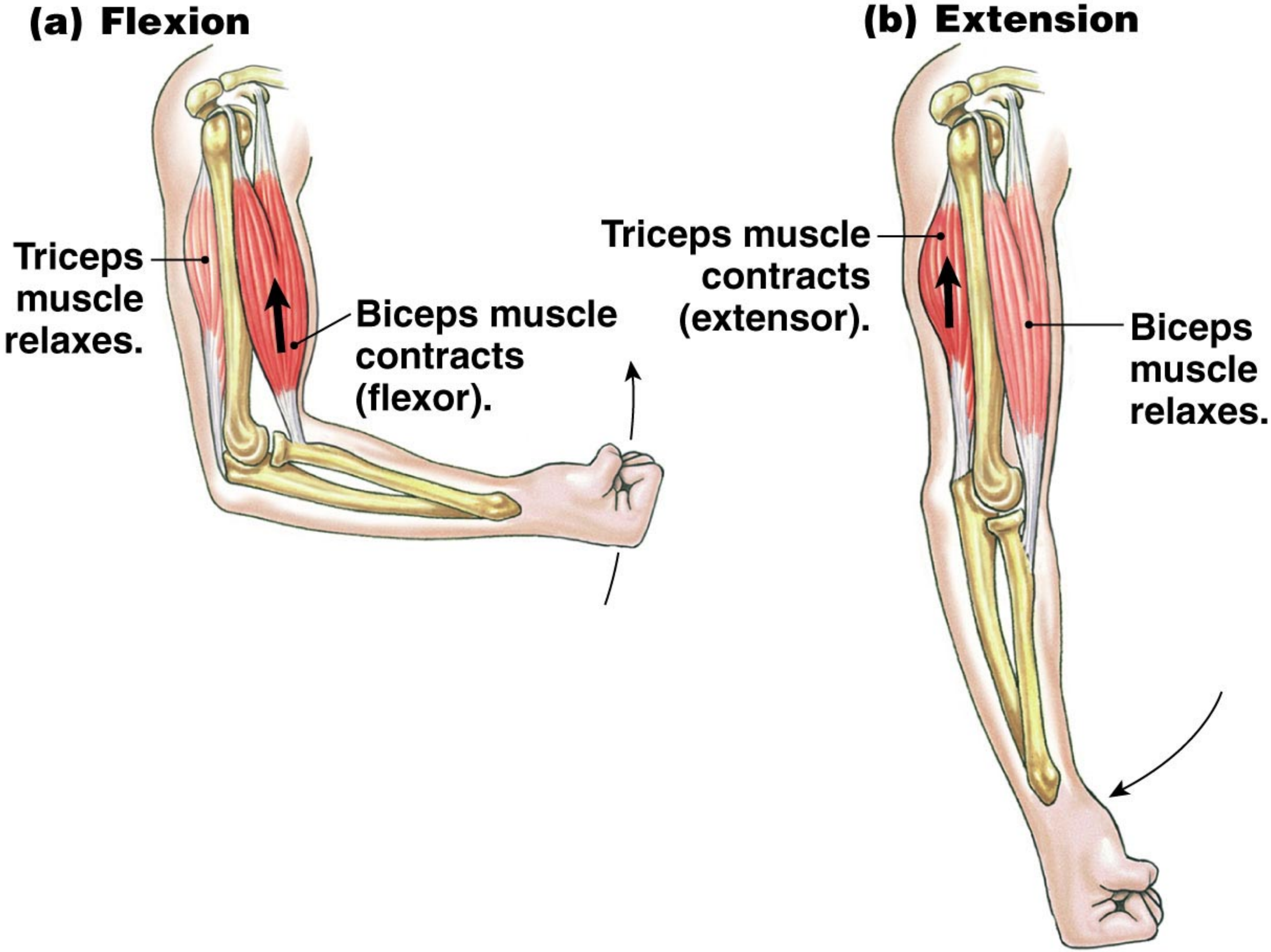


Figure 12-2 Overview

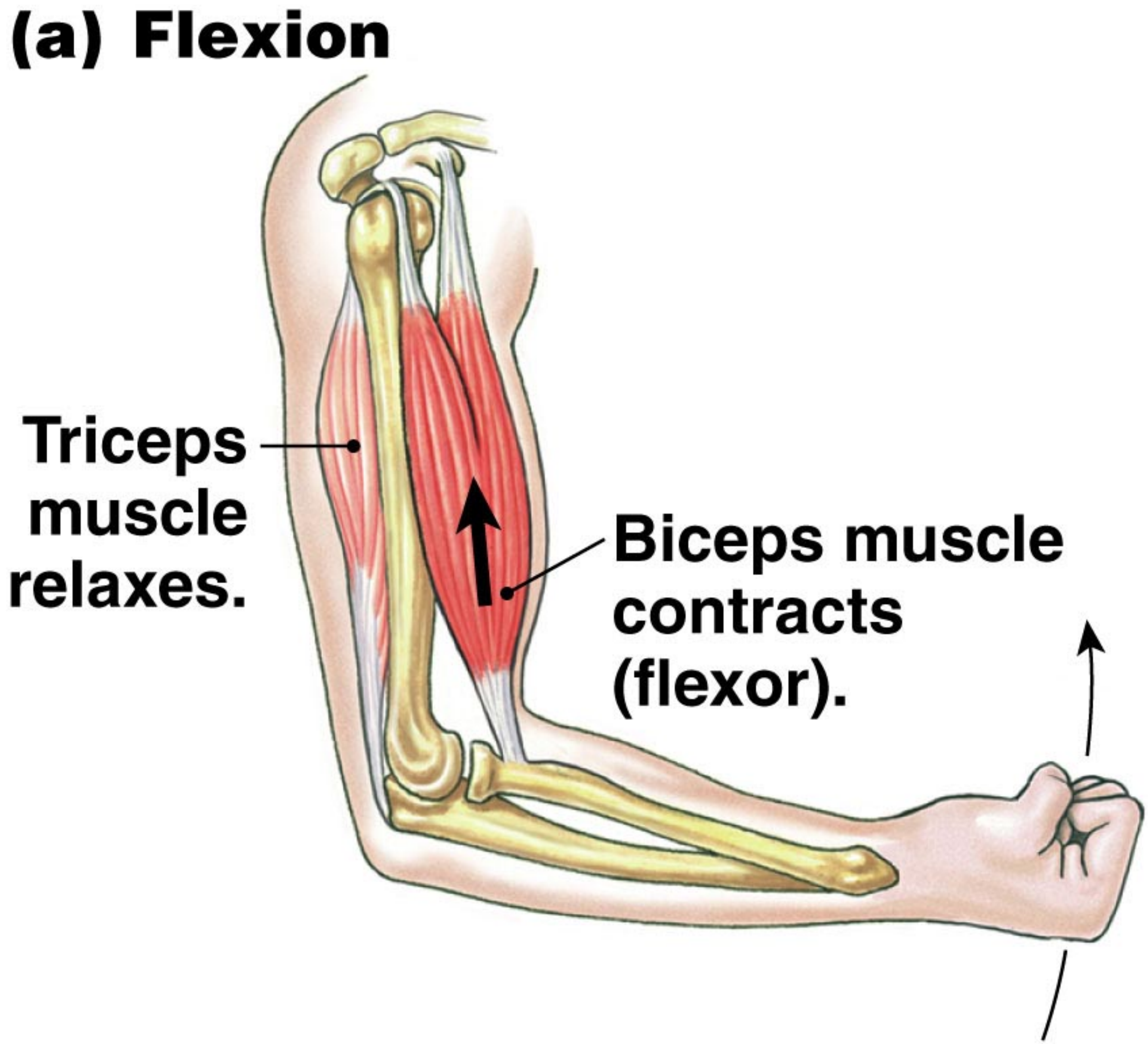

(a) Flexion
Triceps muscle relaxes.
Biceps muscle contracts (flexor).

Figure 12-2a

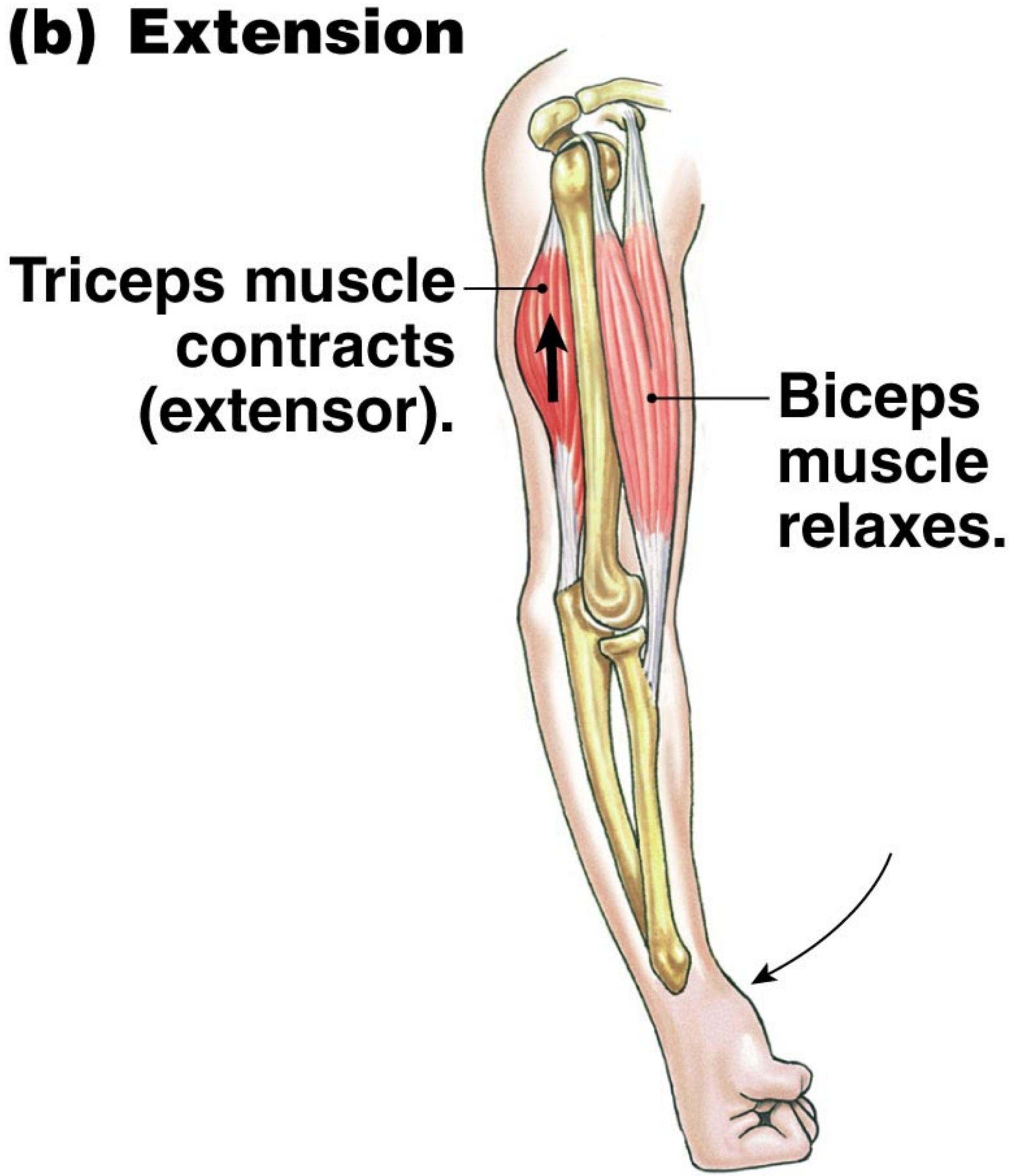

(b) Extension
Triceps muscle contracts (extensor).
Biceps muscle relaxes.

Figure 12-2b

TABLE 12-1	Muscle Terminology
GENERAL TERM	**MUSCLE EQUIVALENT**
Muscle cell	Muscle fiber
Cell membrane	Sarcolemma
Cytoplasm	Sarcoplasm
Modified endoplasmic reticulum	Sarcoplasmic reticulum

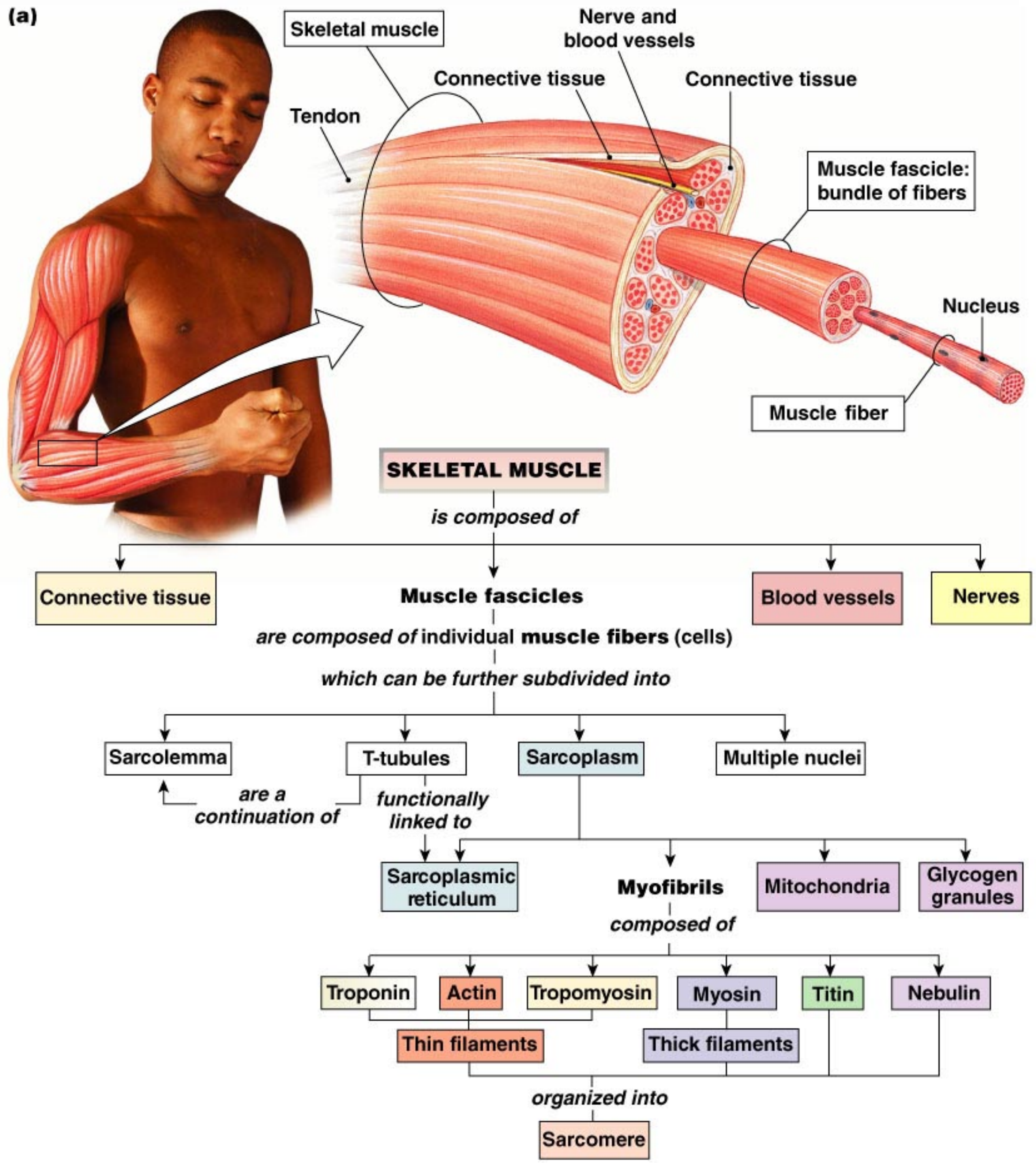
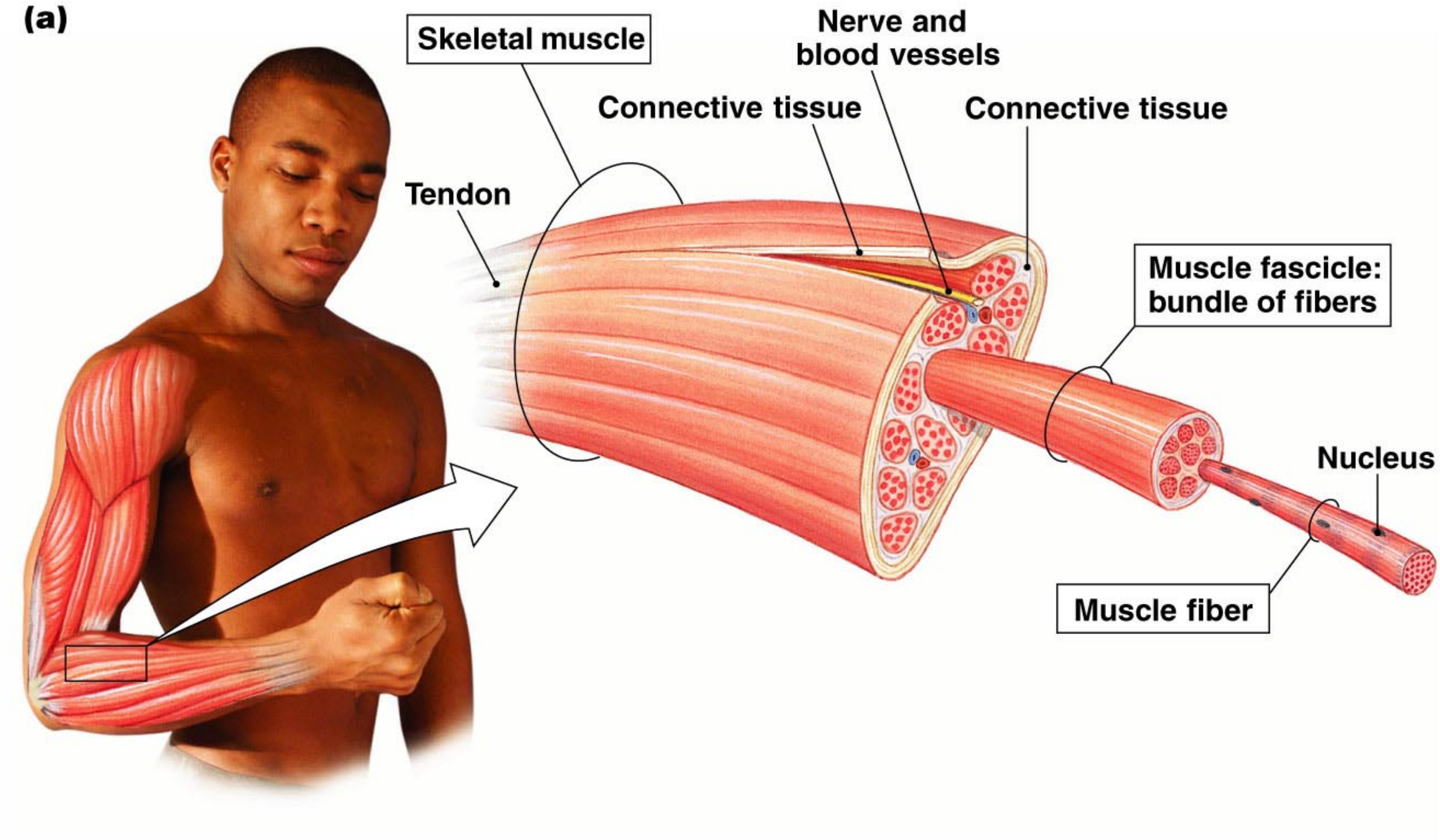


Figure 12-3a: Overview


(a)
Skeletal muscle
Nerve and blood vessels
Connective tissue
Connective tissue
Tendon
Muscle fascicle: bundle of fibers
Nucleus
Muscle fiber

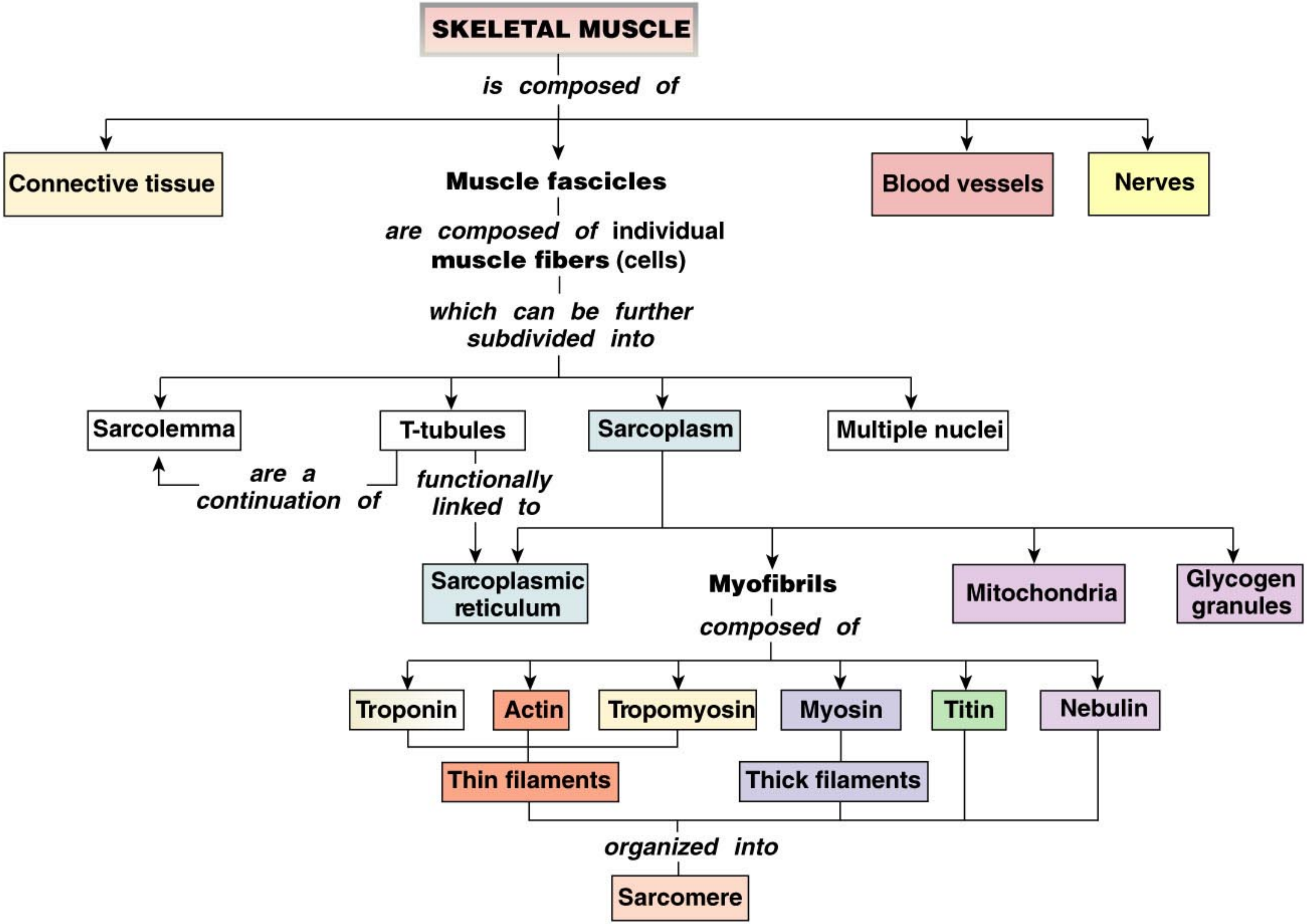


Figure 12-3a (2 of 2)

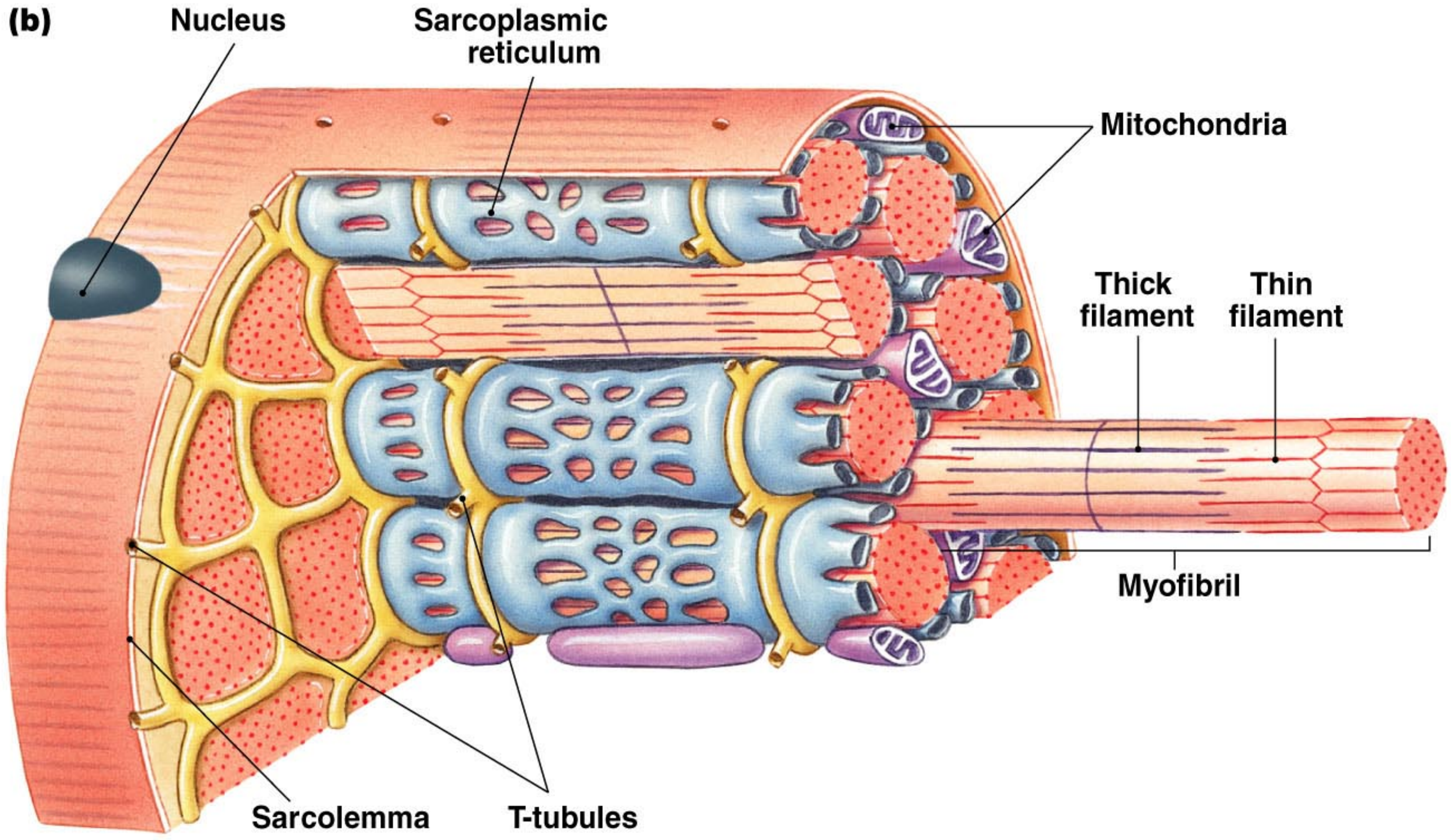

(b)
Nucleus
Sarcoplasmic reticulum
Mitochondria
Thick filament
Thin filament
Myofibril
Sarcolemma
T-tubules

Figure 12-3b

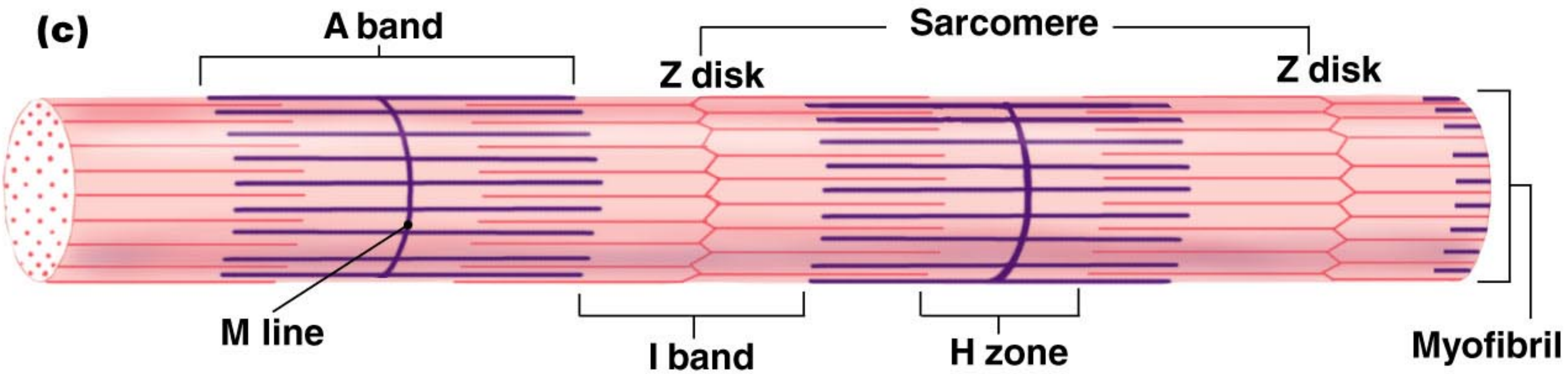


Figure 12-3c

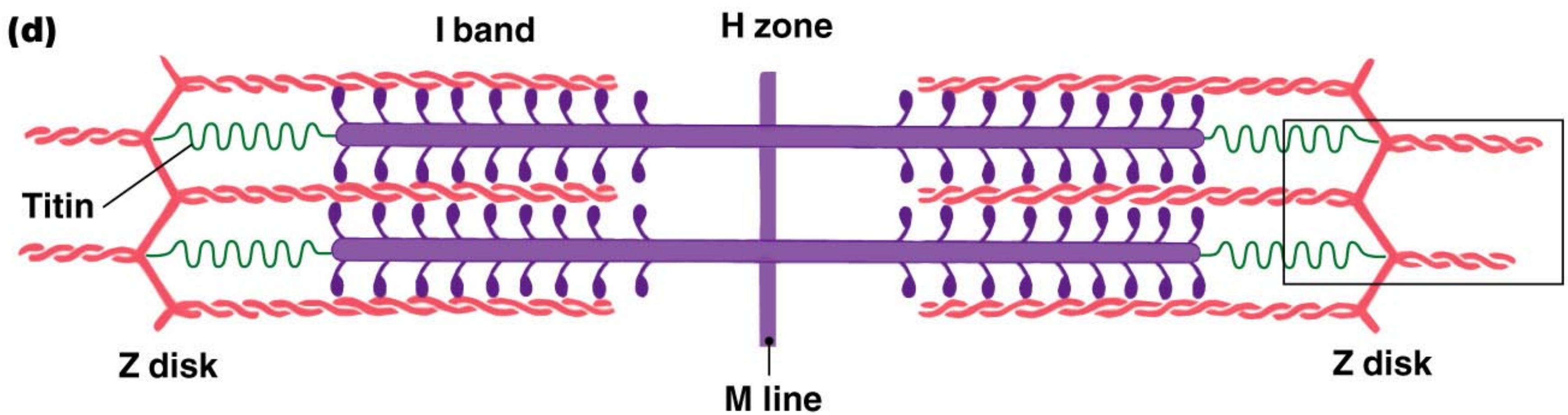


Figure 12-3d

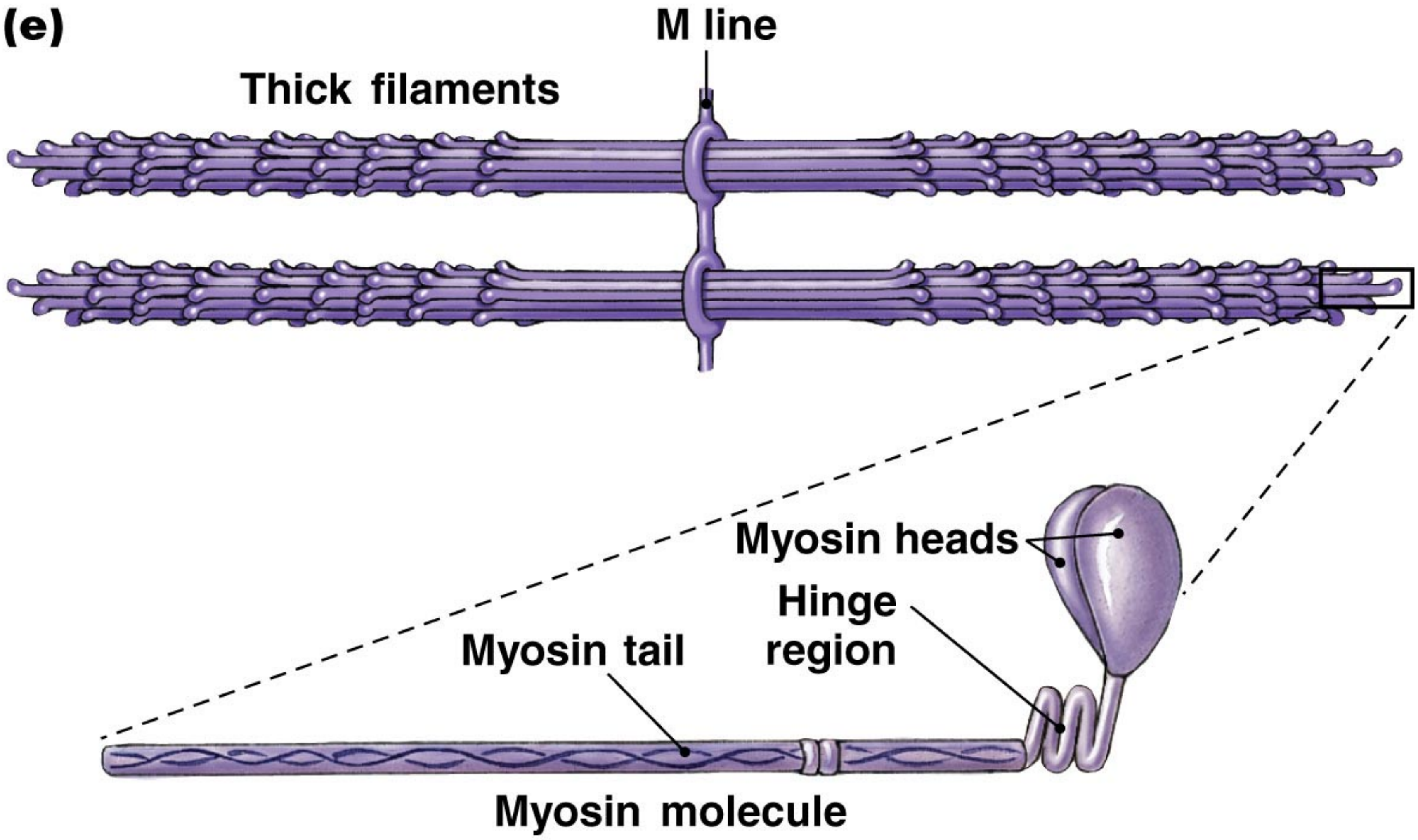

(e)
M line
Thick filaments
Myosin heads
Hinge region
Myosin tail
Myosin molecule

Figure 12-3e

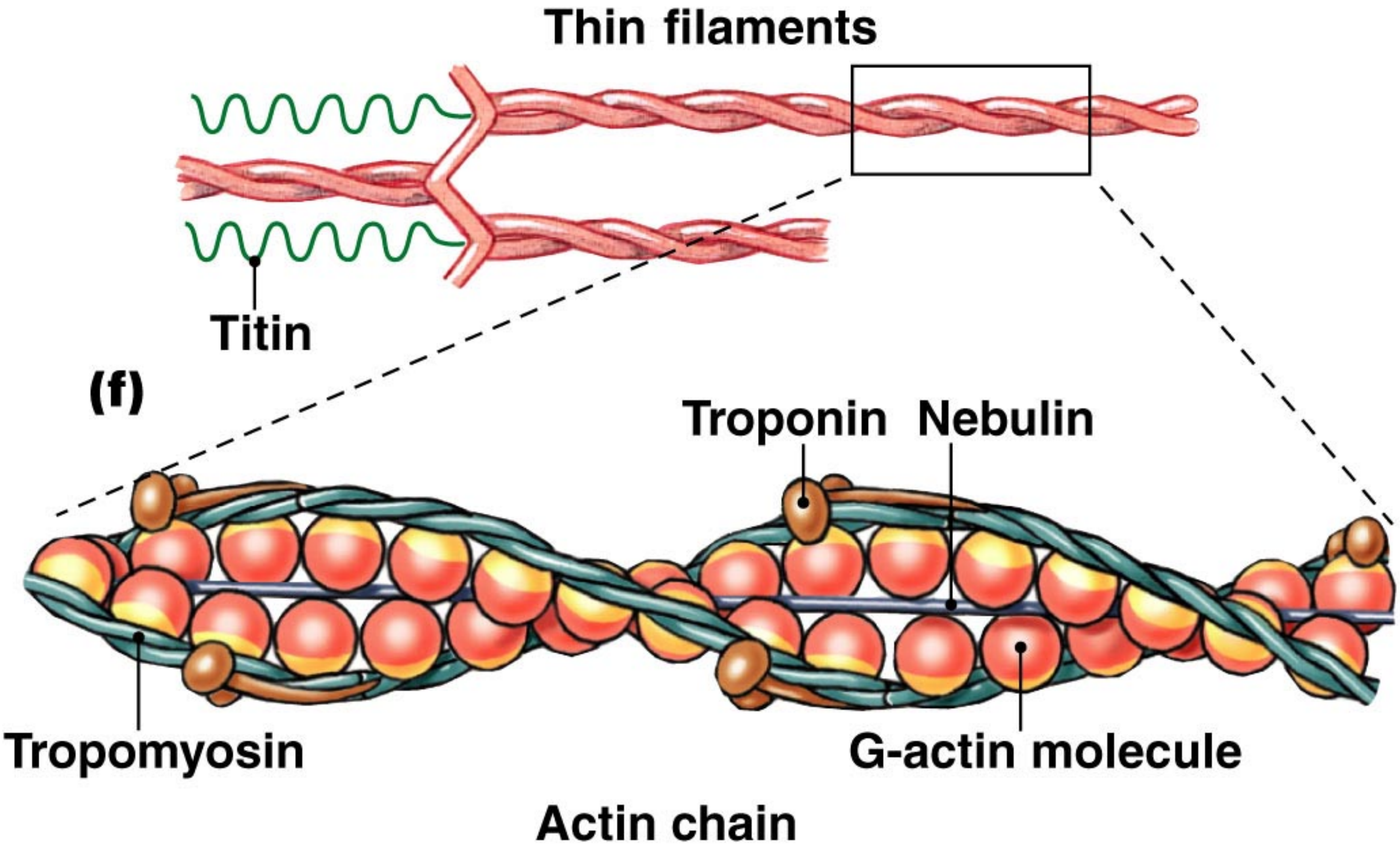
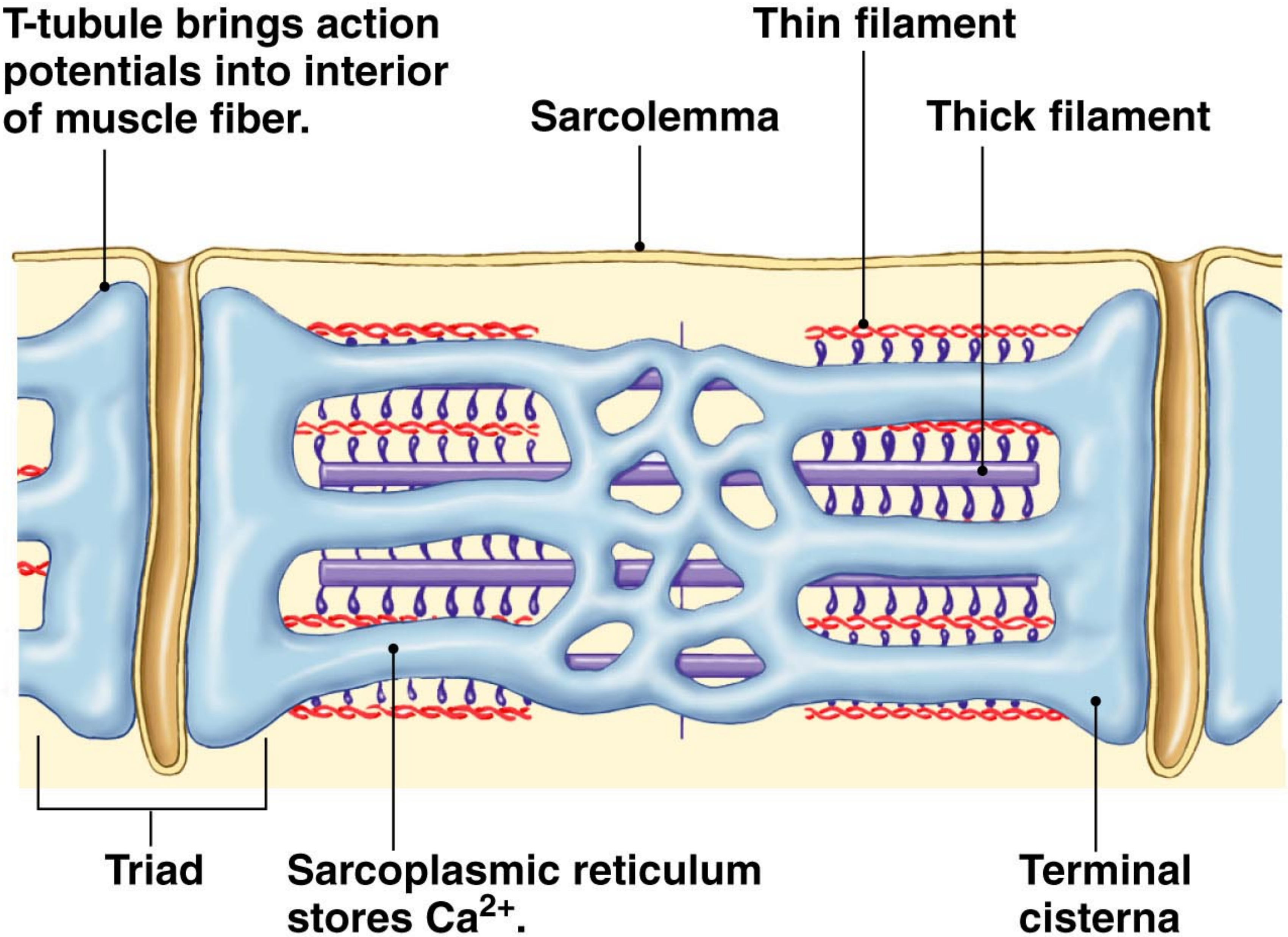

Thin filaments
Titin
(f)
Troponin
Nebulin
Tropomyosin
G-actin molecule
Actin chain

Figure 12-3f



T-tubule brings action potentials into interior of muscle fiber.
Sarcolemma
Thin filament
Thick filament
Triad
Sarcoplasmic reticulum stores Ca^{2+}.
Terminal cisterna

Figure 12-4

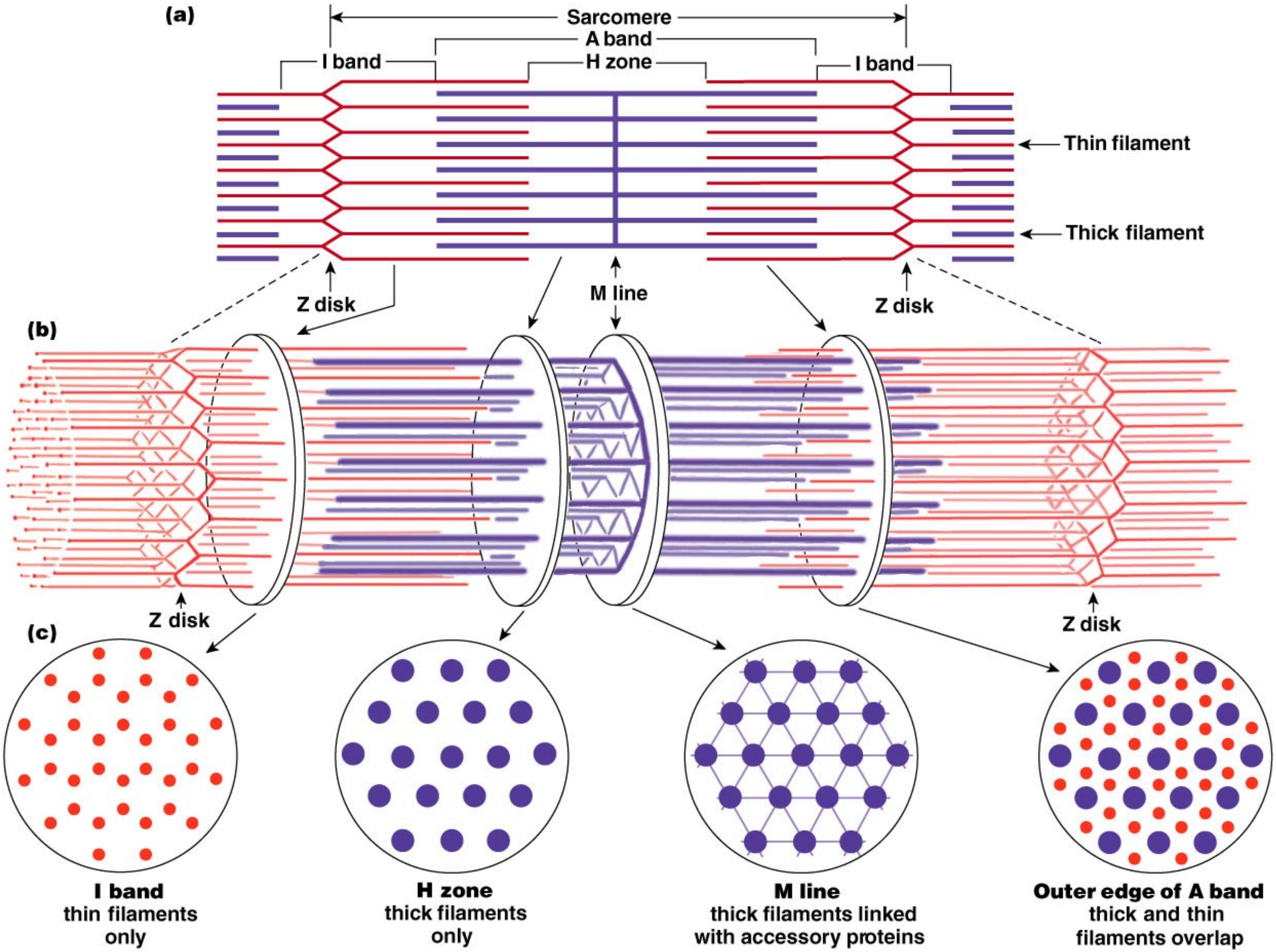


Figure 12-5 - Overview

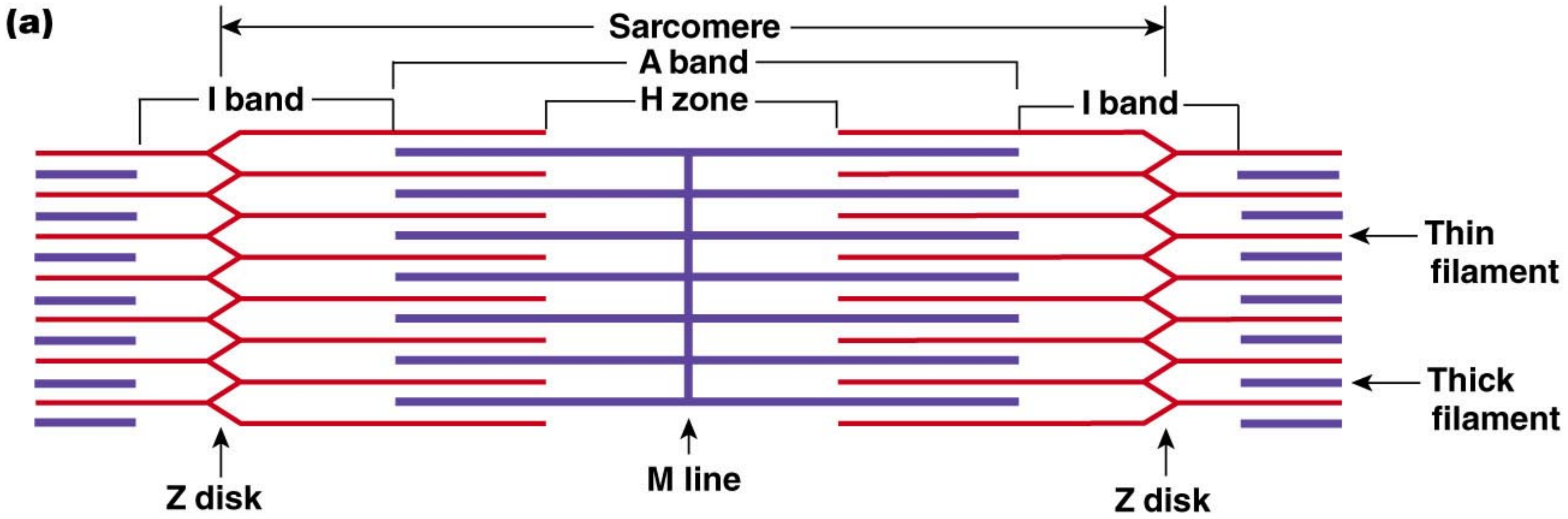

(a)
Sarcomere
A band
H zone
I band
I band
Thin filament
Thick filament
Z disk
M line
Z disk

Figure 12-5a

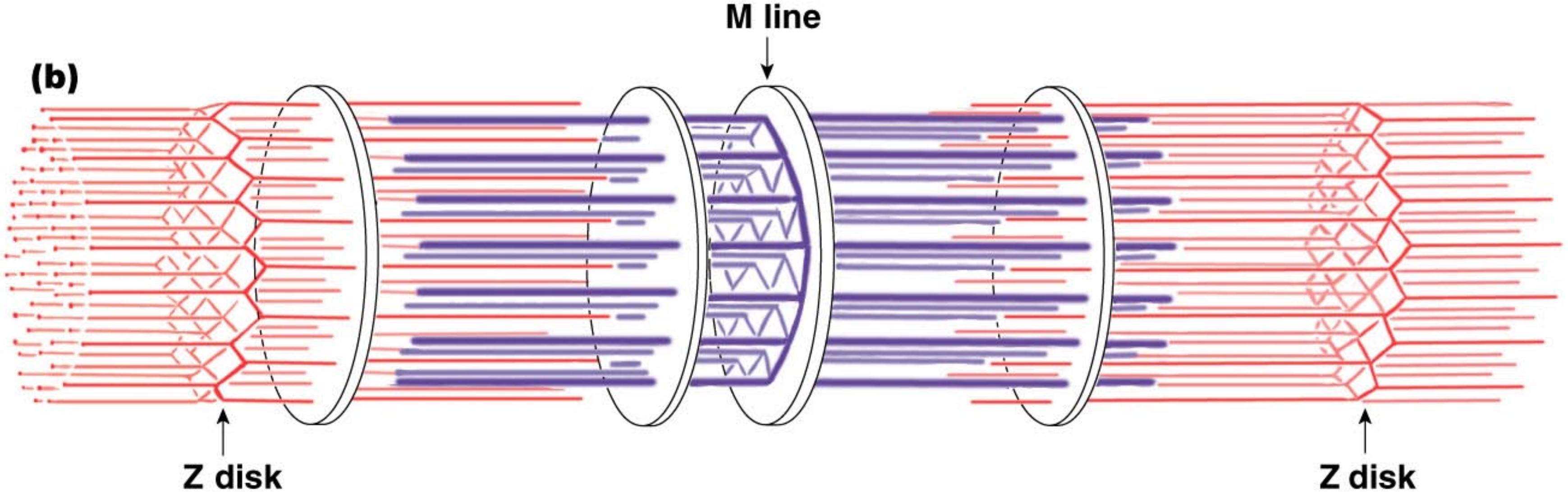


Figure 12-5b

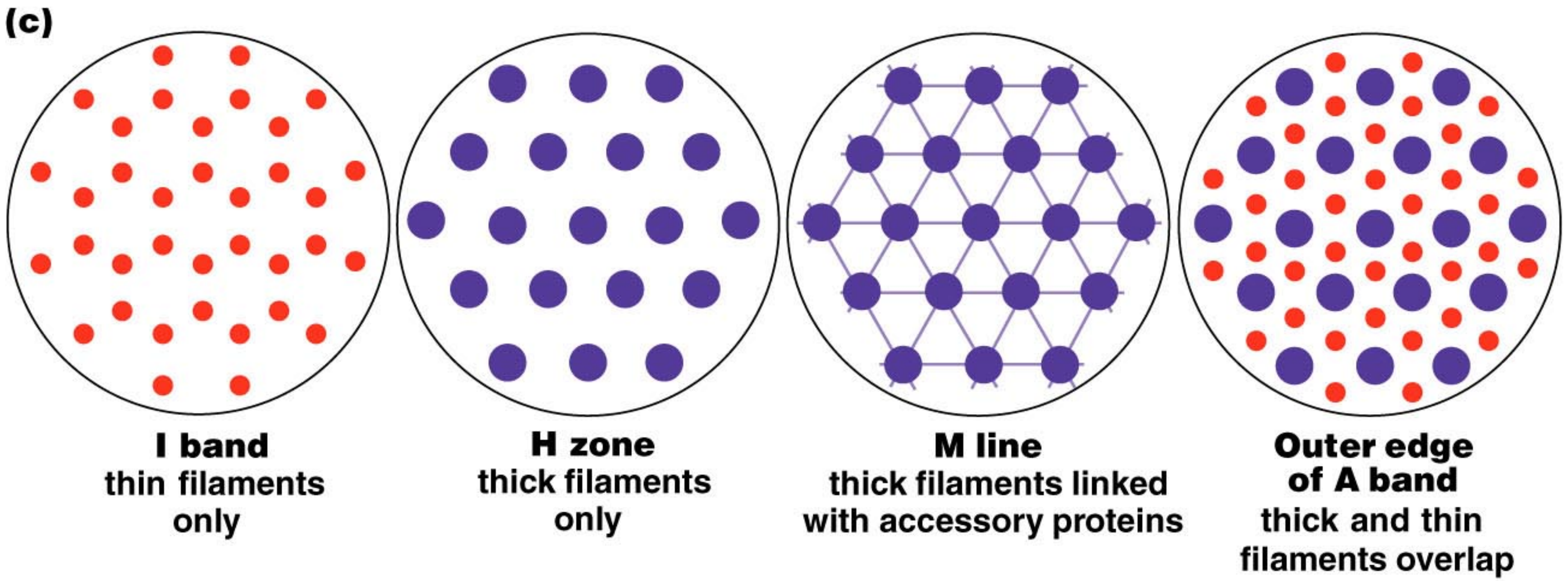

(c)
I band
thin filaments only
H zone
thick filaments only
M line
thick filaments linked with accessory proteins
Outer edge of A band
thick and thin filaments overlap

Figure 12-5c

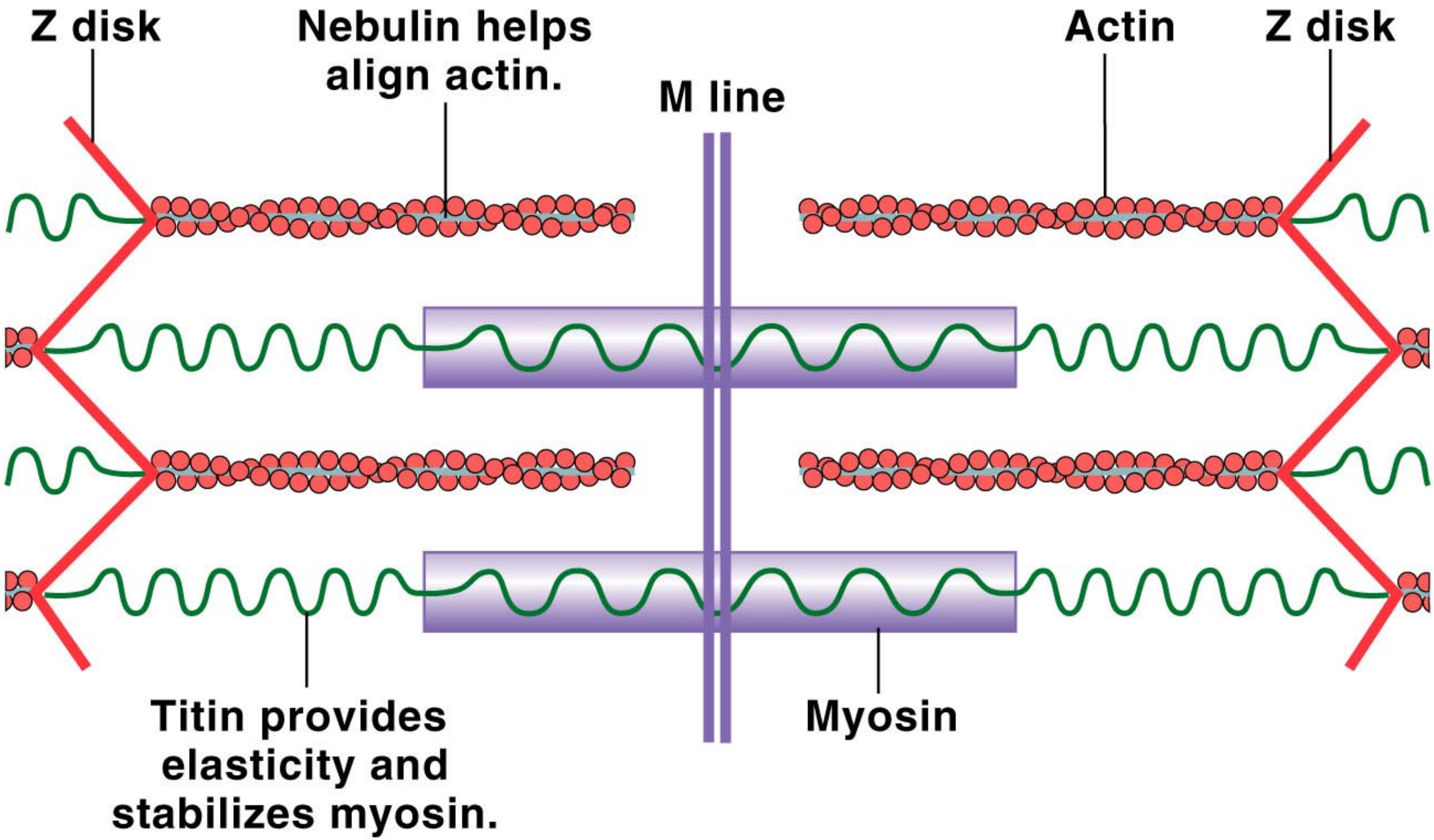

Z disk
Nebulin helps align actin.
M line
Actin
Z disk
Titin provides elasticity and stabilizes myosin.
Myosin

Figure 12-6

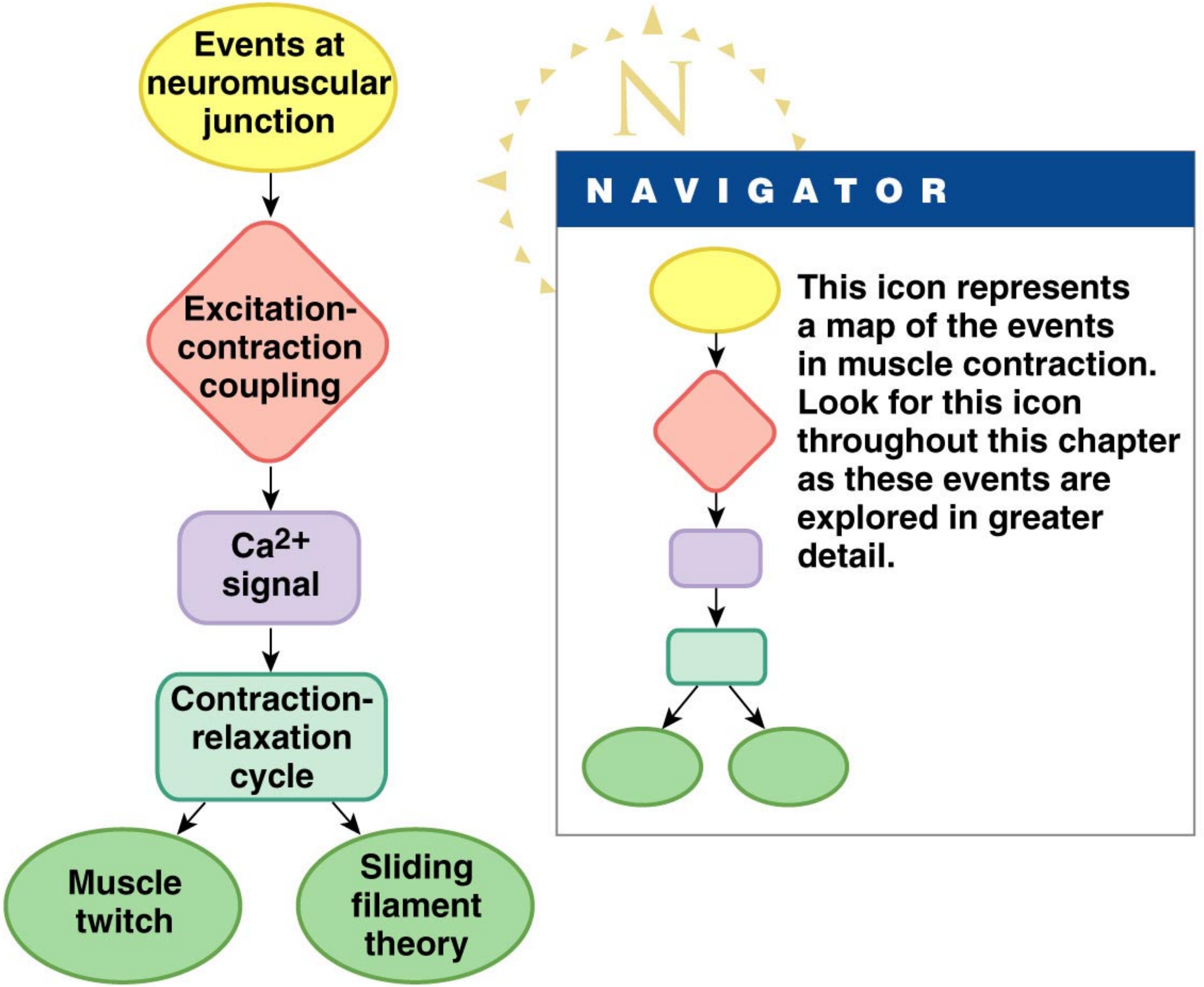

Events at neuromuscular junction
Excitation-contraction coupling
Ca2+ signal
Contraction-relaxation cycle
Muscle twitch
Sliding filament theory
N
NAVIGATOR
This icon represents a map of the events in muscle contraction. Look for this icon throughout this chapter as these events are explored in greater detail.

Figure 12-7

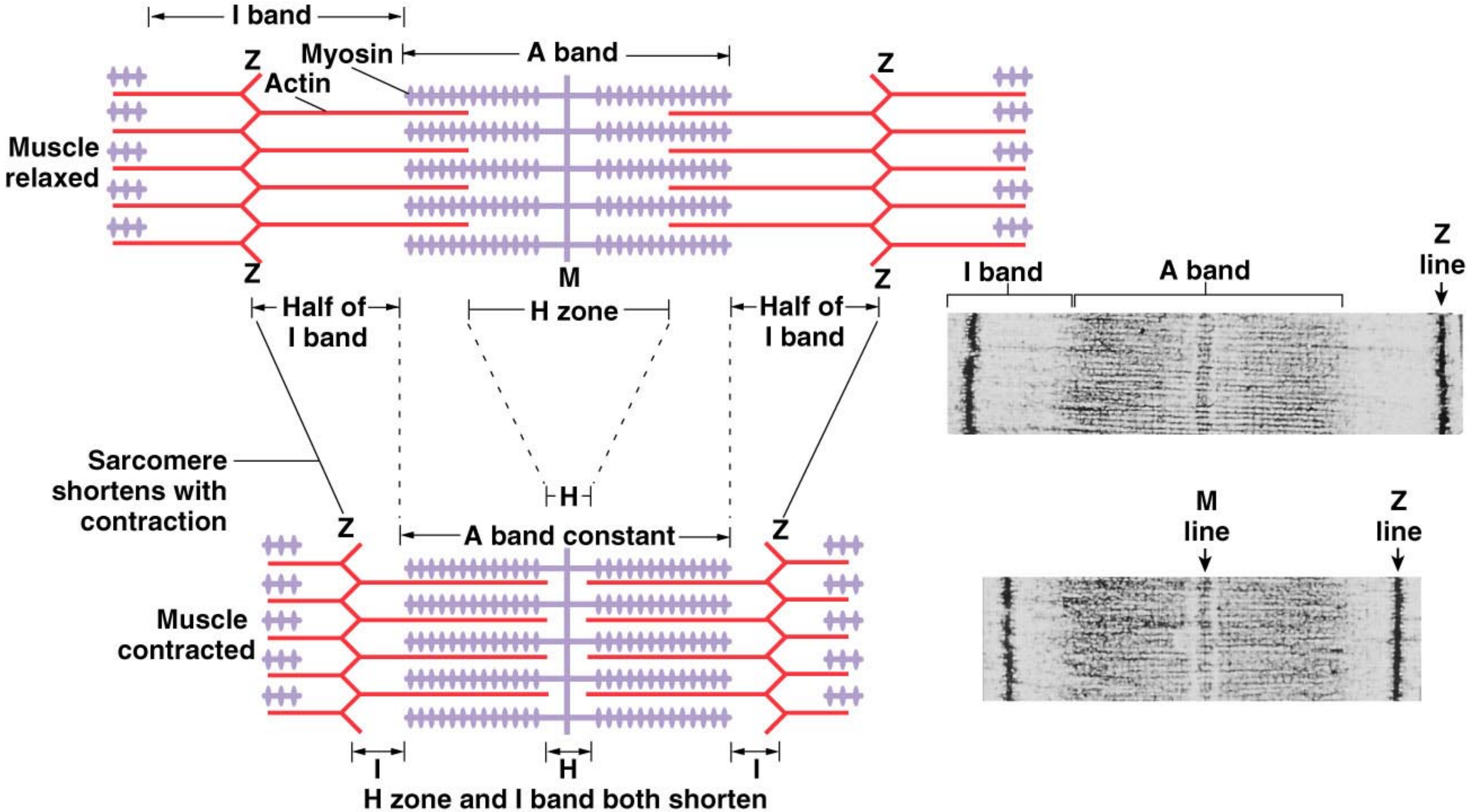

I band
Myosin
A band
Z
Actin
Muscle relaxed
M
Z
Half of I band
H zone
Half of I band
Sarcomere shortens with contraction
H
Z
A band constant
Z
Muscle contracted
I
H
I
H zone and I band both shorten
I band
A band
Z line
M line
Z line

Figure 12-8

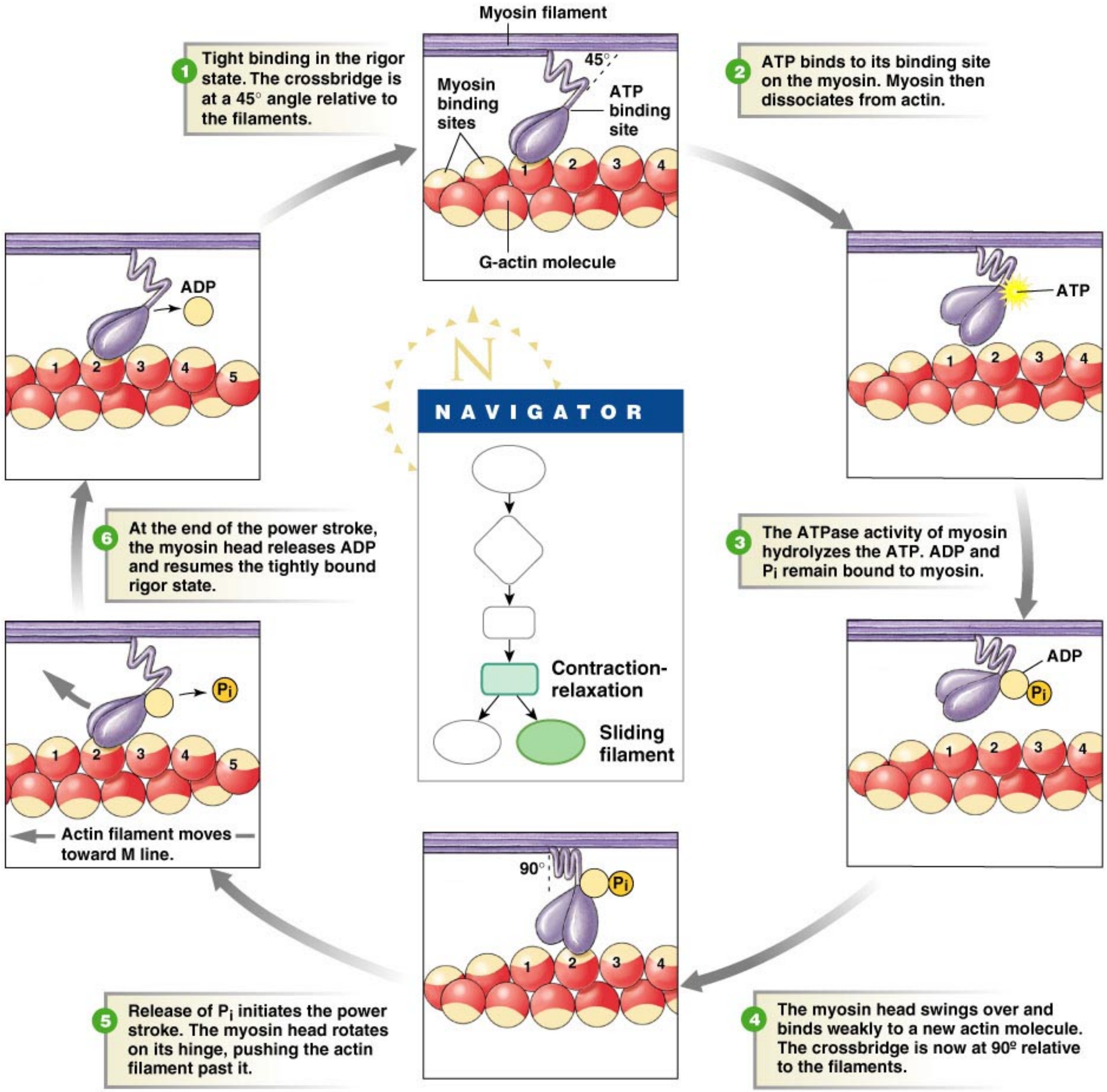


Figure 12-9 Overview

1 Tight binding in the rigor state. The crossbridge is at a 45° angle relative to the filaments.

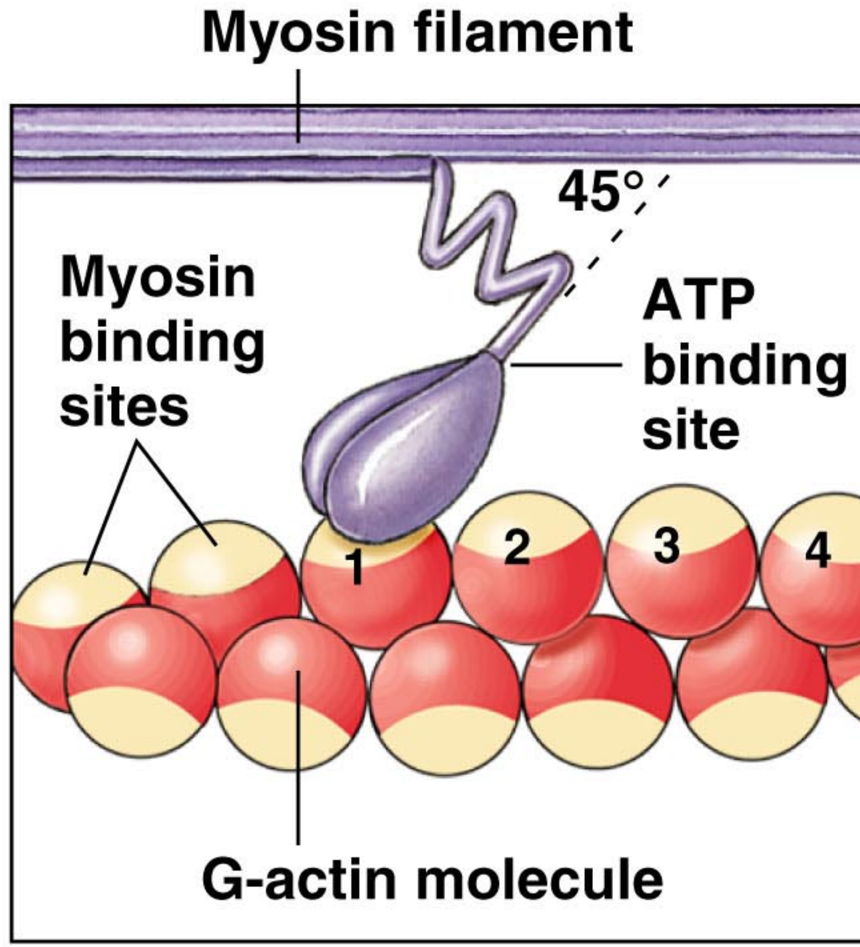


Figure 12-9, step 1

2 ATP binds to its binding site on the myosin. Myosin then dissociates from actin.

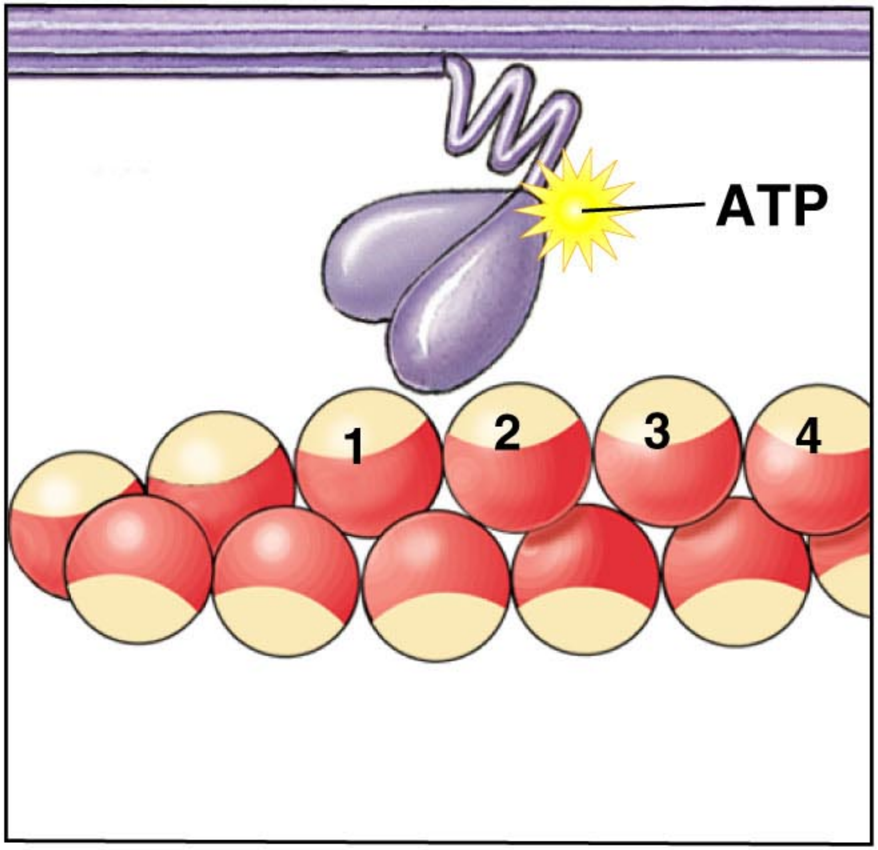


Figure 12-9, step 2

3 The ATPase activity of myosin hydrolyzes the ATP. ADP and P_i remain bound to myosin.

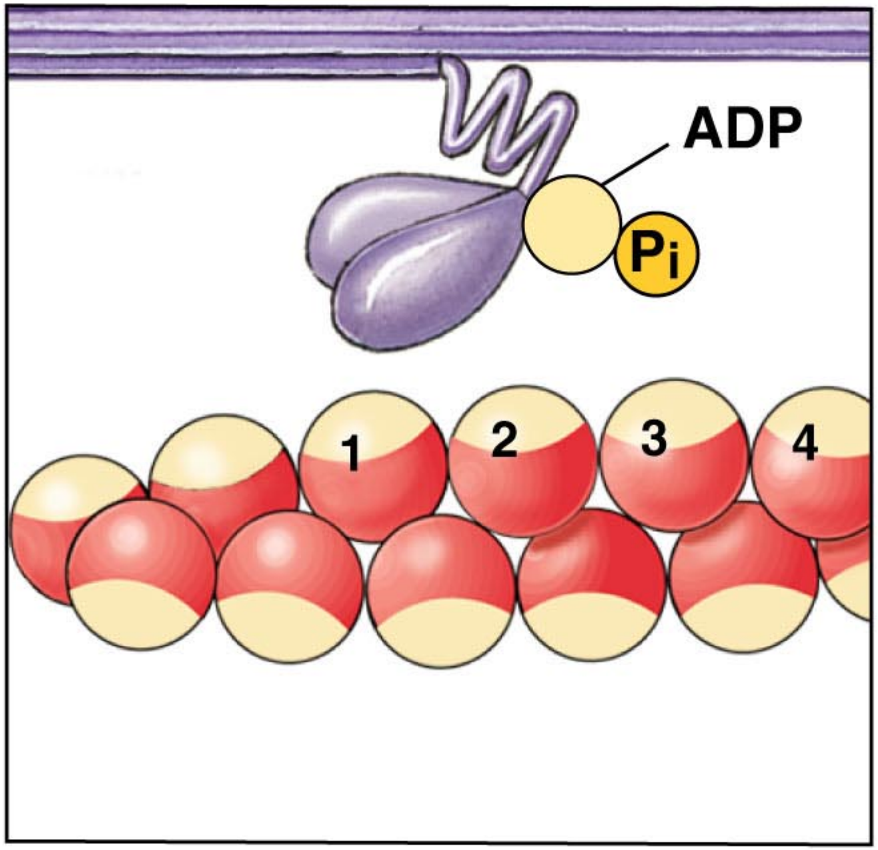


Figure 12-9, step 3

4 The myosin head swings over and binds weakly to a new actin molecule. The crossbridge is now at 90° relative to the filaments.

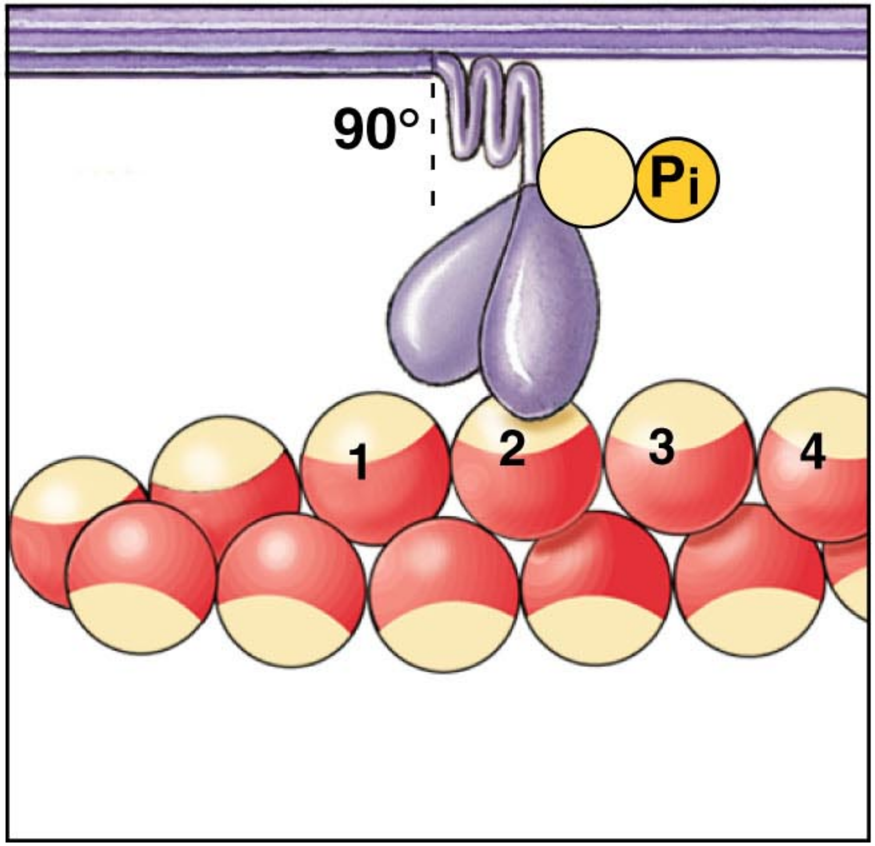


Figure 12-9, step 4

5 **Release of P_i initiates the power stroke. The myosin head rotates on its hinge, pushing the actin filament past it.**

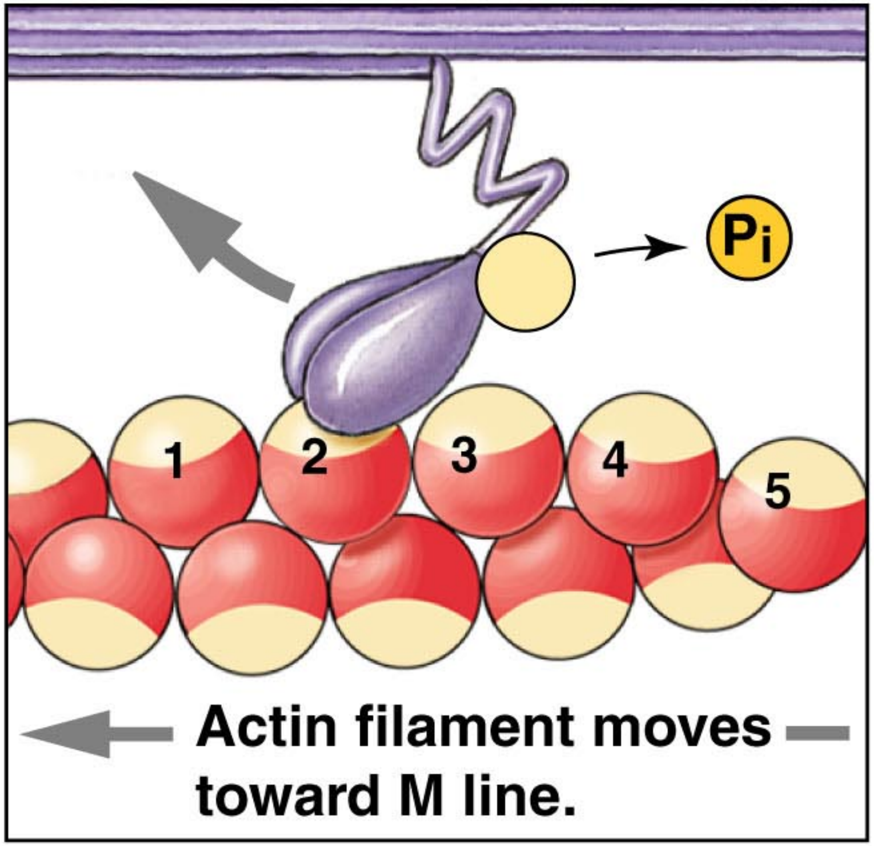


Figure 12-9, step 5

6 At the end of the power stroke, the myosin head releases ADP and resumes the tightly bound rigor state.

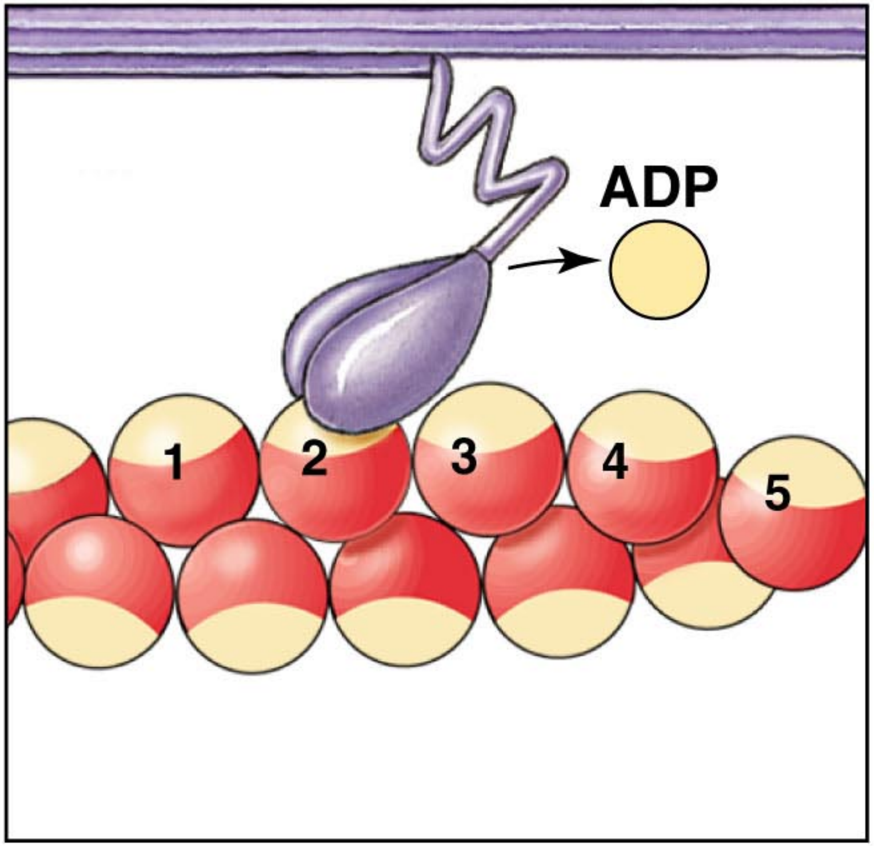


Figure 12-9, step 6

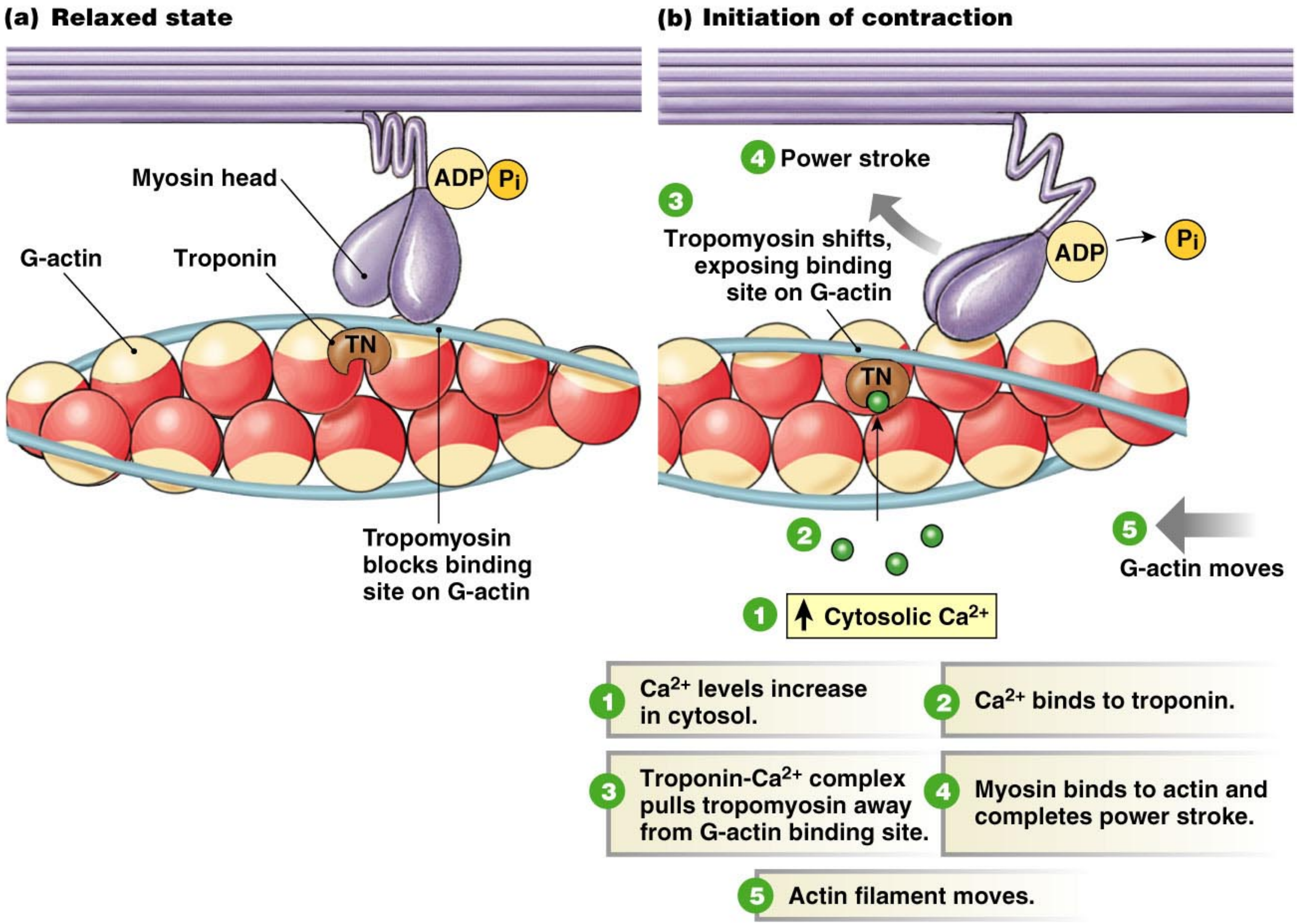


Figure 12-10 Overview

(a) Relaxed state

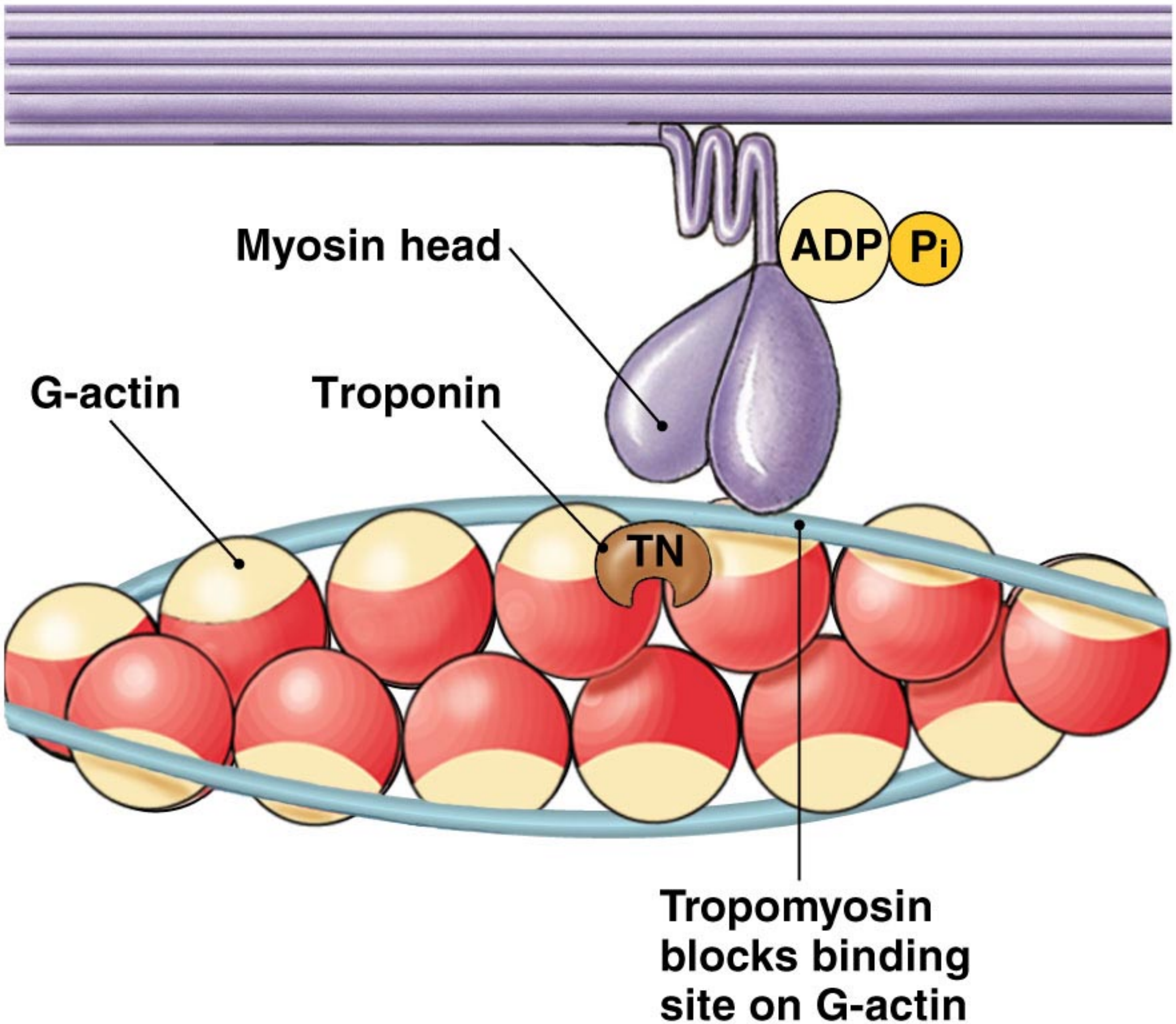


Figure 12-10a

(b) Initiation of contraction

1. Ca^{2+} levels increase in cytosol.
2. Ca^{2+} binds to troponin.
3. Troponin-Ca^{2+} complex pulls tropomyosin away from G-actin binding site.
4. Myosin binds to actin and completes power stroke.
5. Actin filament moves.

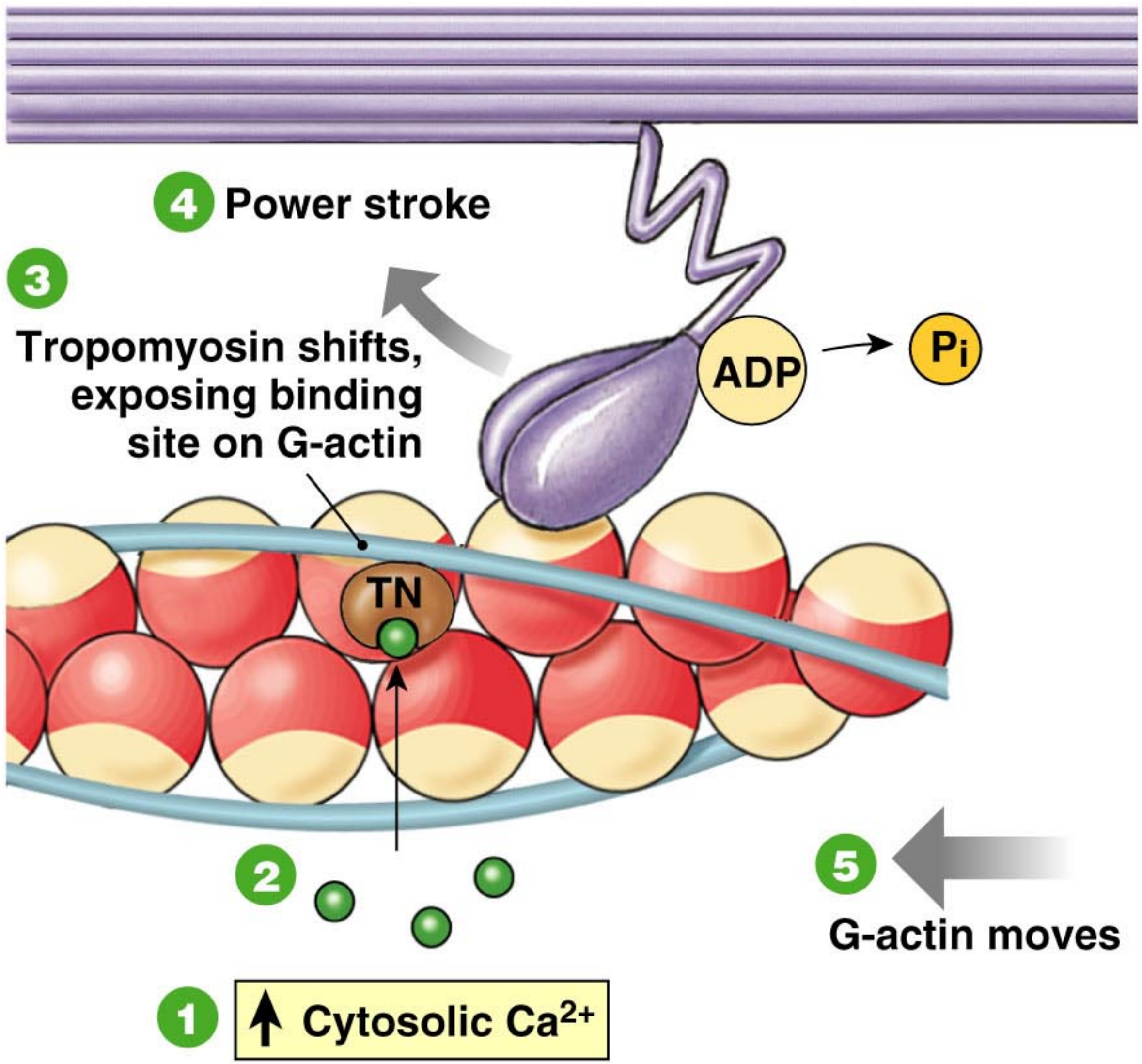


Figure 12-10b Overview

(b) Initiation of contraction

1 Ca^{2+} levels increase in cytosol.

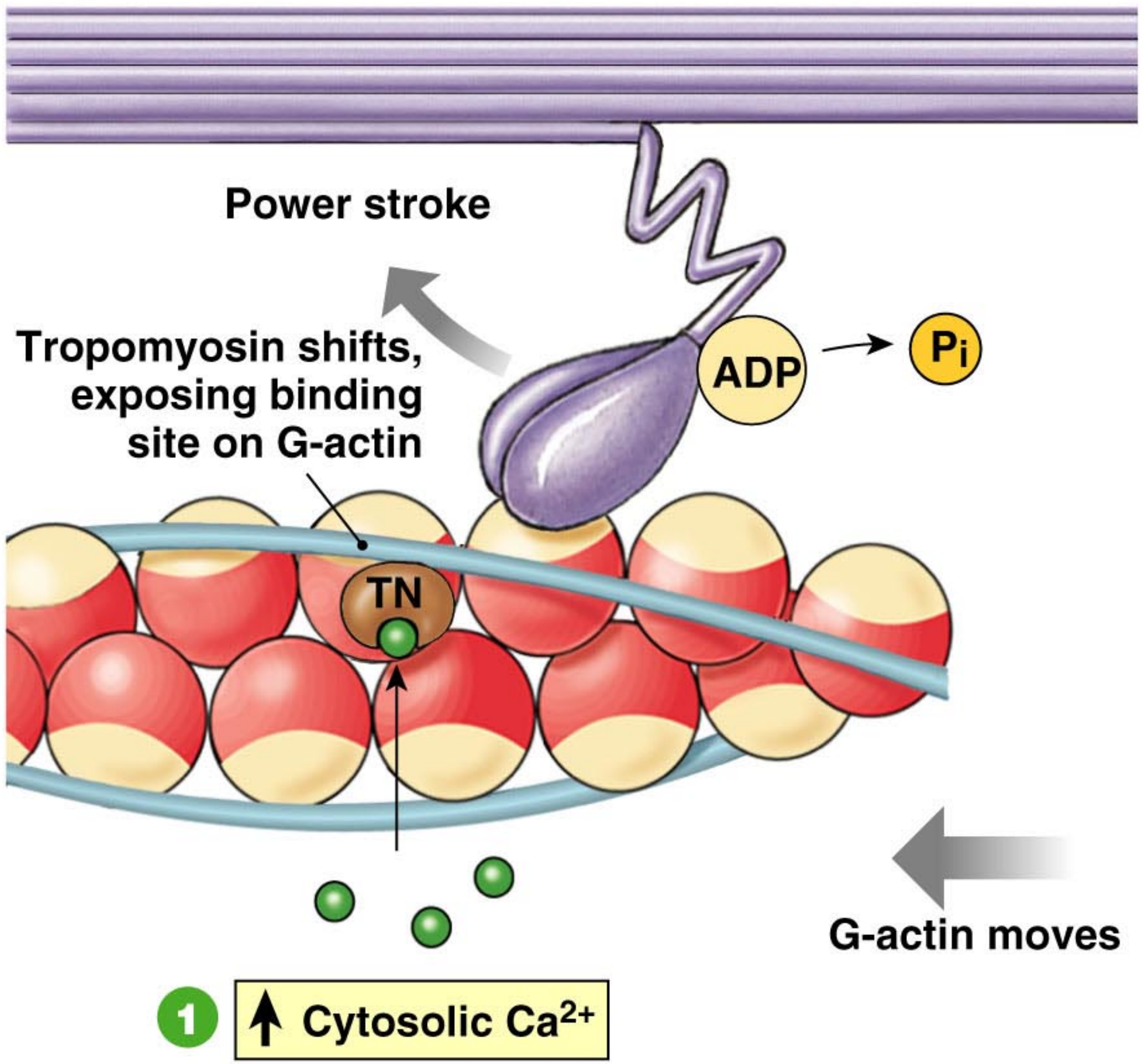
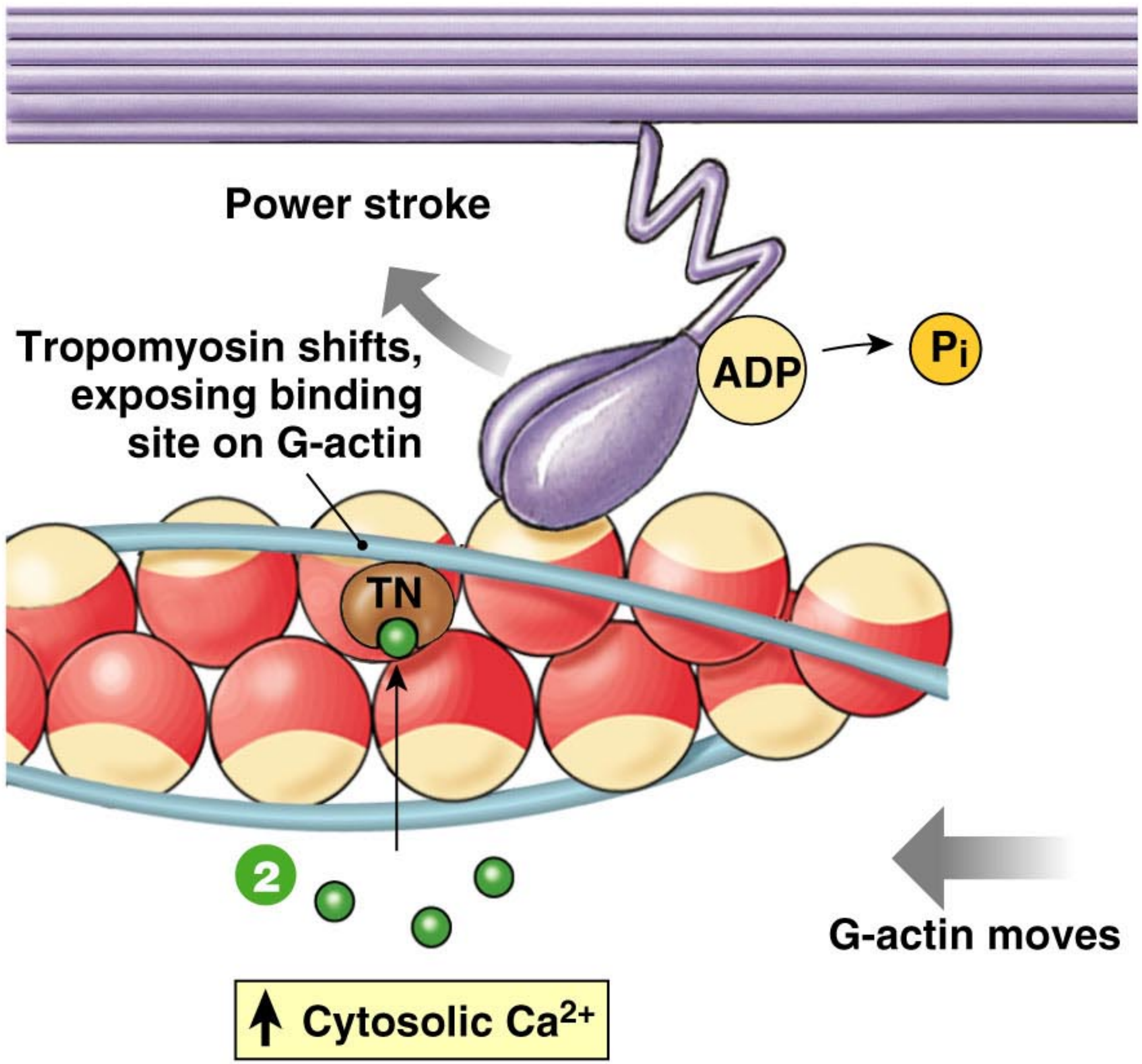


Figure 12-10b, step 1

2 Ca^{2+} binds to troponin.

(b) Initiation of contraction



(b) Initiation of contraction

3 Troponin-Ca^{2+} complex pulls tropomyosin away from G-actin binding site.

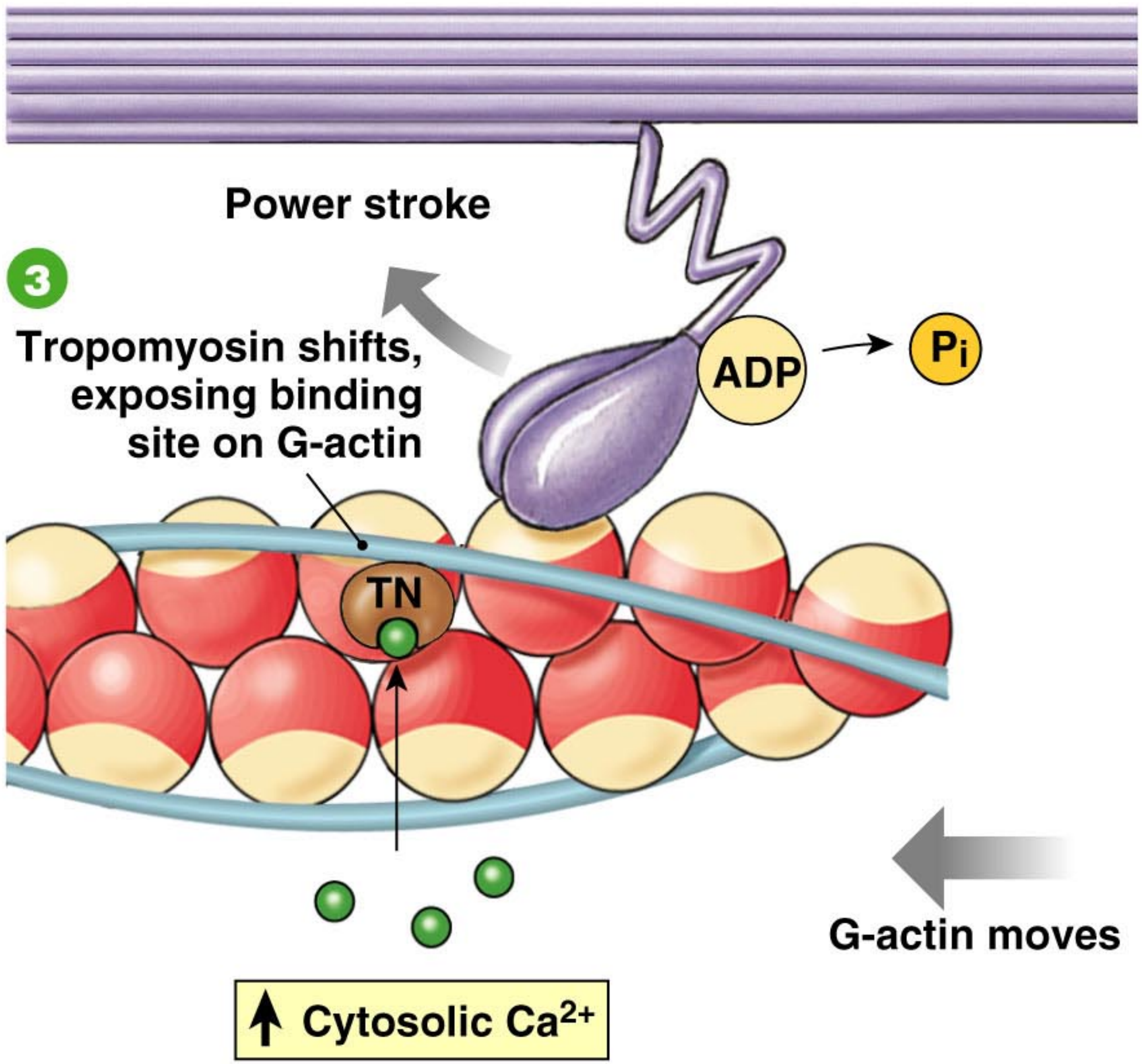
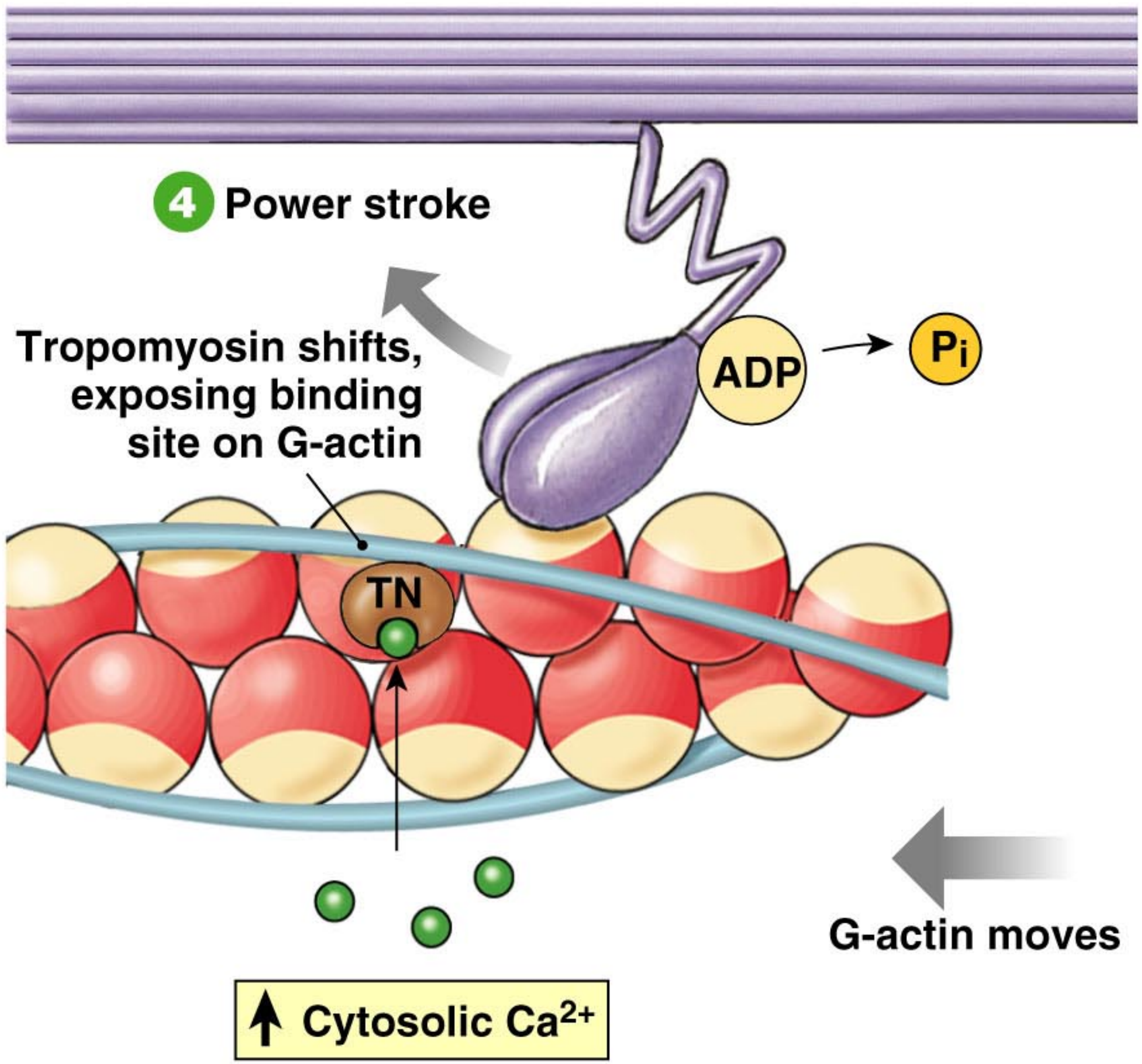


Figure 12-10b, step 3

4 **Myosin binds to actin and completes power stroke.**

(b) Initiation of contraction



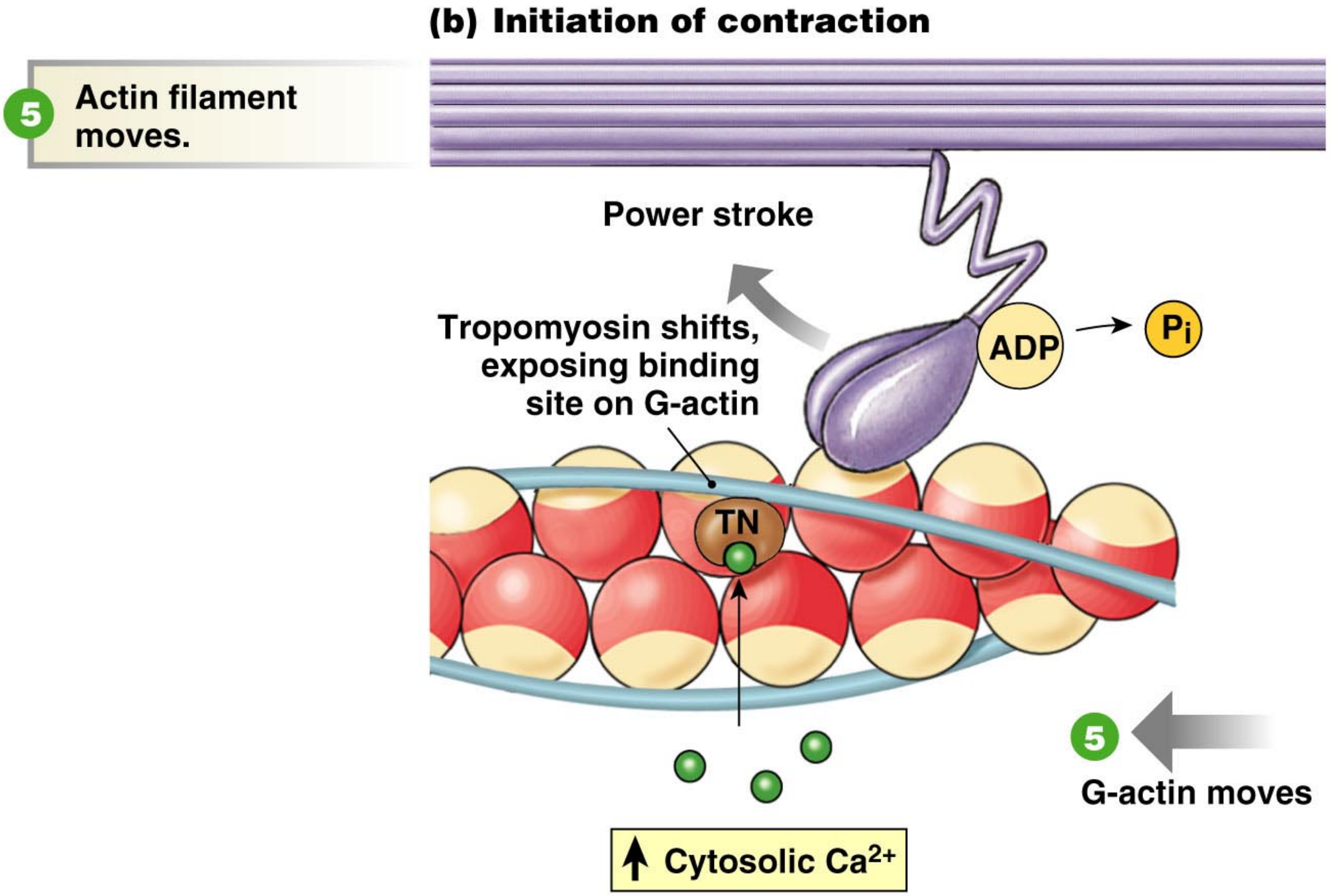


Figure 12-10b, step 5

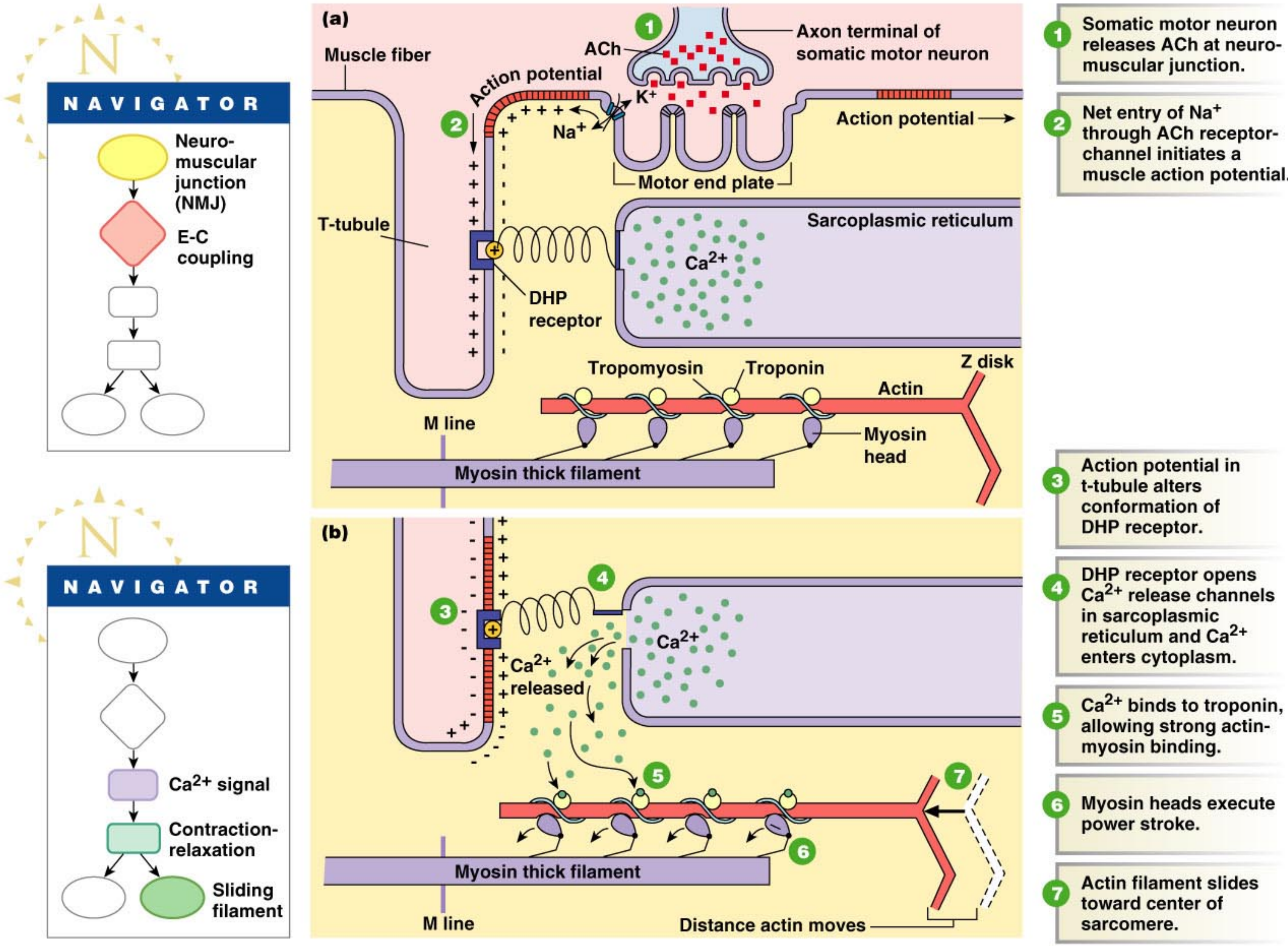


Figure 12-11a Overview

1 Somatic motor neuron releases ACh at neuro-muscular junction.

2 Net entry of Na^+ through ACh receptor-channel initiates a muscle action potential.

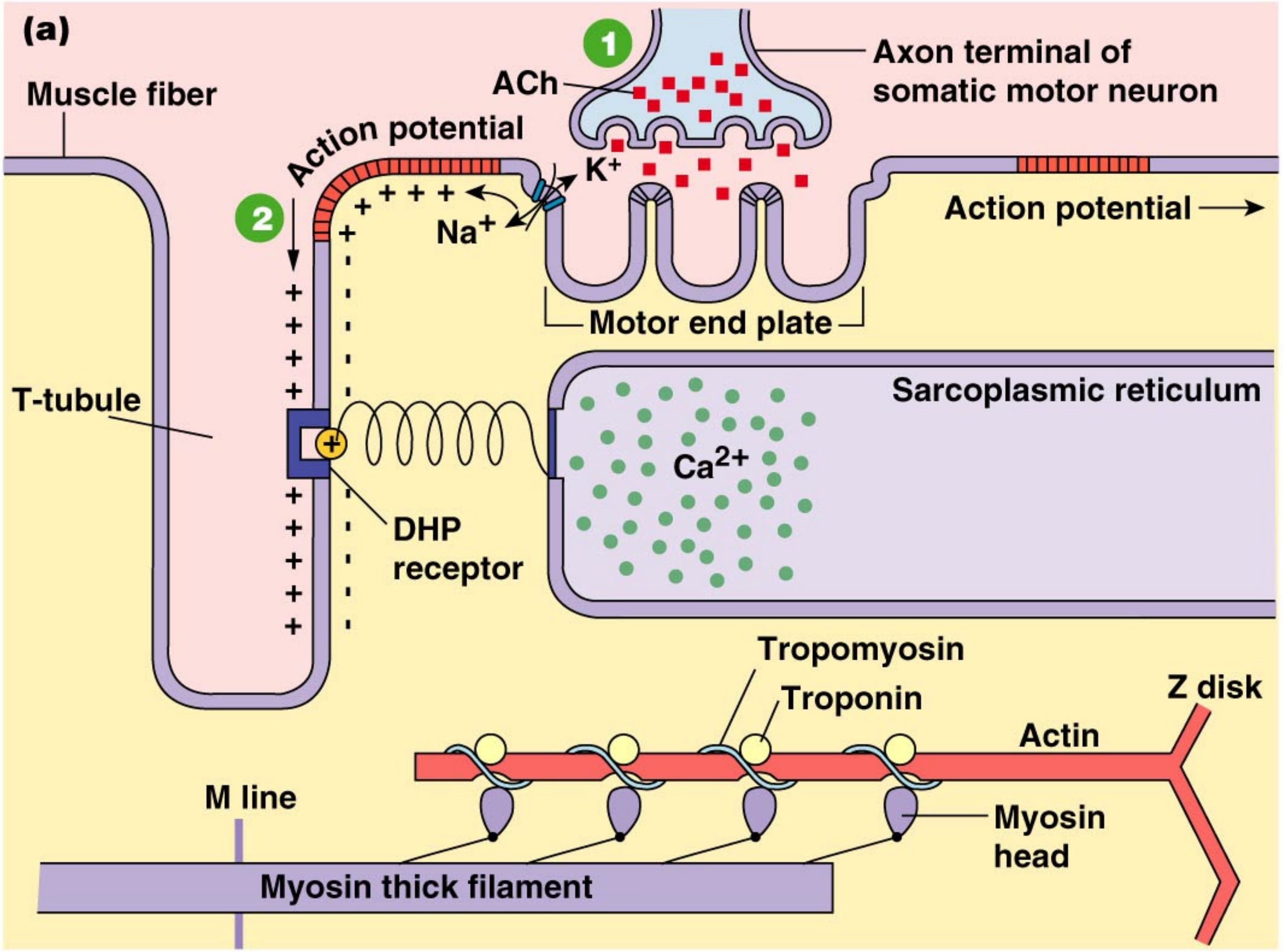
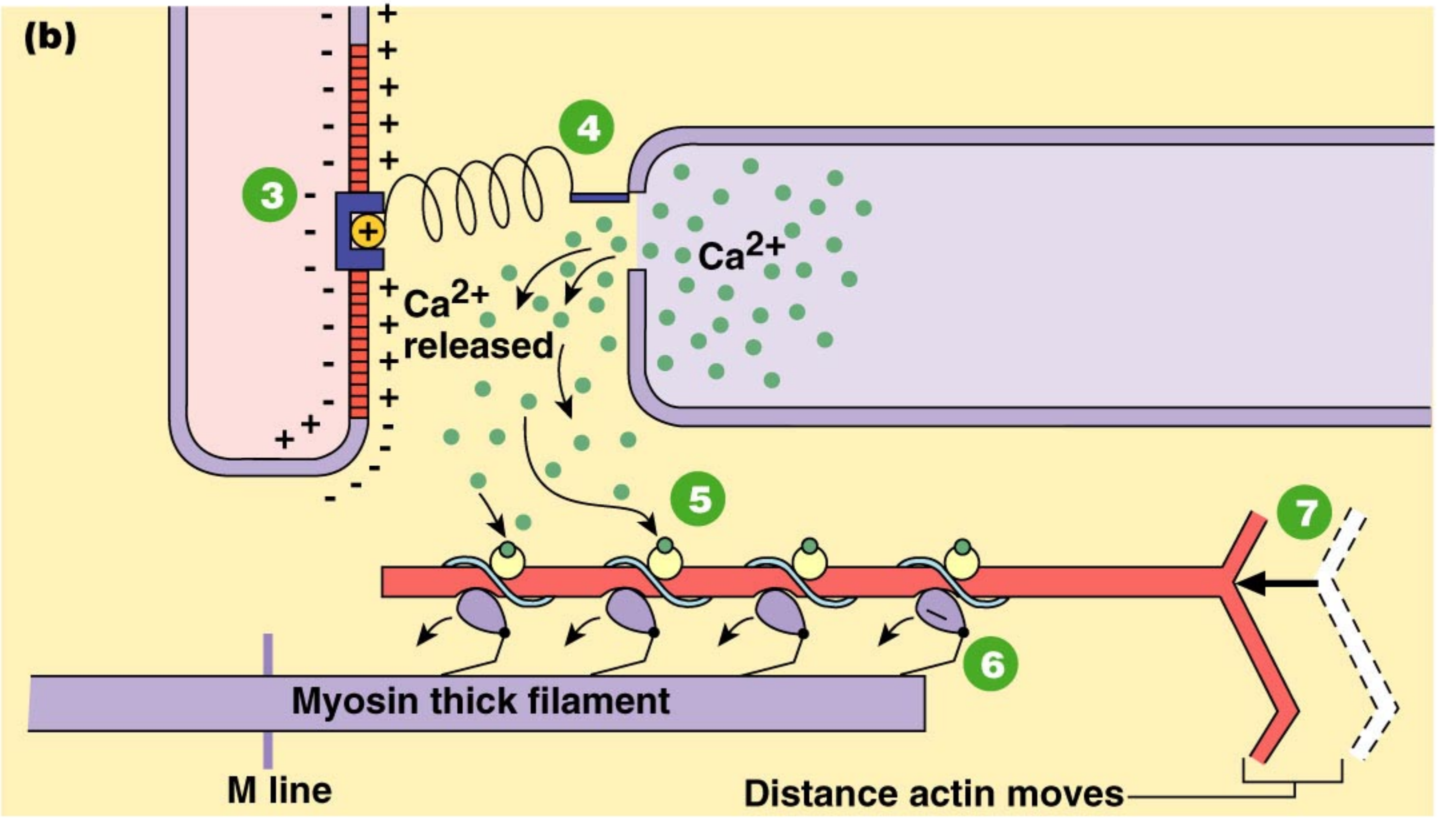


Figure 12-11a

3 Action potential in t-tubule alters conformation of DHP receptor.

4 DHP receptor opens Ca^{2+} release channels in sarcoplasmic reticulum and Ca^{2+} enters cytoplasm.

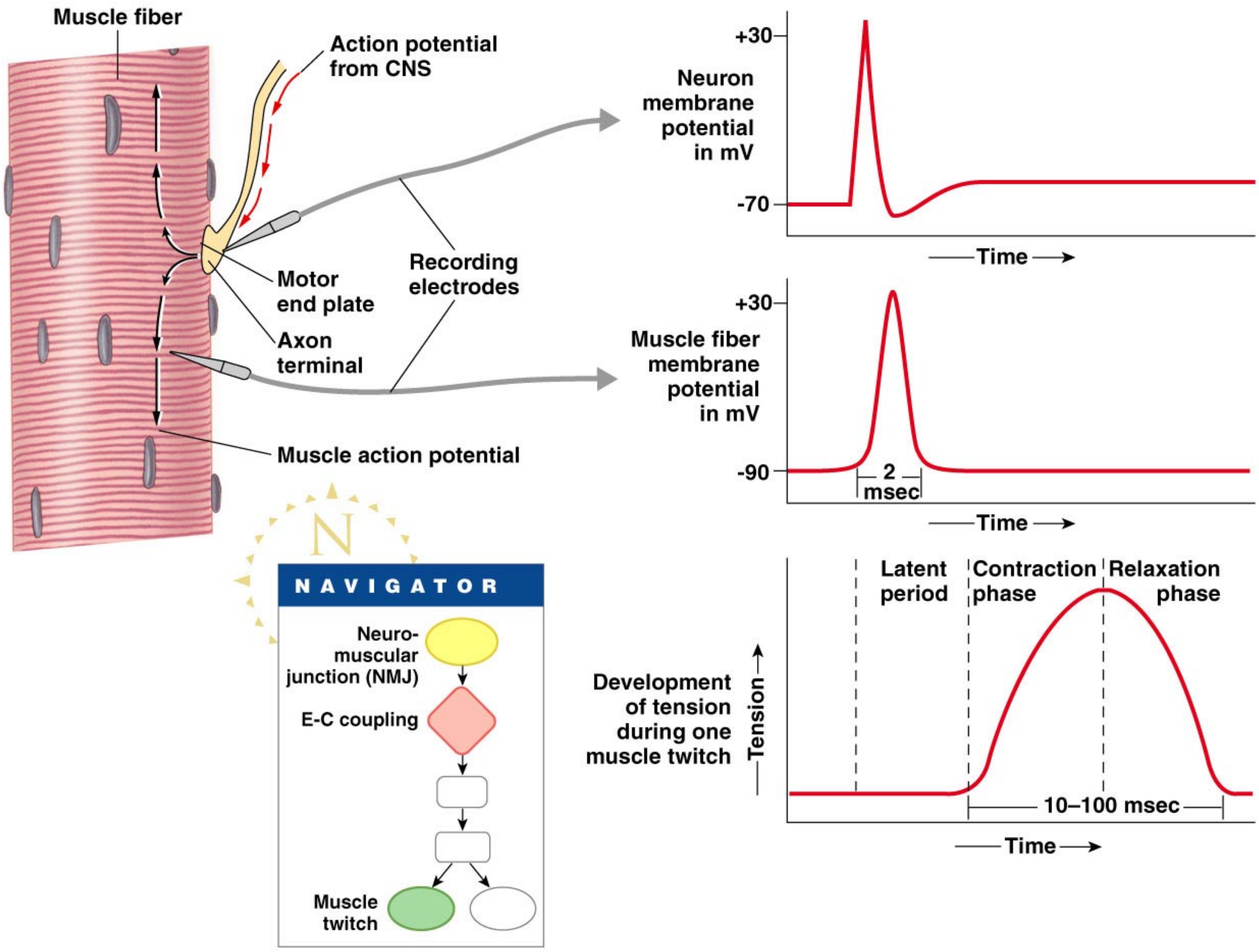
5 Ca^{2+} binds to troponin, allowing strong actin-myosin binding.



6 Myosin heads execute power stroke.

7 Actin filament slides toward center of sarcomere.

Figure 12-11b



Muscle fiber
Action potential from CNS
Motor end plate
Axon terminal
Recording electrodes
Muscle action potential
+30
Neuron membrane potential in mV
-70
Time
+30
Muscle fiber membrane potential in mV
-90
2 msec
Time
Latent period
Contraction phase
Relaxation phase
Development of tension during one muscle twitch
Tension
10–100 msec
Time
NAVIGATOR
Neuro-muscular junction (NMJ)
E-C coupling
Muscle twitch

Figure 12-12

Muscle at rest

ATP from metabolism + creatine $\xrightarrow[\text{kinase}]{\text{creatine}}$ ADP + phosphocreatine

Working muscle

Phosphocreatine + ADP $\xrightarrow[\text{kinase}]{\text{creatine}}$ Creatine + ATP

needed for

- Myosin ATPase (contraction)
- Ca^{2+}-ATPase (relaxation)
- Na^{+}-K^{+} ATPase (restores ions that cross cell membrane during action potential to their original compartments)

Figure 12-13

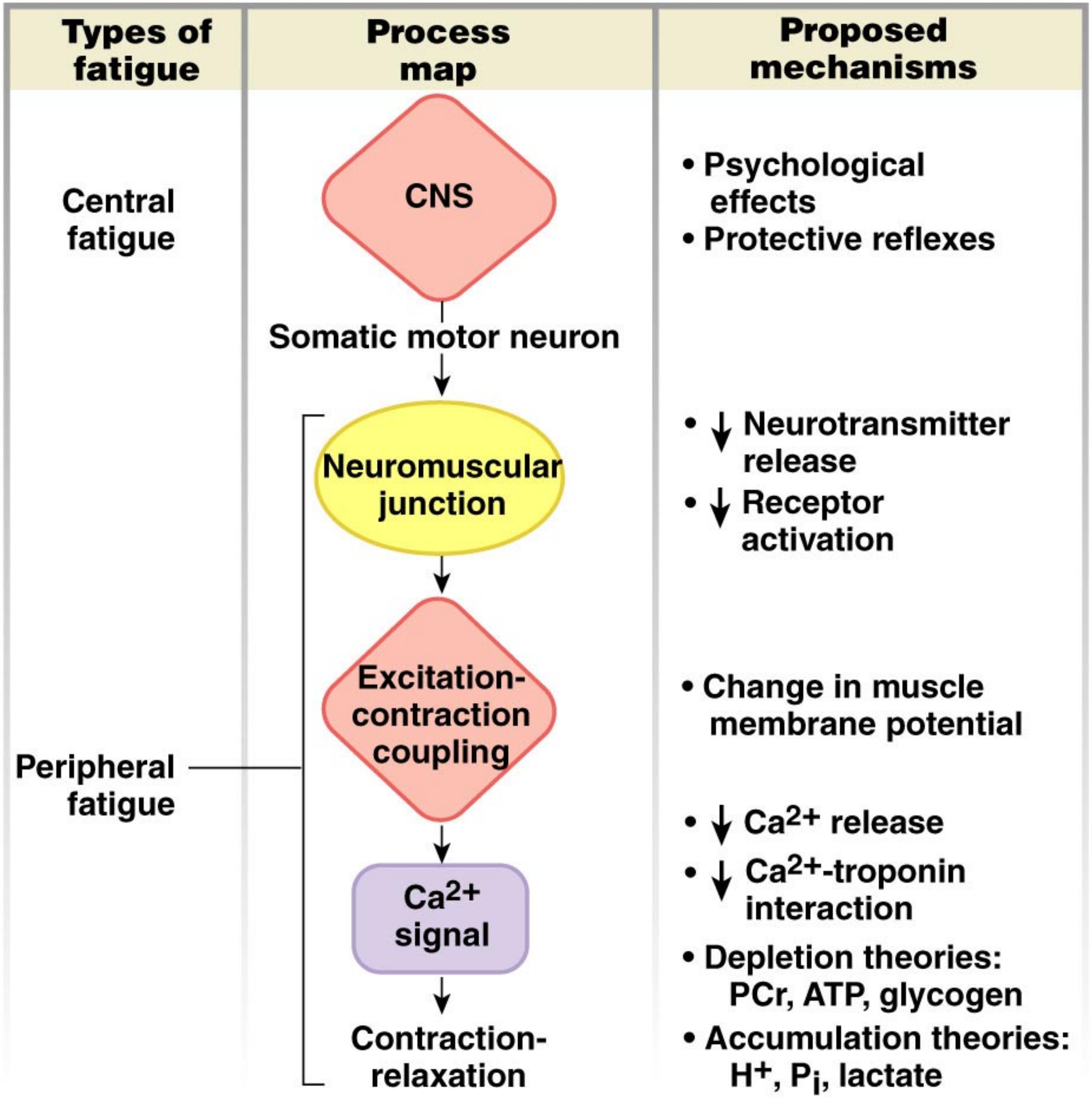
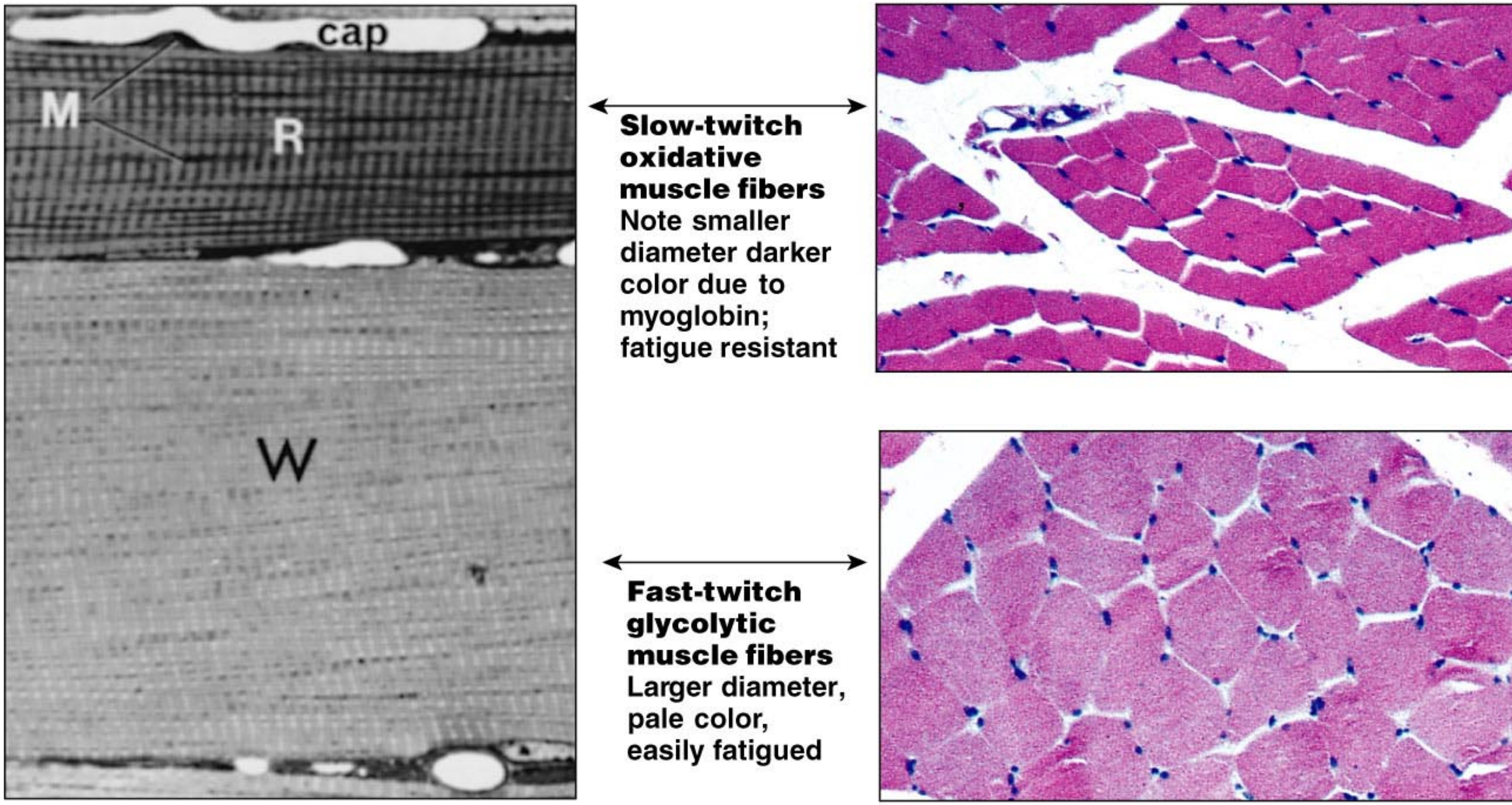

Types of fatigue
Process map
Proposed mechanisms
Central fatigue
CNS
• Psychological effects
• Protective reflexes
Somatic motor neuron
Neuromuscular junction
• ↓ Neurotransmitter release
• ↓ Receptor activation
Excitation-contraction coupling
• Change in muscle membrane potential
Peripheral fatigue
Ca2+ signal
• ↓ Ca2+ release
• ↓ Ca2+-troponin interaction
• Depletion theories: PCr, ATP, glycogen
Contraction-relaxation
• Accumulation theories: H+, Pi, lactate

Figure 12-14



cap
M
R
W
Slow-twitch oxidative muscle fibers Note smaller diameter darker color due to myoglobin; fatigue resistant
Fast-twitch glycolytic muscle fibers Larger diameter, pale color, easily fatigued

Figure 12-15

TABLE 12-2 Characteristics of Muscle Fiber Types

	SLOW-TWITCH OXIDATIVE; RED MUSCLE	FAST-TWITCH OXIDATIVE-GLYCOLYTIC; RED MUSCLE	FAST-TWITCH GLYCOLYTIC; WHITE MUSCLE
Speed of development of maximum tension	Slowest	Intermediate	Fastest
Myosin ATPase activity	Slow	Fast	Fast
Diameter	Small	Medium	Large
Contraction duration	Longest	Short	Short
Ca^{2+}-ATPase activity in SR	Moderate	High	High
Endurance	Fatigue resistant	Fatigue resistant	Easily fatigued
Use	Most used: posture	Standing, walking	Least used: jumping
Metabolism	Oxidative; aerobic;	Glycolytic but becomes more oxidative with endurance training	Glycolytic; more anaerobic than fast-twitch oxidative-glycolytic type
Capillary density	High	Medium	Low
Mitochondria	Numerous	Moderate	Few
Color	Dark red (myoglobin)	Red	Pale

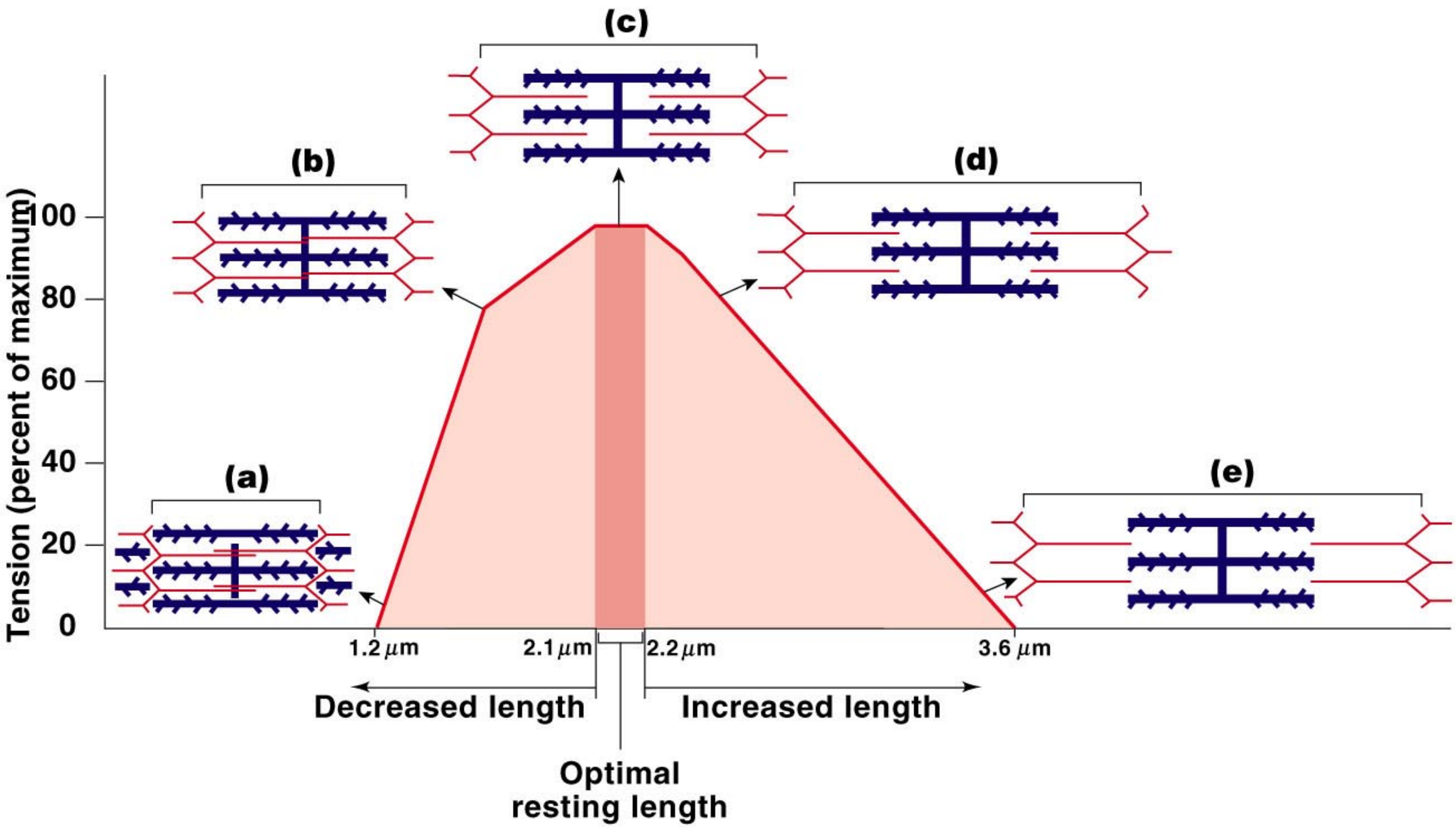


Figure 12-16 - Overview

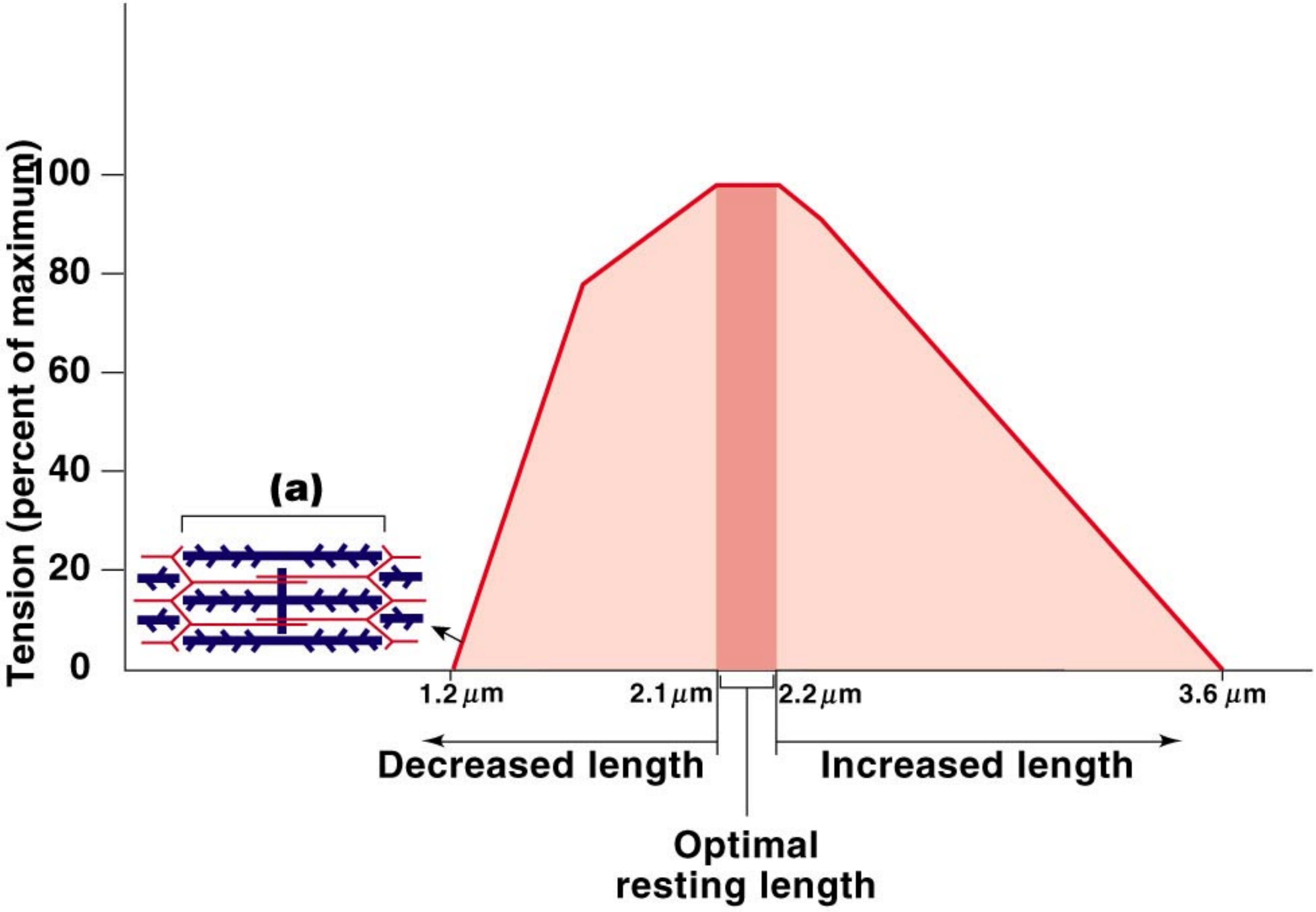


Figure 12-16a

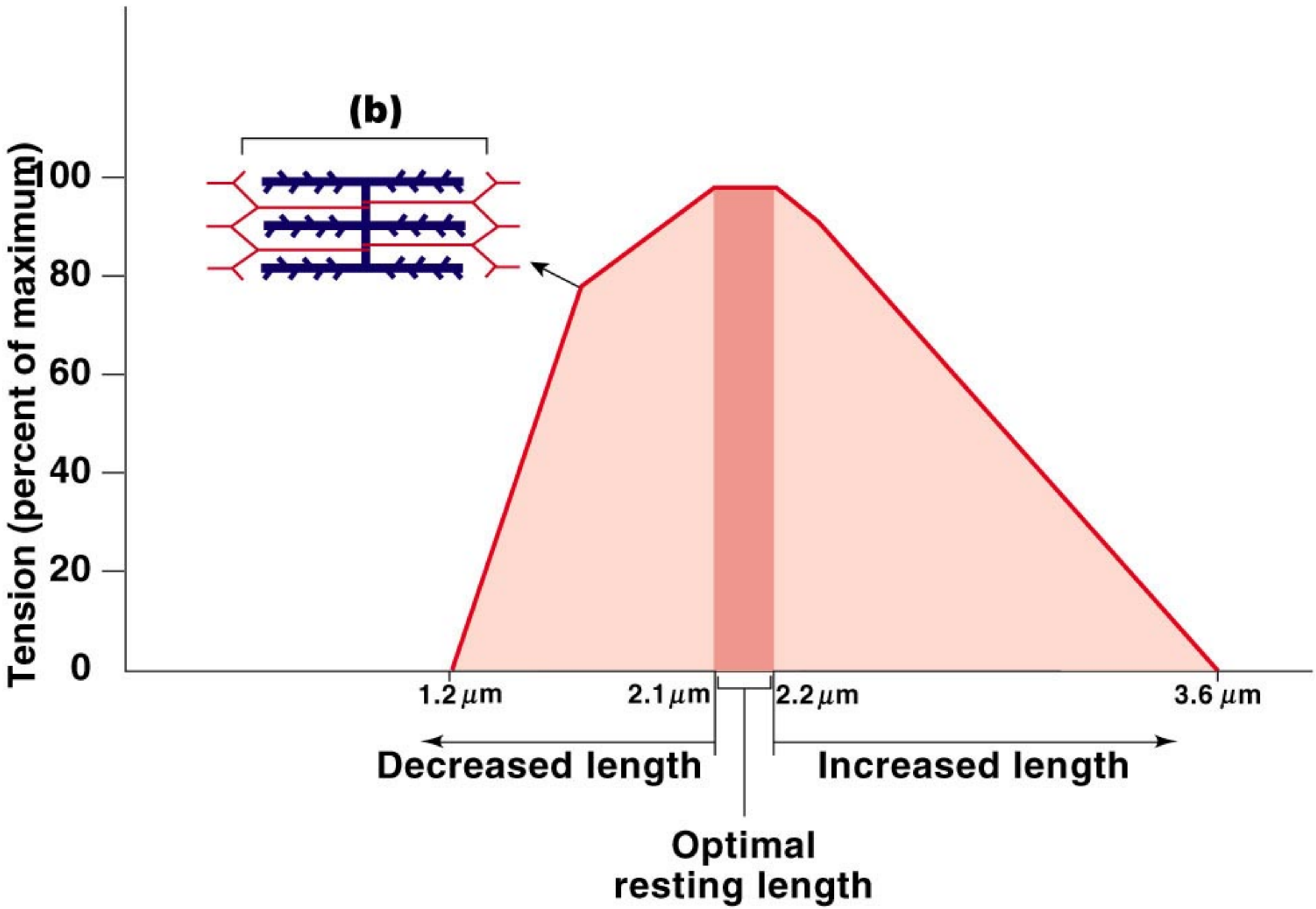


Figure 12-16b

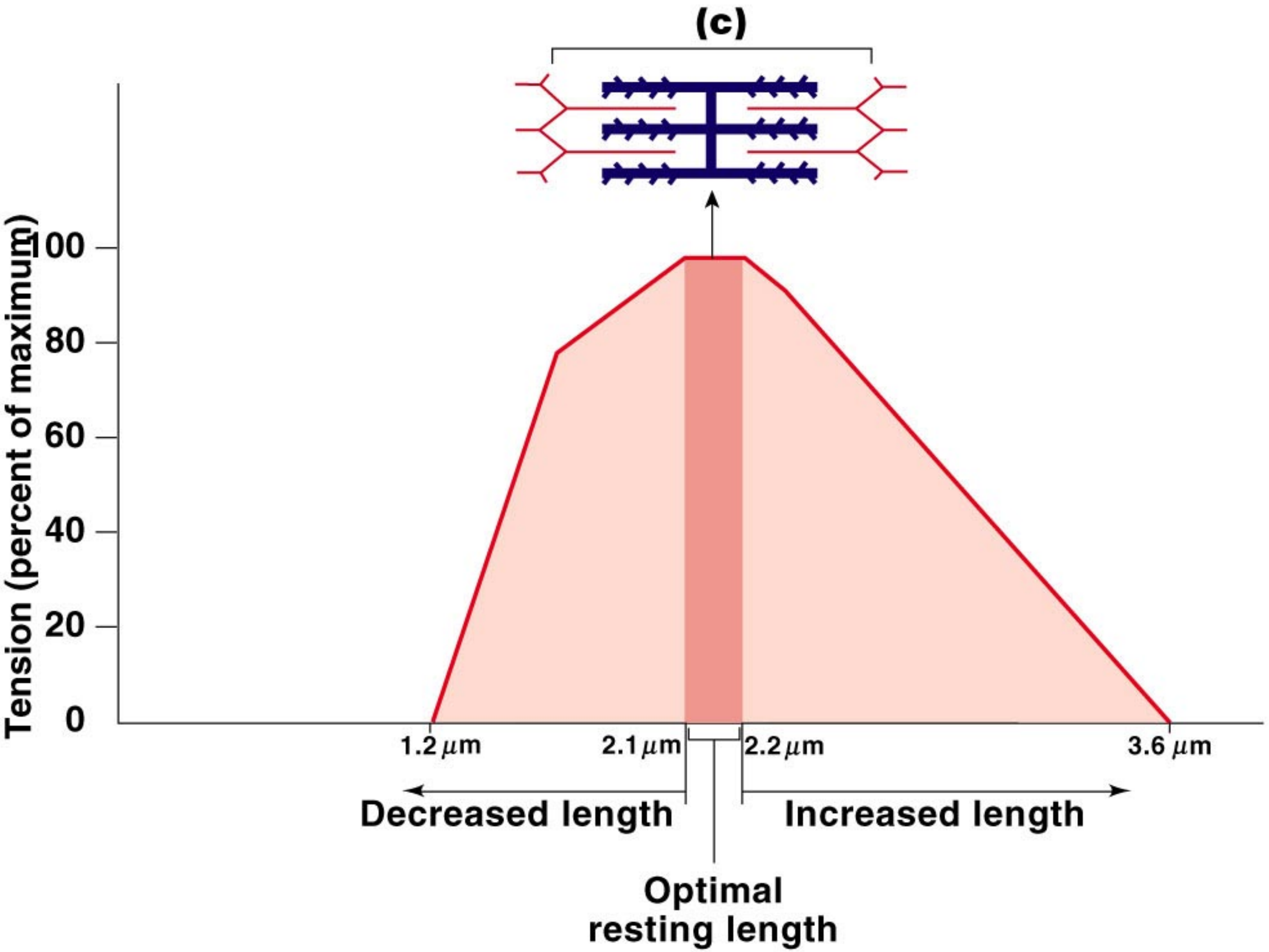


Figure 12-16c

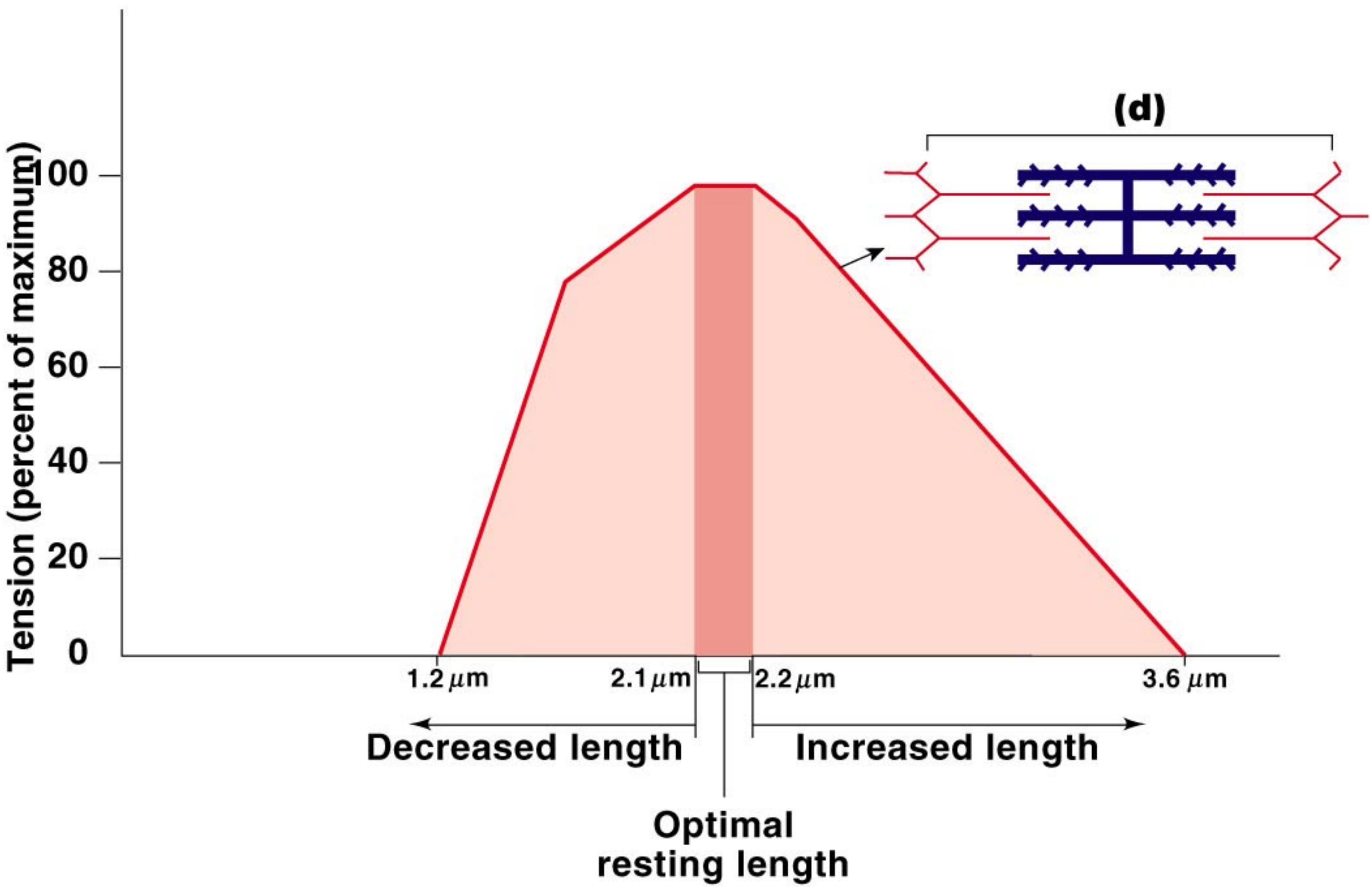


Figure 12-16d

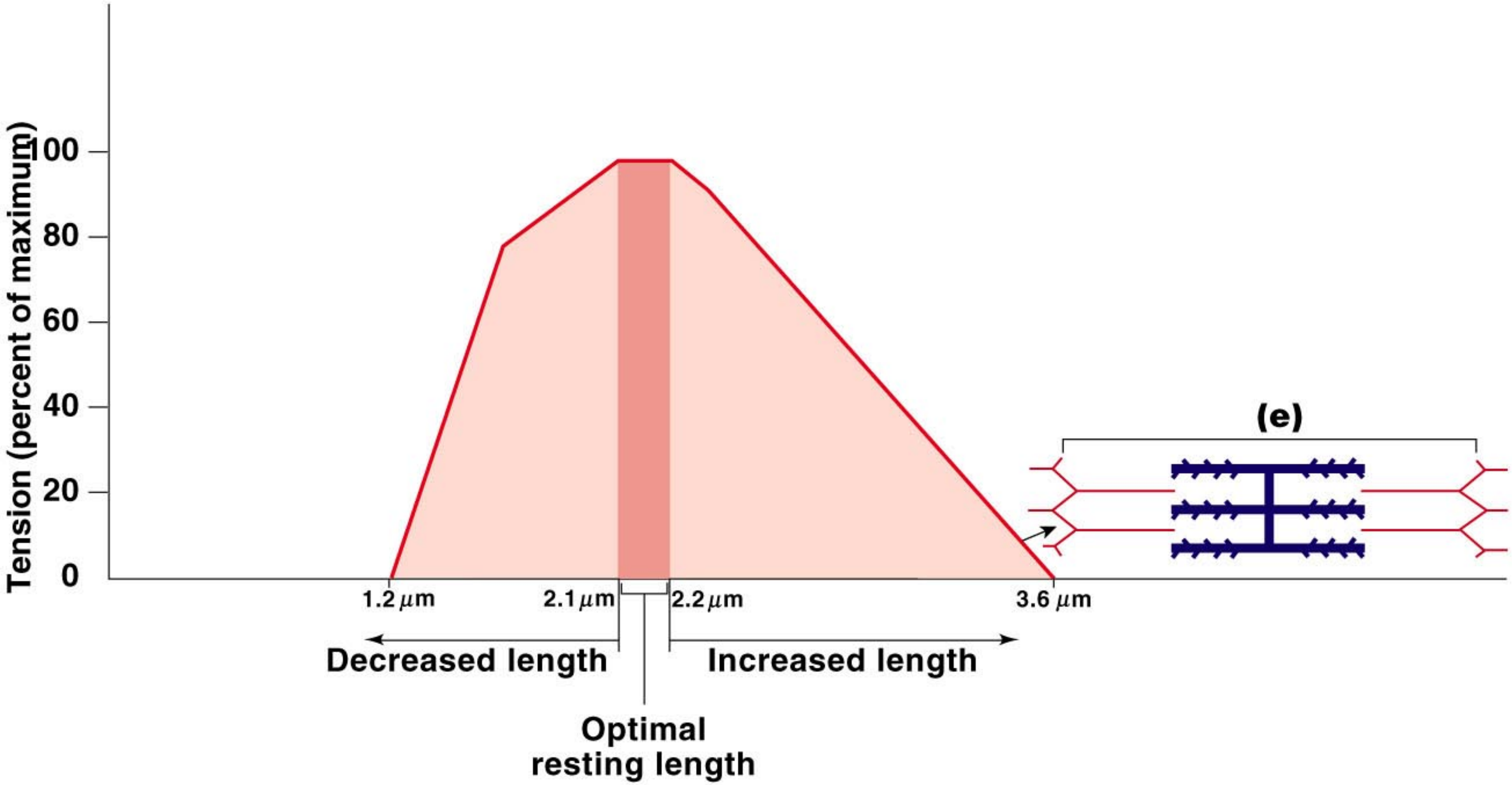
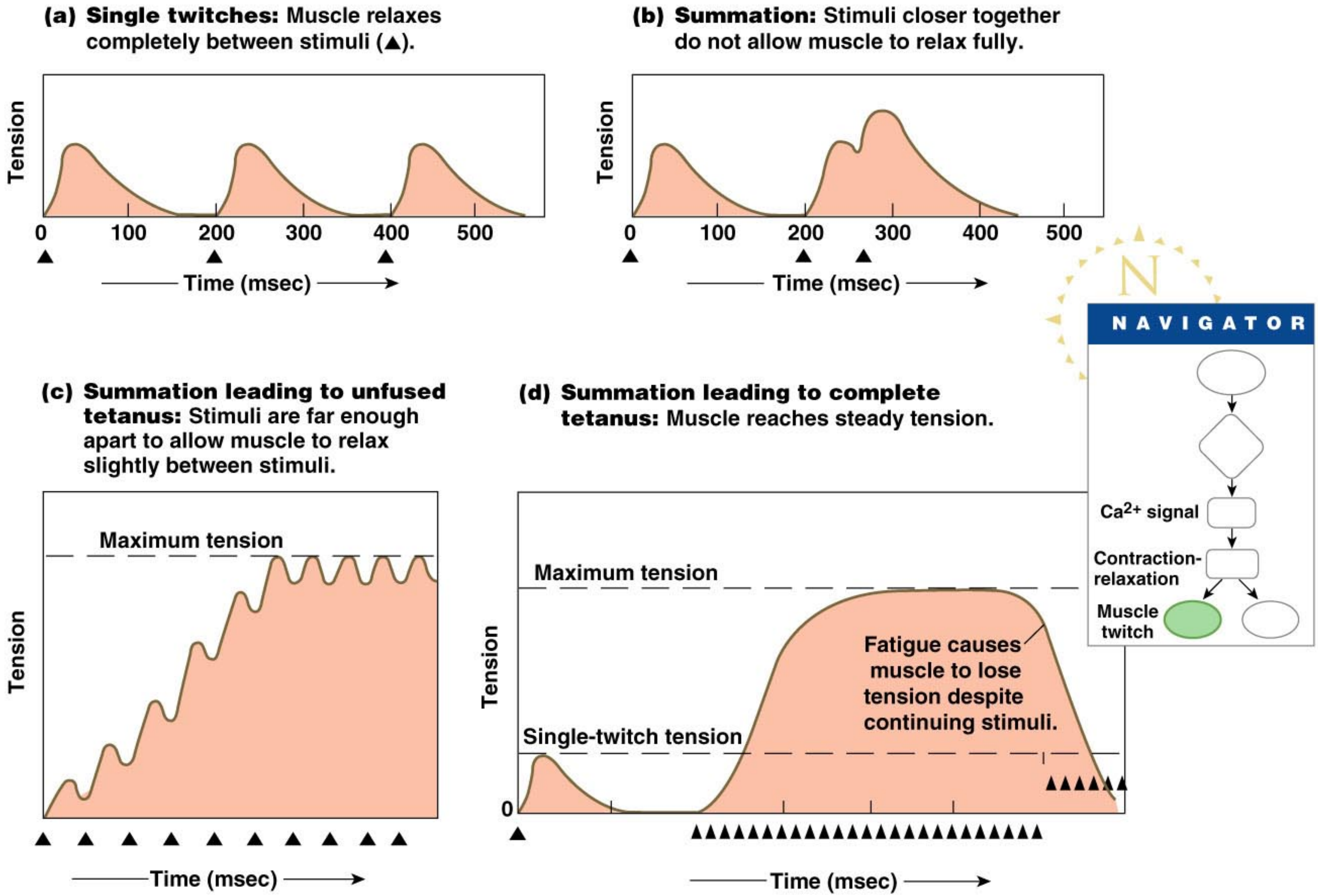


Figure 12-16e


(a) Single twitches: Muscle relaxes completely between stimuli (▲).
Tension
0
100
200
300
400
500
Time (msec)
(b) Summation: Stimuli closer together do not allow muscle to relax fully.
Tension
0
100
200
300
400
500
Time (msec)
(c) Summation leading to unfused tetanus: Stimuli are far enough apart to allow muscle to relax slightly between stimuli.
Maximum tension
Tension
Time (msec)
(d) Summation leading to complete tetanus: Muscle reaches steady tension.
Maximum tension
Fatigue causes muscle to lose tension despite continuing stimuli.
Single-twitch tension
Tension
0
Time (msec)
NAVIGATOR
Ca2+ signal
Contraction-relaxation
Muscle twitch

(a) Single twitches: Muscle relaxes completely between stimuli (▲).

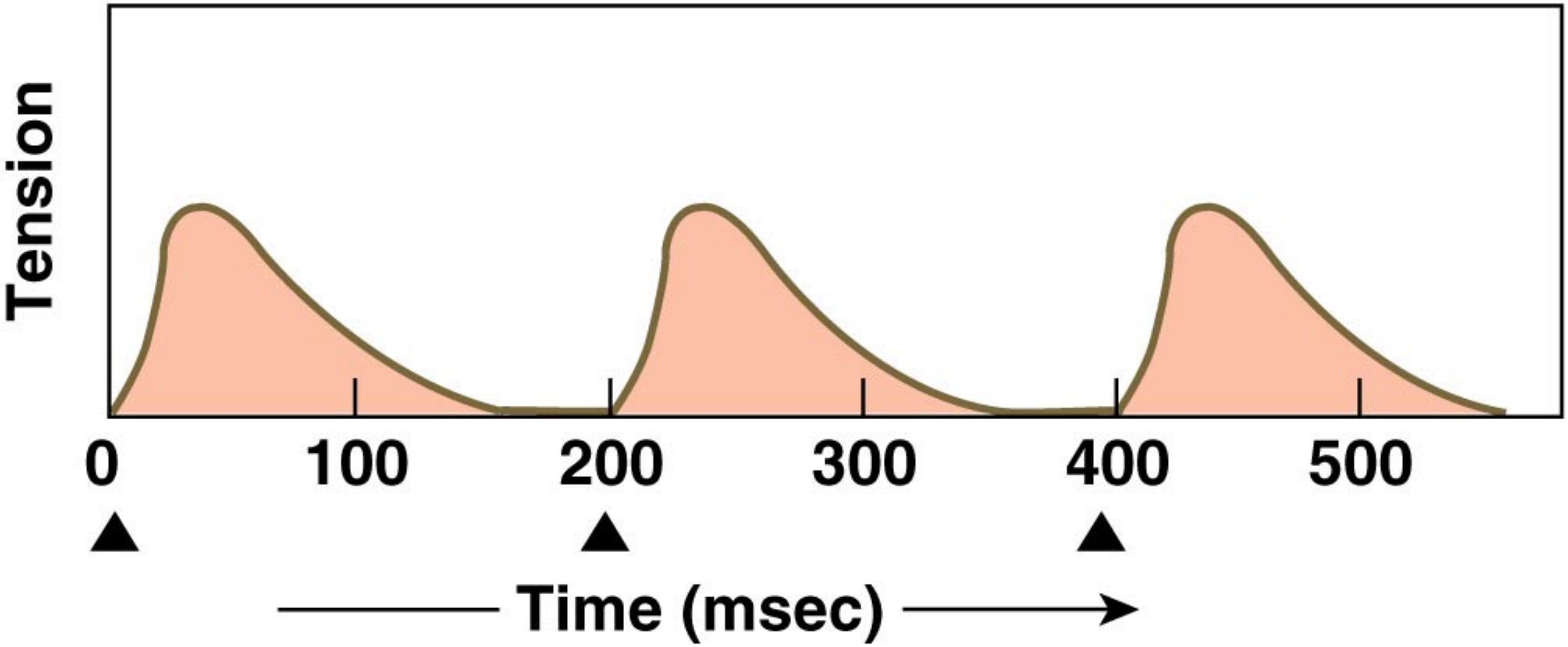


Figure 12-17a

(b) Summation: Stimuli closer together do not allow muscle to relax fully.

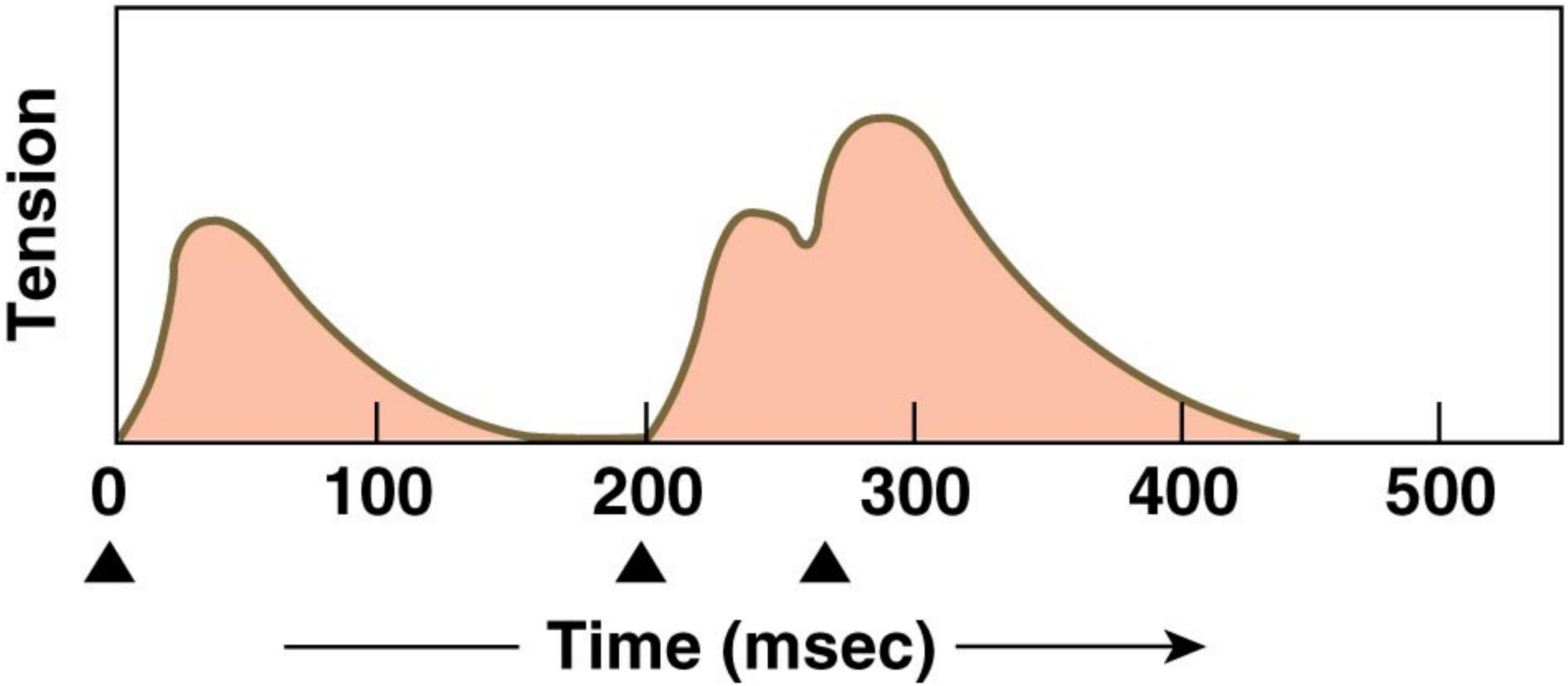


Figure 12-17b

(c) Summation leading to unfused tetanus: Stimuli are far enough apart to allow muscle to relax slightly between stimuli.

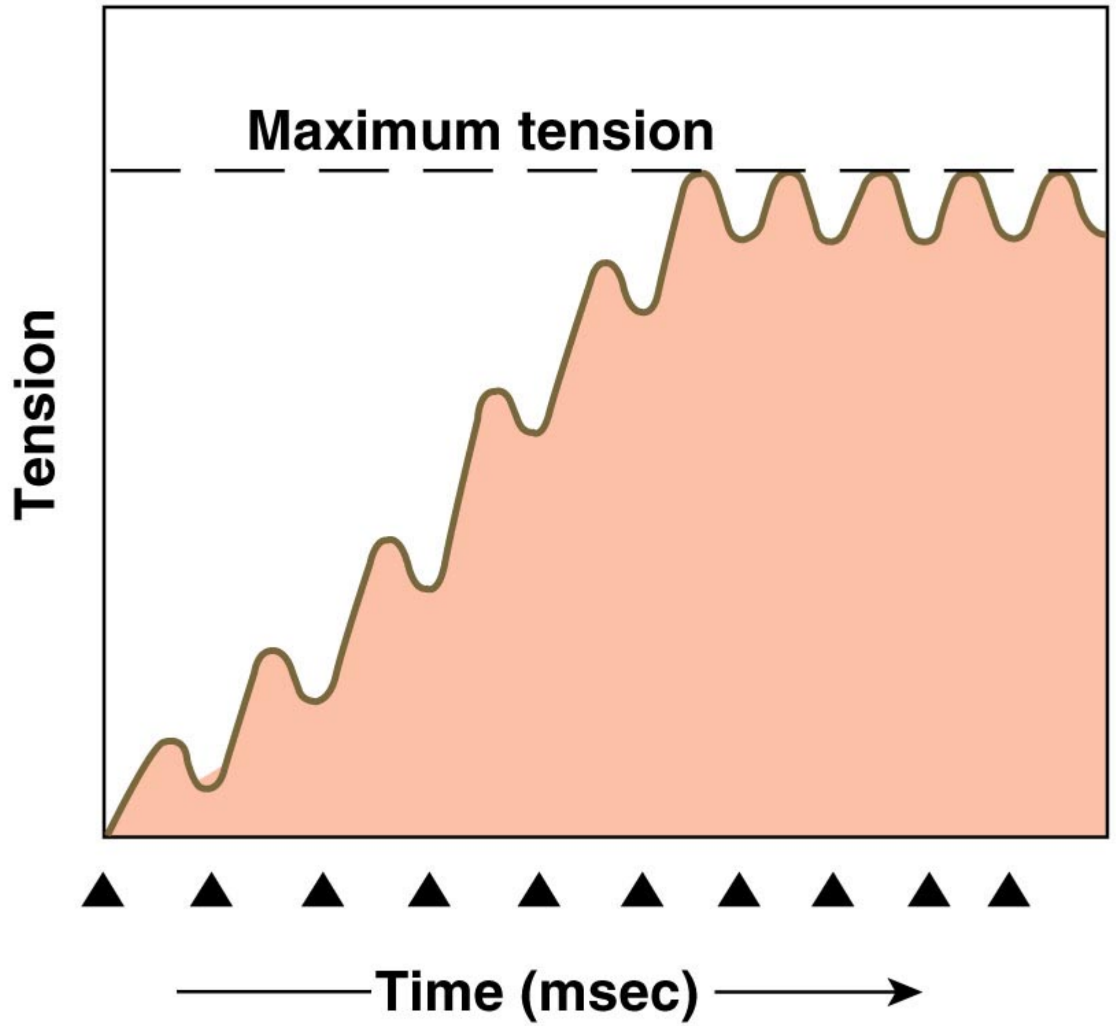


Figure 12-17c

(d) Summation leading to complete tetanus: Muscle reaches steady tension.

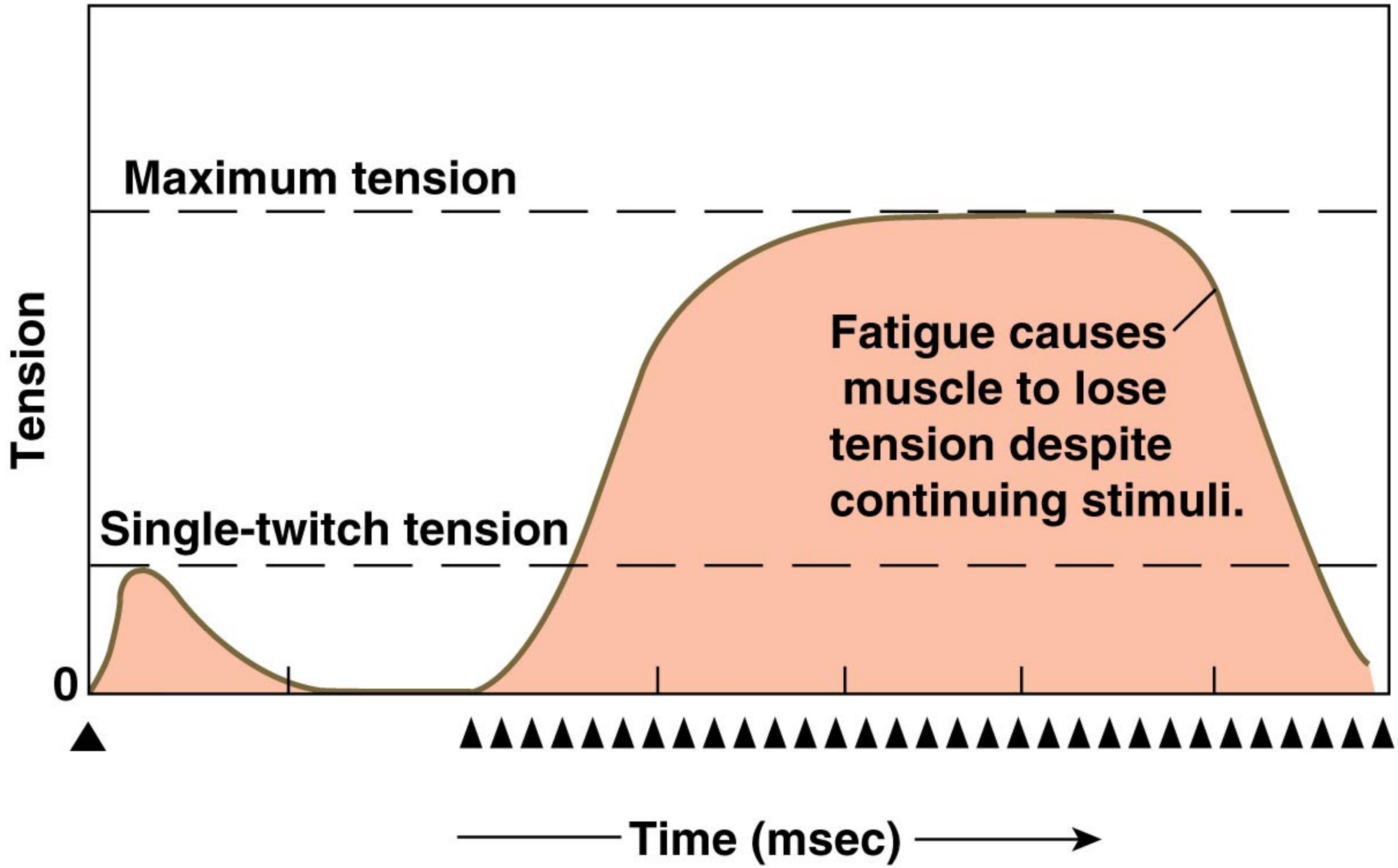


Figure 12-17d

One muscle may have many motor units of different fiber types.

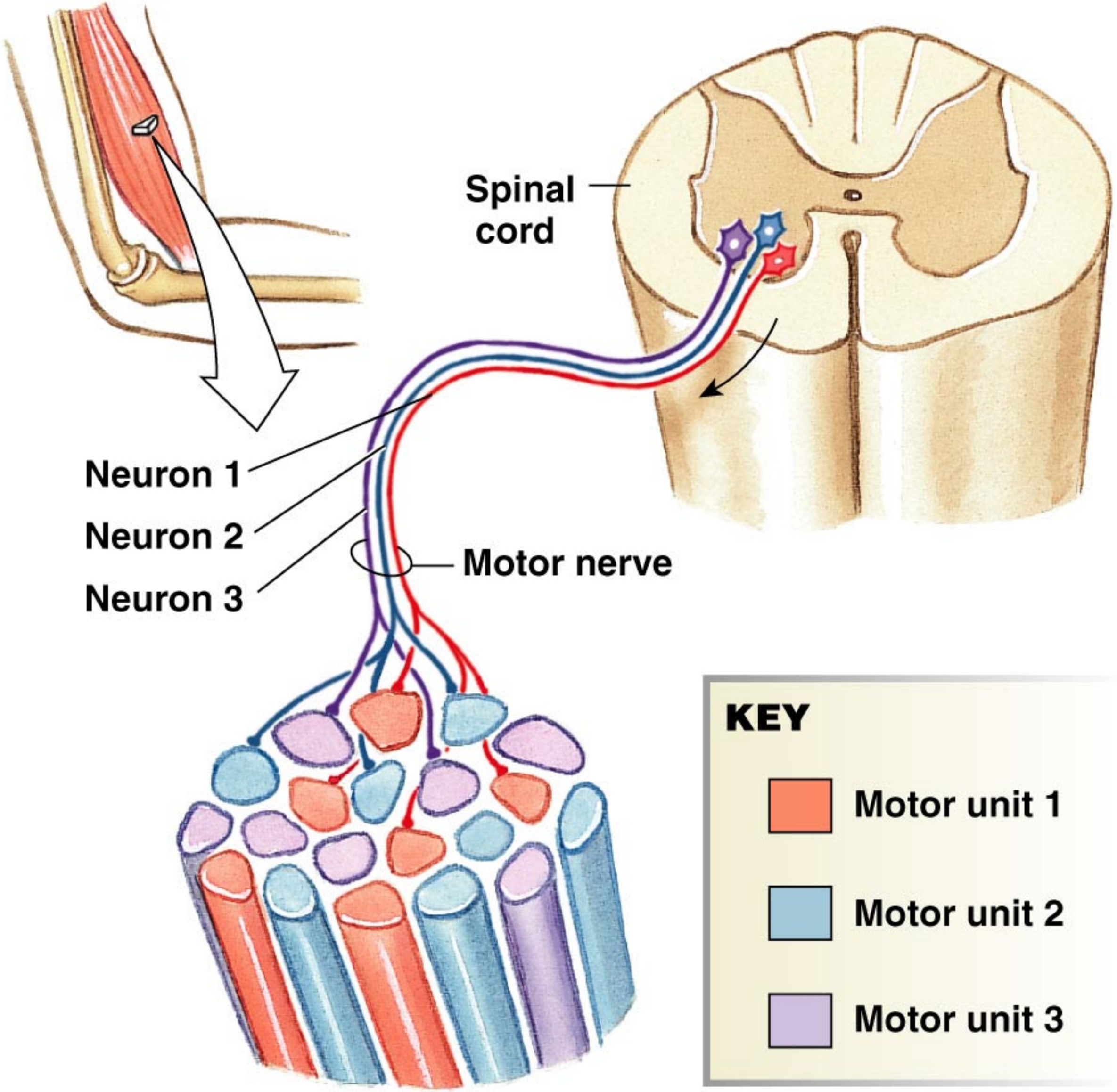
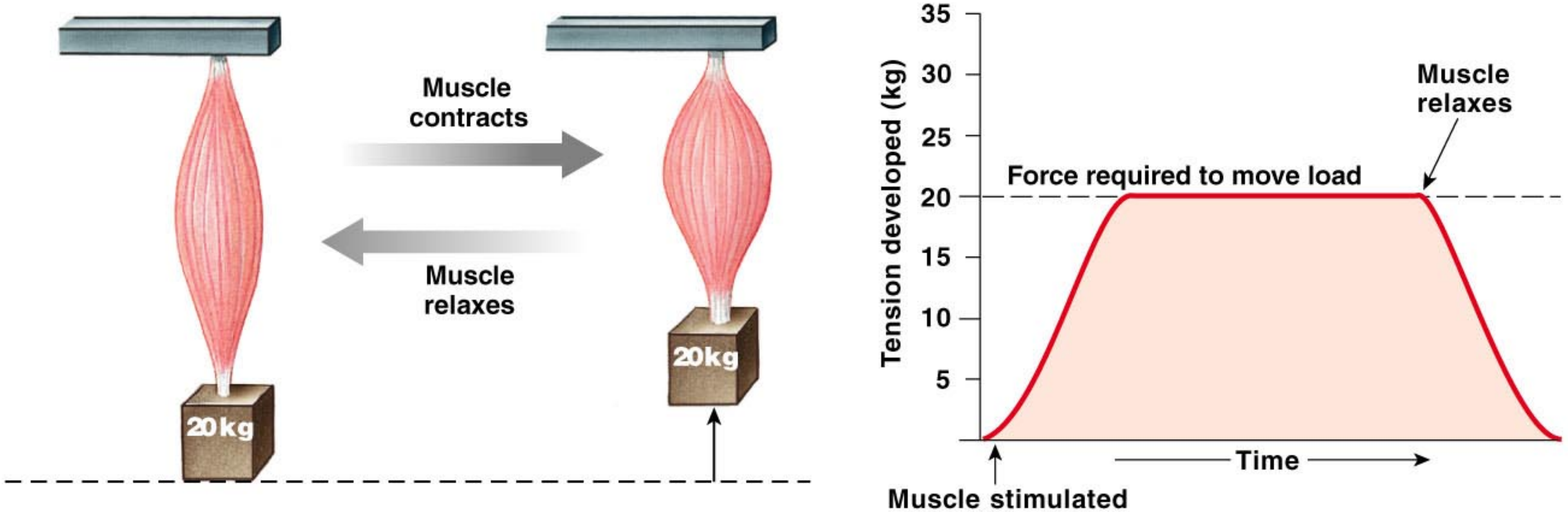
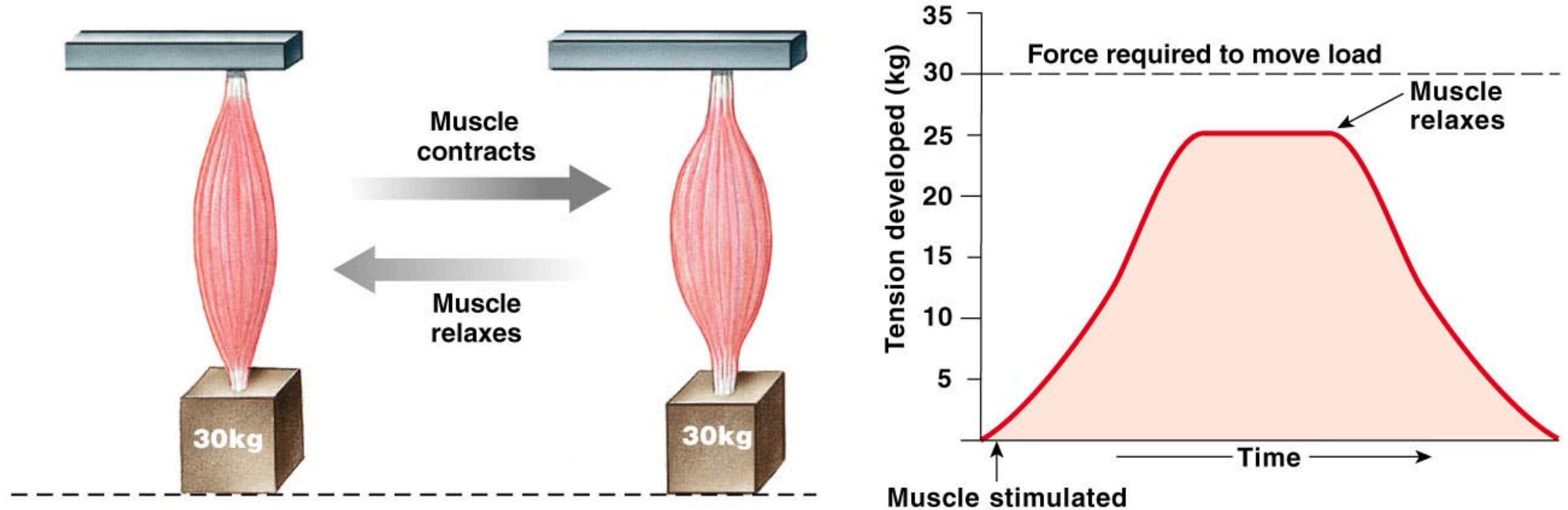


Figure 12-18

(a) Isotonic contraction: muscle contracts, shortens, and creates enough force to move the load.



(b) Isometric contraction: muscle contracts but does not shorten. Force cannot move the load.



(a) Isotonic contraction: muscle contracts, shortens, and creates enough force to move the load.

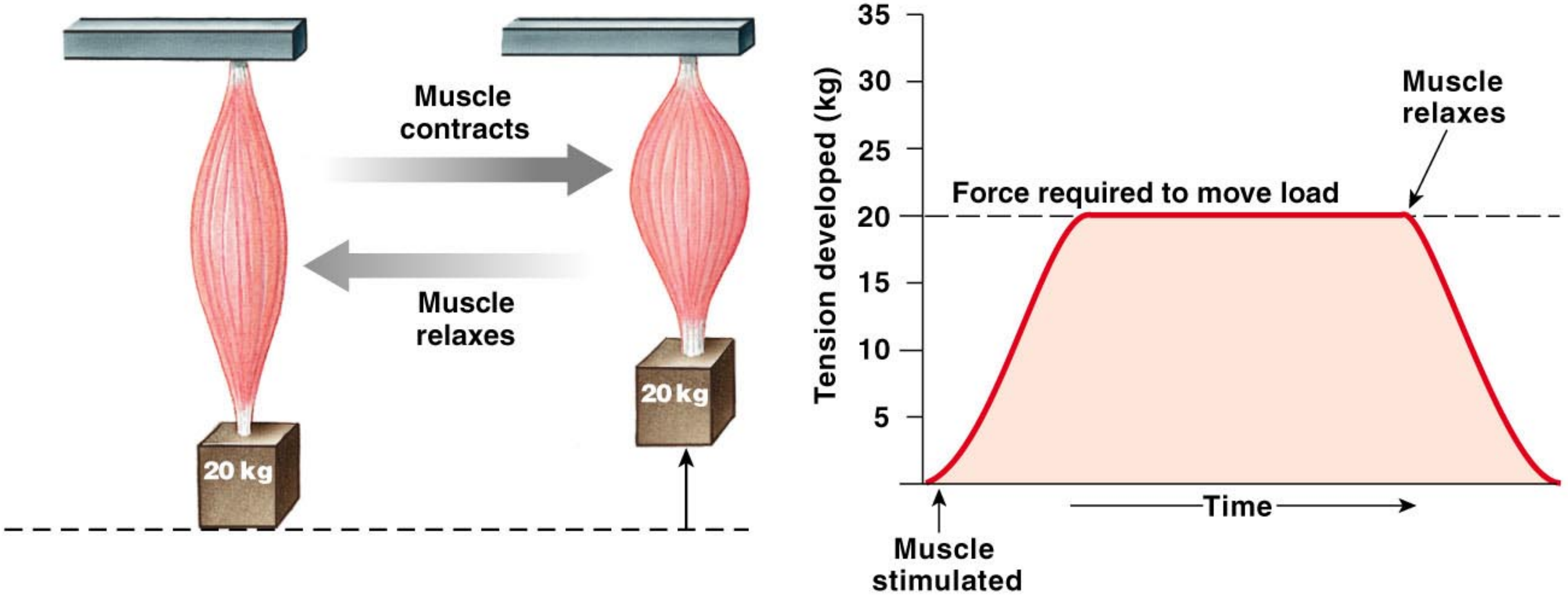


Figure 12-19a

(b) Isometric contraction: muscle contracts but does not shorten. Force cannot move the load.

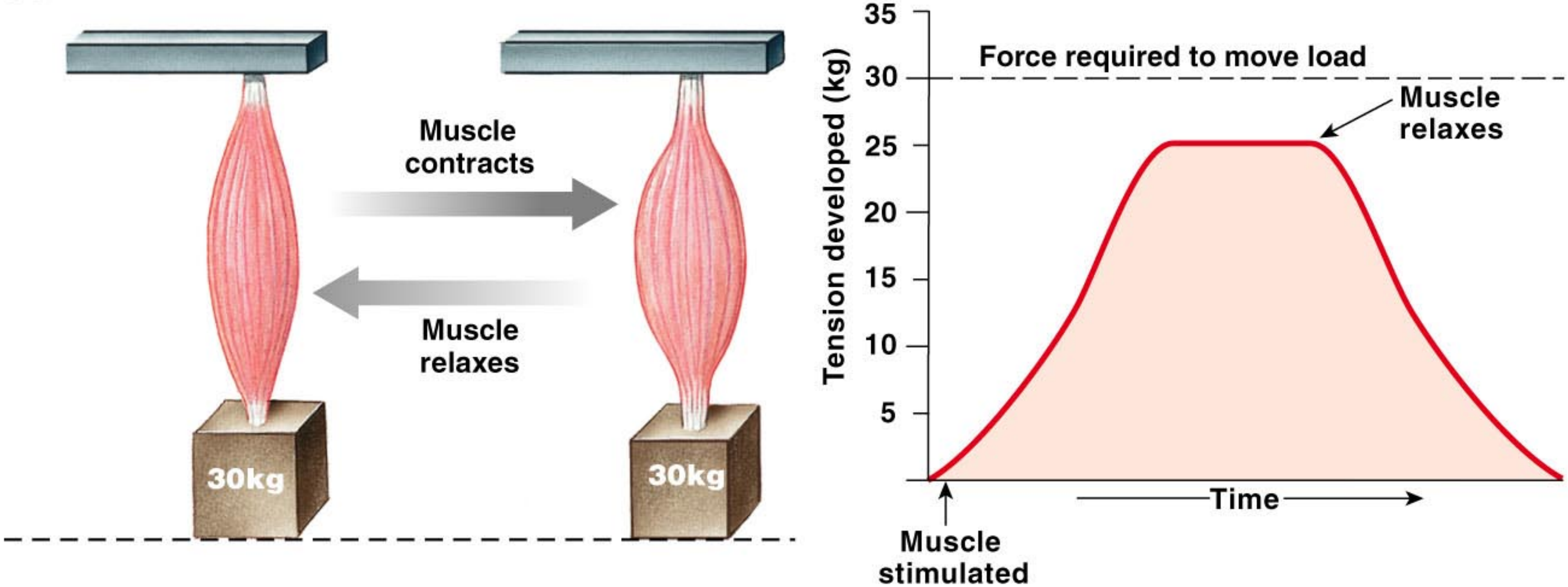
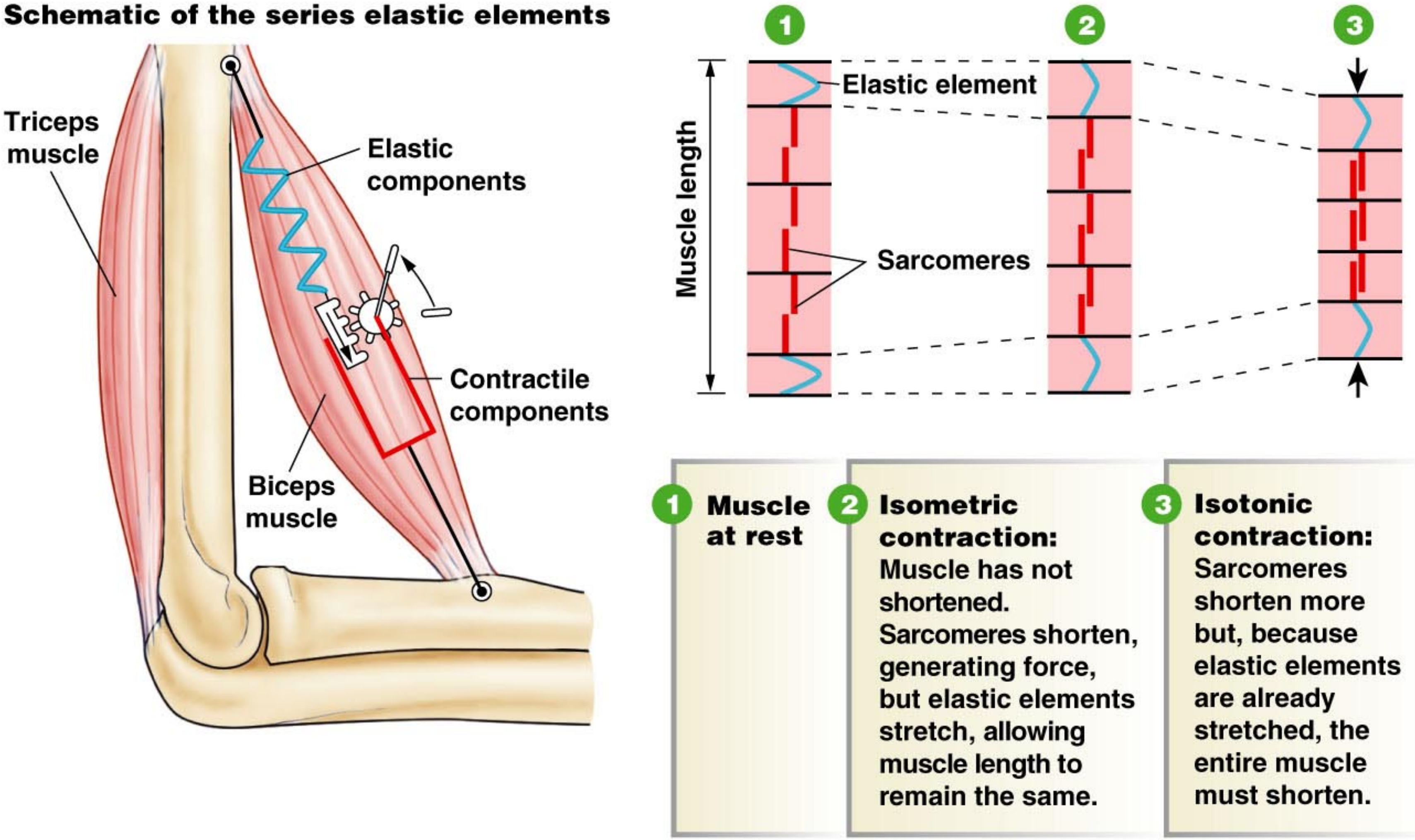


Figure 12-19b


Schematic of the series elastic elements
Triceps muscle
Elastic components
Contractile components
Biceps muscle
Muscle length
Elastic element
Sarcomeres
1 Muscle at rest
2 Isometric contraction: Muscle has not shortened. Sarcomeres shorten, generating force, but elastic elements stretch, allowing muscle length to remain the same.
3 Isotonic contraction: Sarcomeres shorten more but, because elastic elements are already stretched, the entire muscle must shorten.

Schematic of the series elastic elements

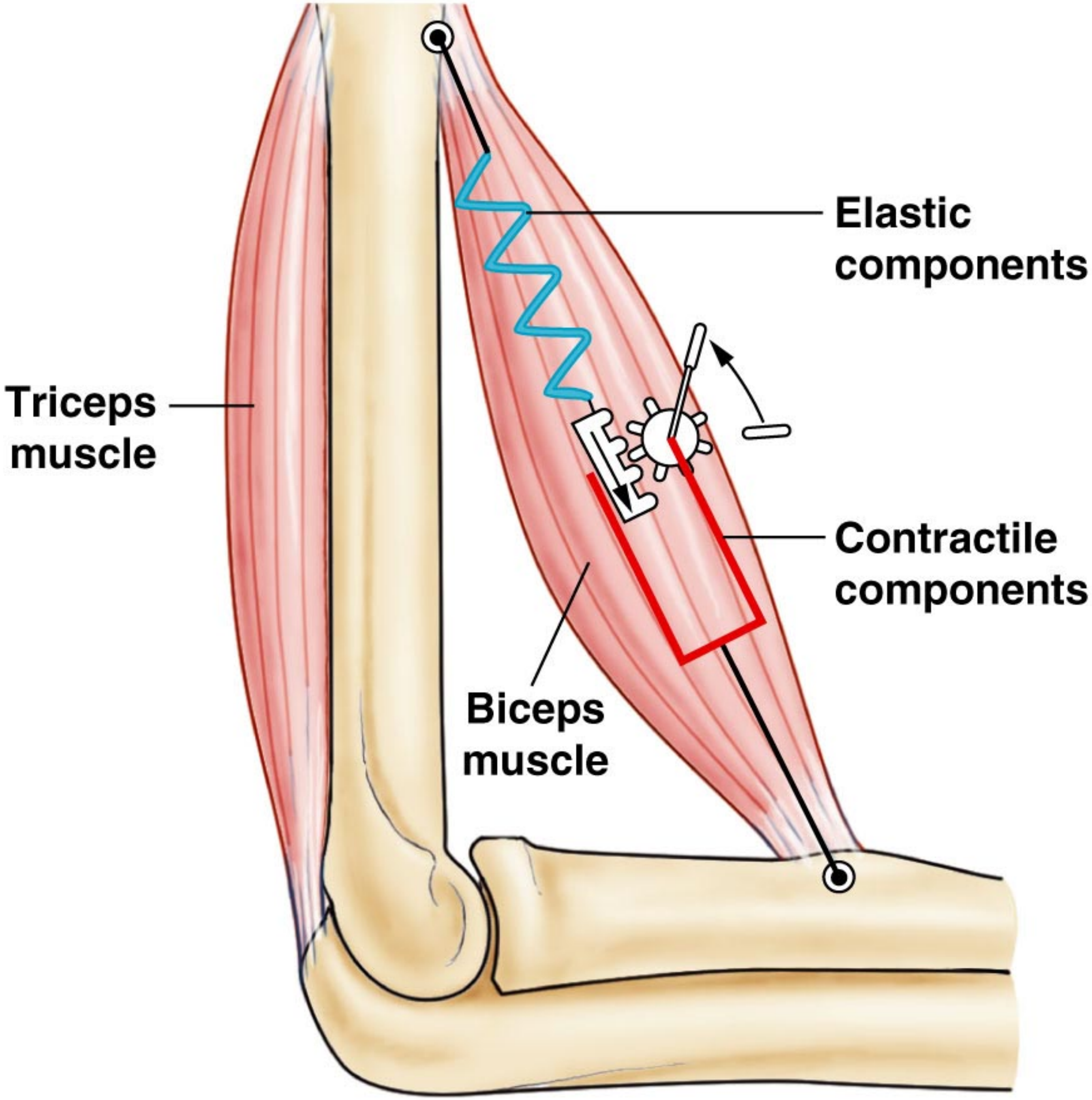
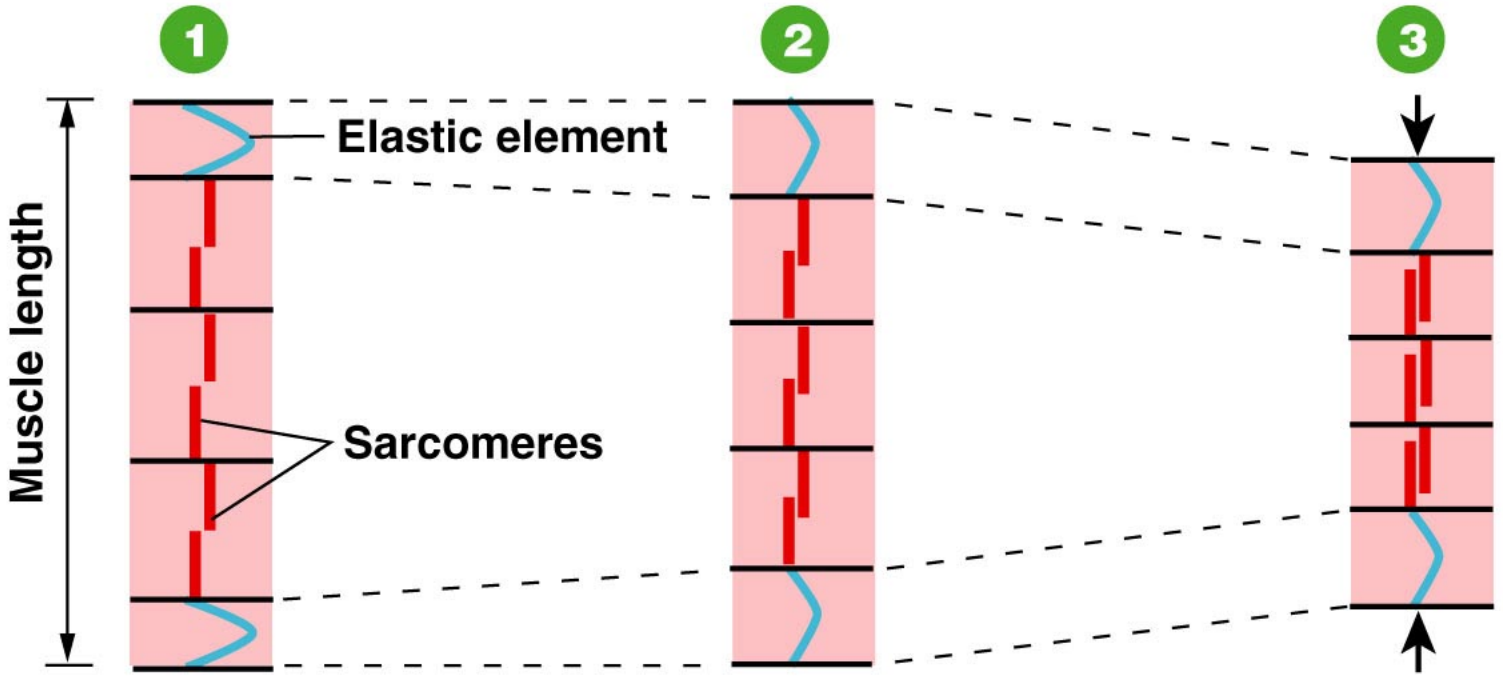


Figure 12-20 (2 of 3)



1 Muscle at rest

2 Isometric contraction: Muscle has not shortened. Sarcomeres shorten, generating force, but elastic elements stretch, allowing muscle length to remain the same.

3 Isotonic contraction: Sarcomeres shorten more but, because elastic elements are already stretched, the entire muscle must shorten.

Figure 12-20 (3 of 3)

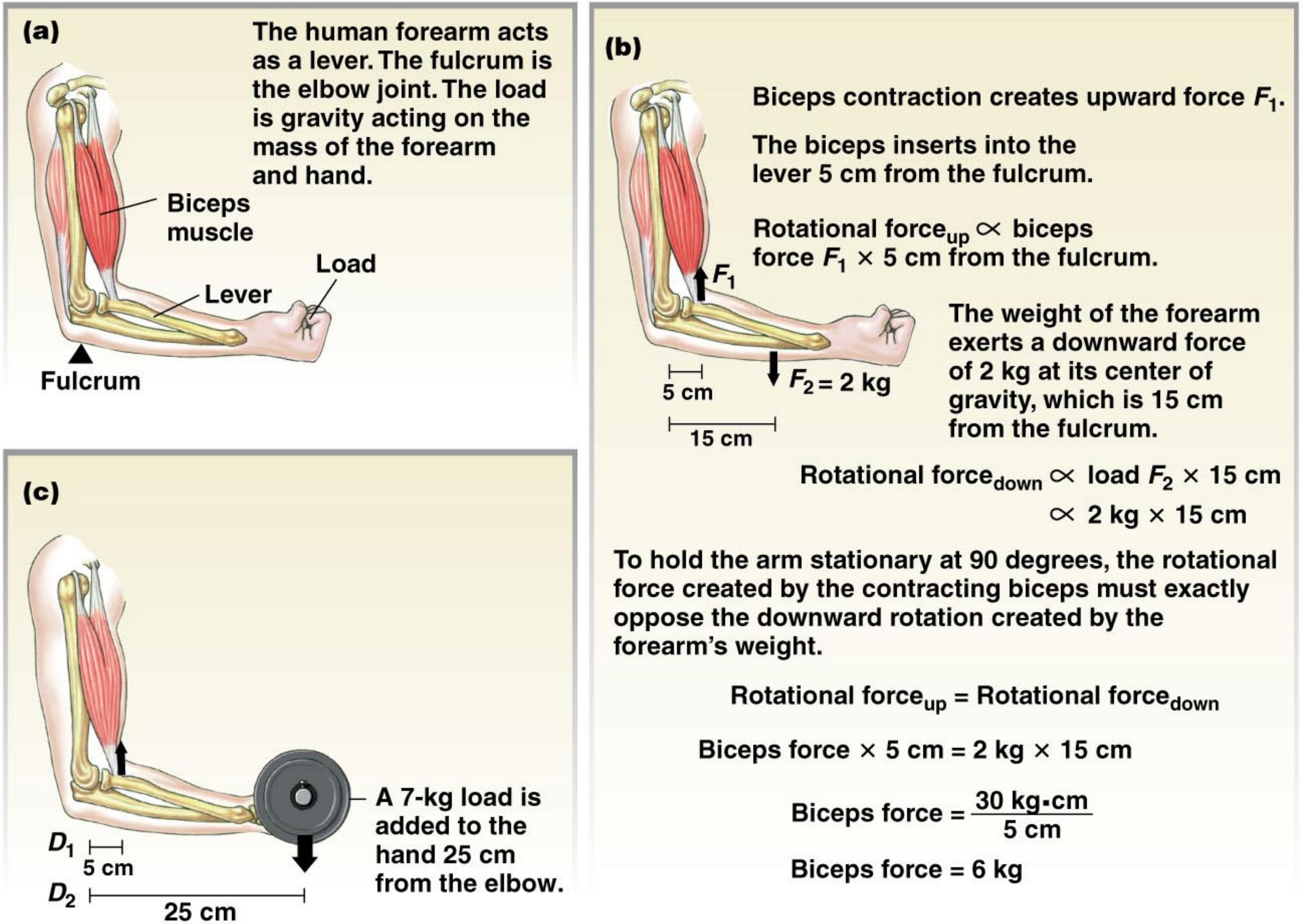
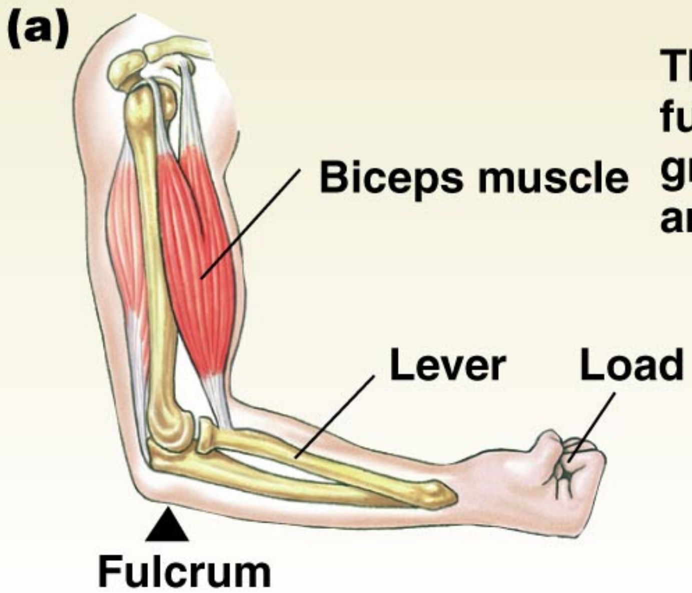


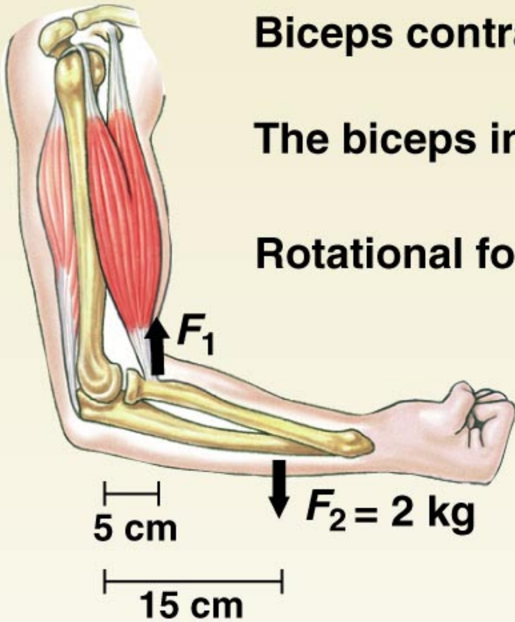
Figure 12-21 - Overview



The human forearm acts as a lever. The fulcrum is the elbow joint. The load is gravity acting on the mass of the forearm and hand.

Figure 12-21a

(b)



Biceps contraction creates upward force F_1.

The biceps inserts into the lever 5 cm from the fulcrum.

Rotational force$_{up}$ $\propto$ biceps force F_1 × 5 cm from the fulcrum.

The weight of the forearm exerts a downward force of 2 kg at its center of gravity, which is 15 cm from the fulcrum.

Rotational force$_{down}$ $\propto$ load F_2 × 15 cm
$\propto$ 2 kg × 15 cm

To hold the arm stationary at 90 degrees, the rotational force created by the contracting biceps must exactly oppose the downward rotation created by the forearm's weight.

Rotational force$_{up}$ = Rotational force$_{down}$

Biceps force × 5 cm = 2 kg × 15 cm

$$\text{Biceps force} = \frac{30\ \text{kg}\cdot\text{cm}}{5\ \text{cm}}$$

Biceps force = 6 kg

 Figure 12-21b

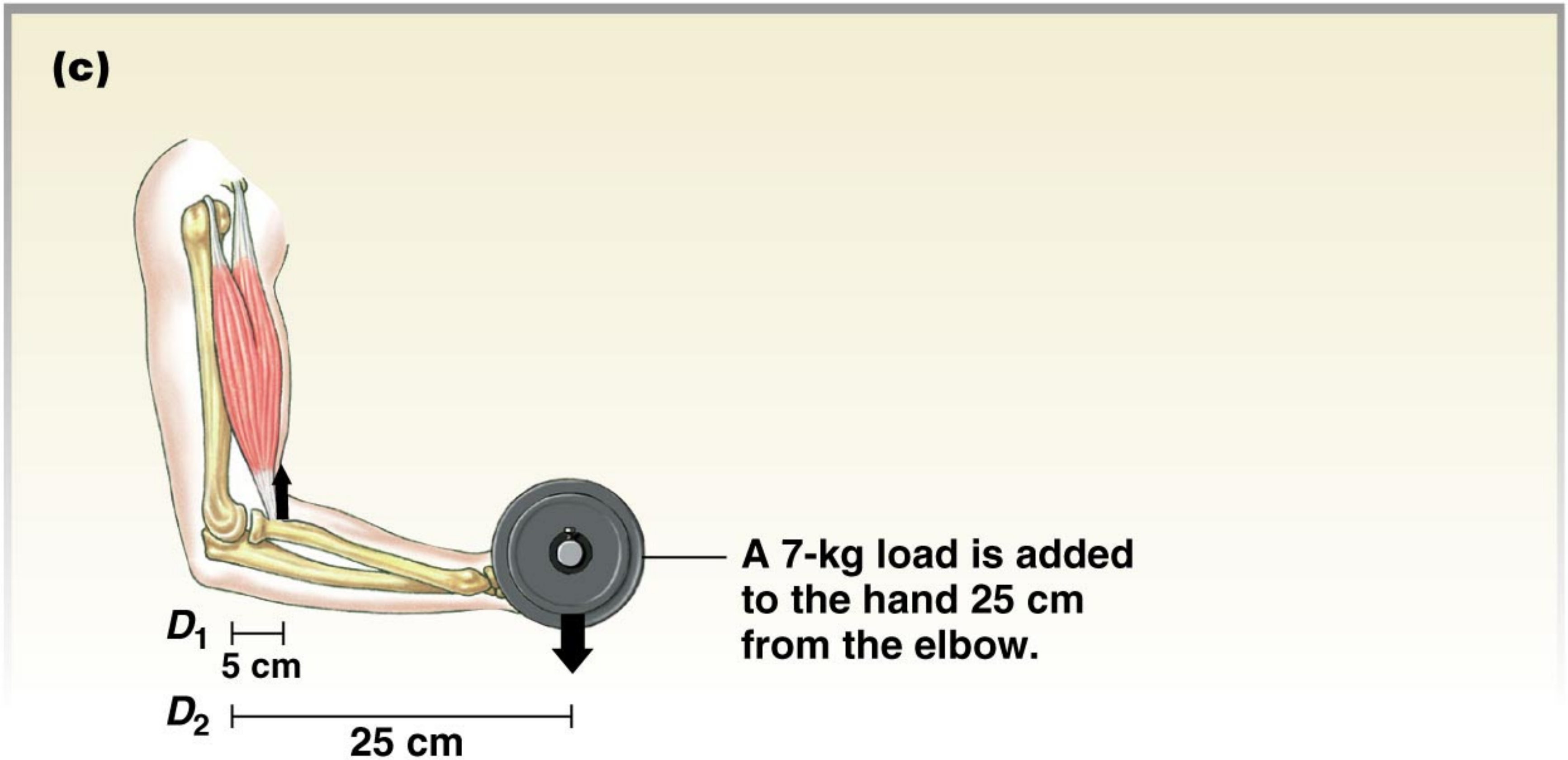
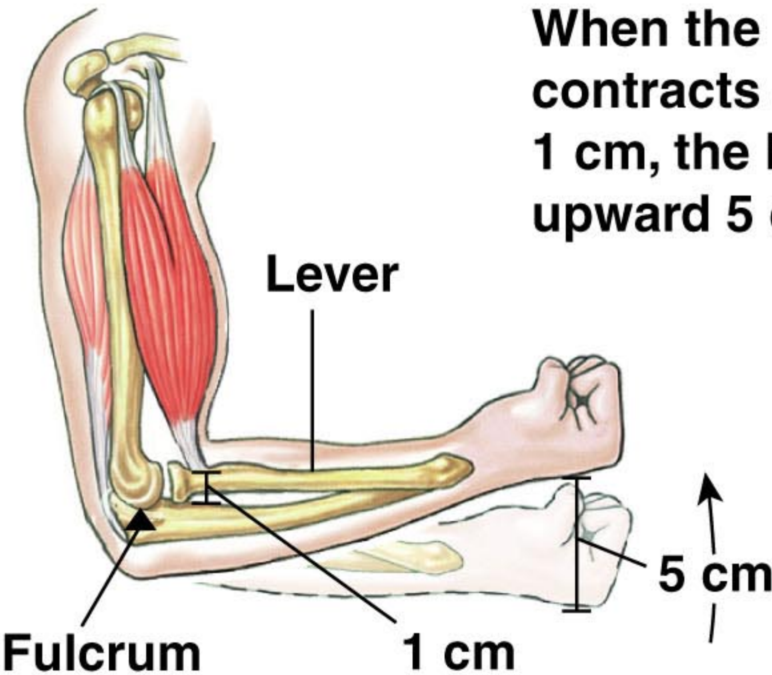


Figure 12-21c

Because the insertion of the biceps is close to the fulcrum, a small movement of the biceps becomes a much larger movement of the hand.



When the biceps contracts and shortens 1 cm, the hand moves upward 5 cm.

Figure 12-22

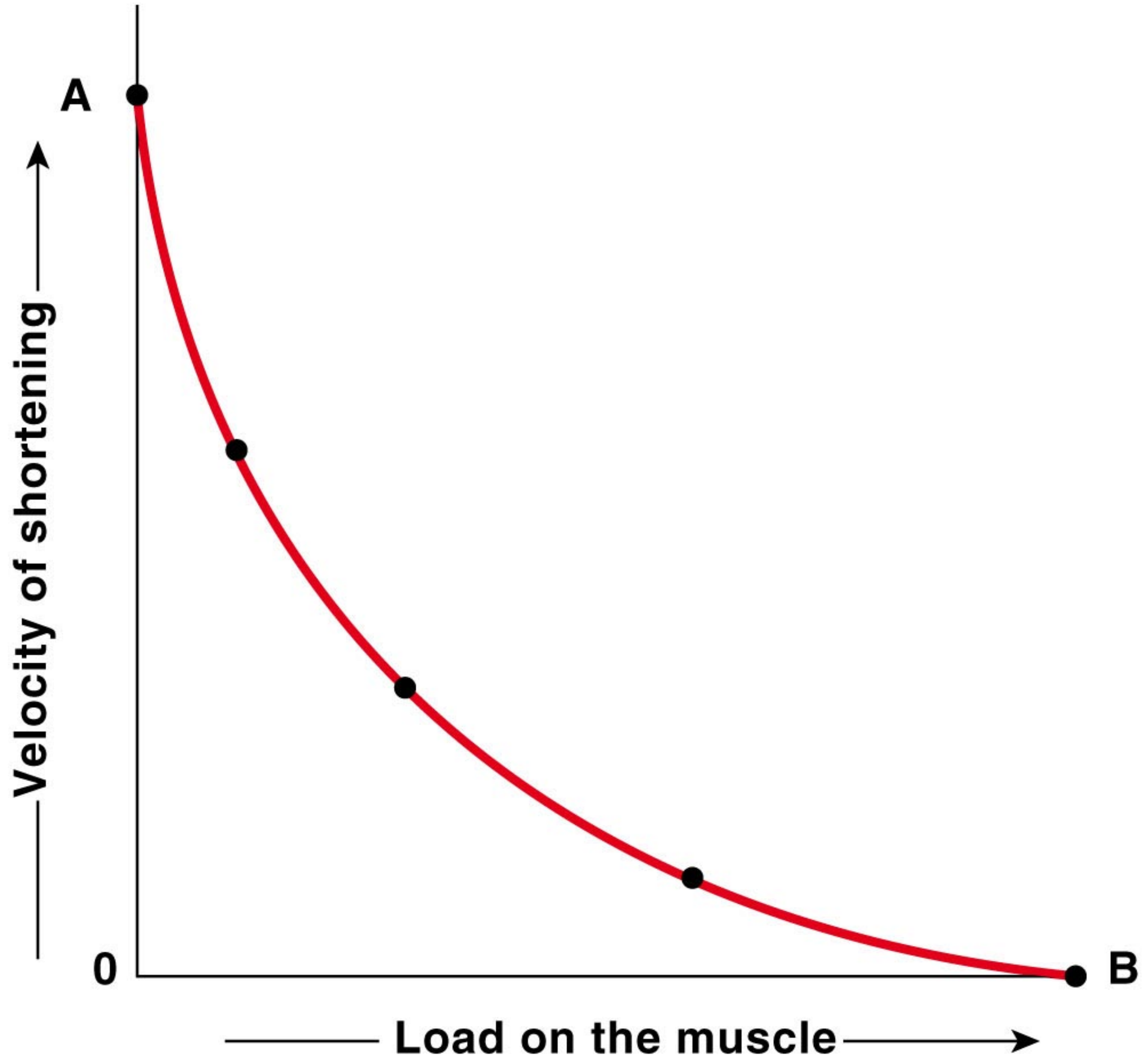


Figure 12-23

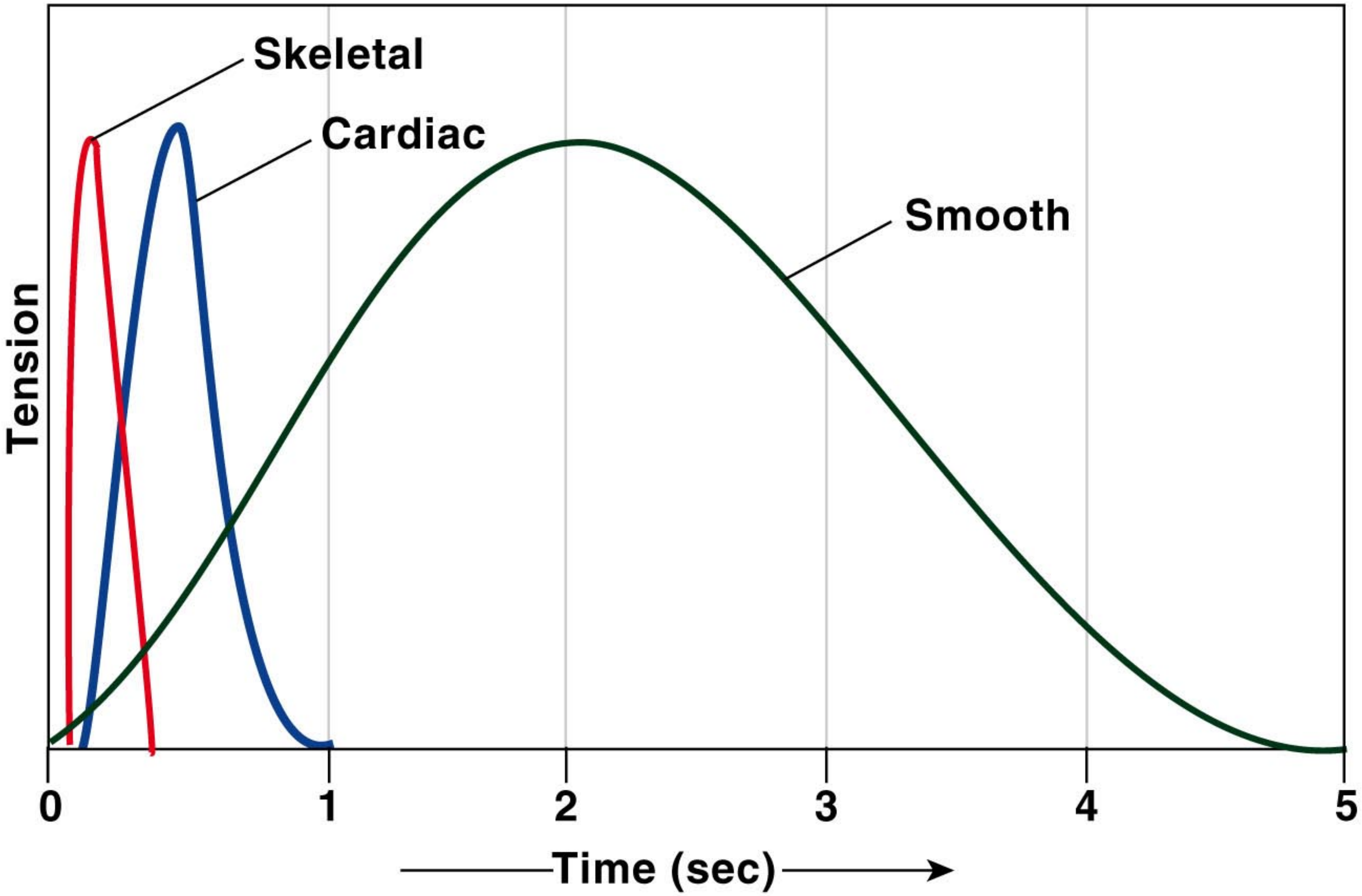


Figure 12-24

(a) Single-unit smooth muscle cells are connected by gap junctions, and the cells contract as a single unit.

(b) Multi-unit smooth muscle cells are not electrically linked, and each cell must be stimulated independently.

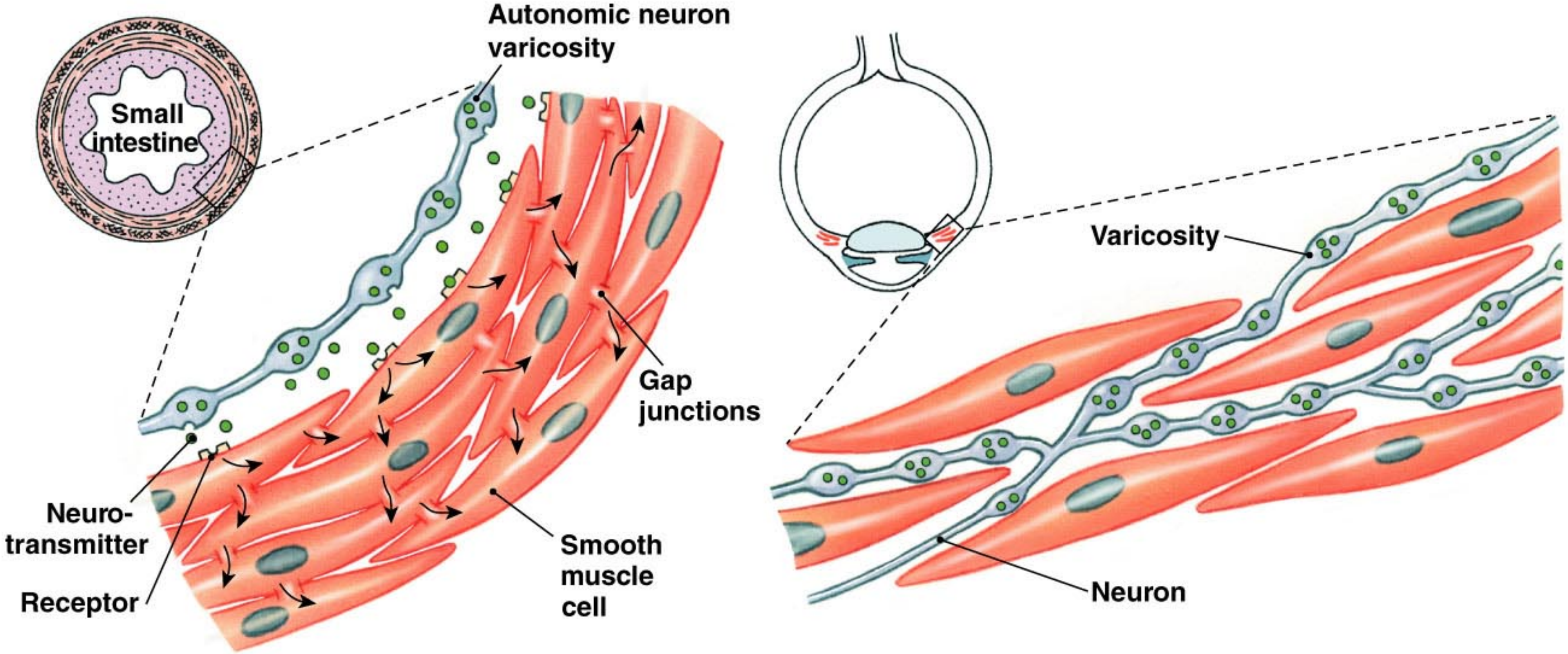


Figure 12-25 Overview

(a) Single-unit smooth muscle cells are connected by gap junctions, and the cells contract as a single unit.

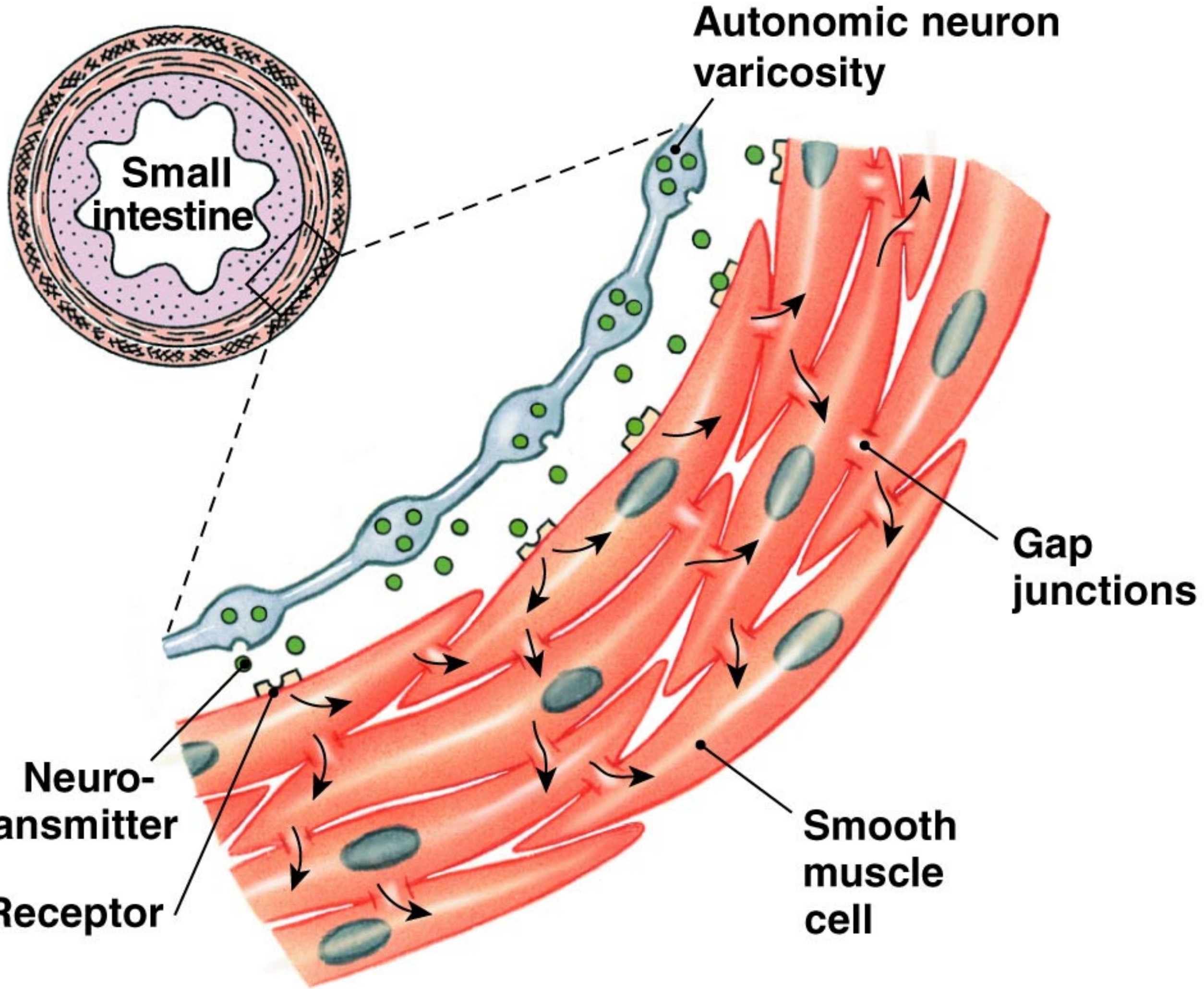


Figure 12-25a

(b) Multi-unit smooth muscle cells are not electrically linked, and each cell must be stimulated independently.

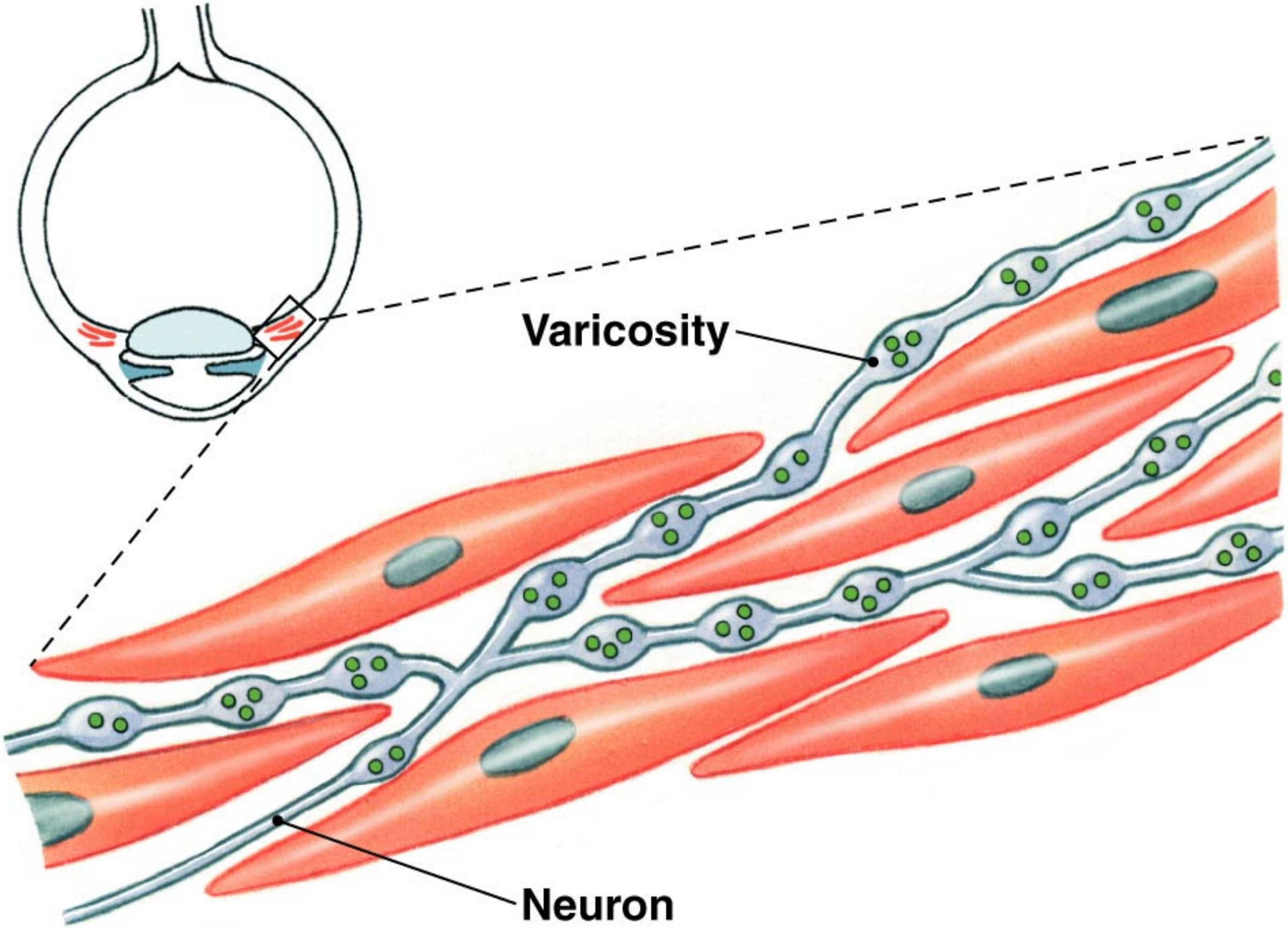
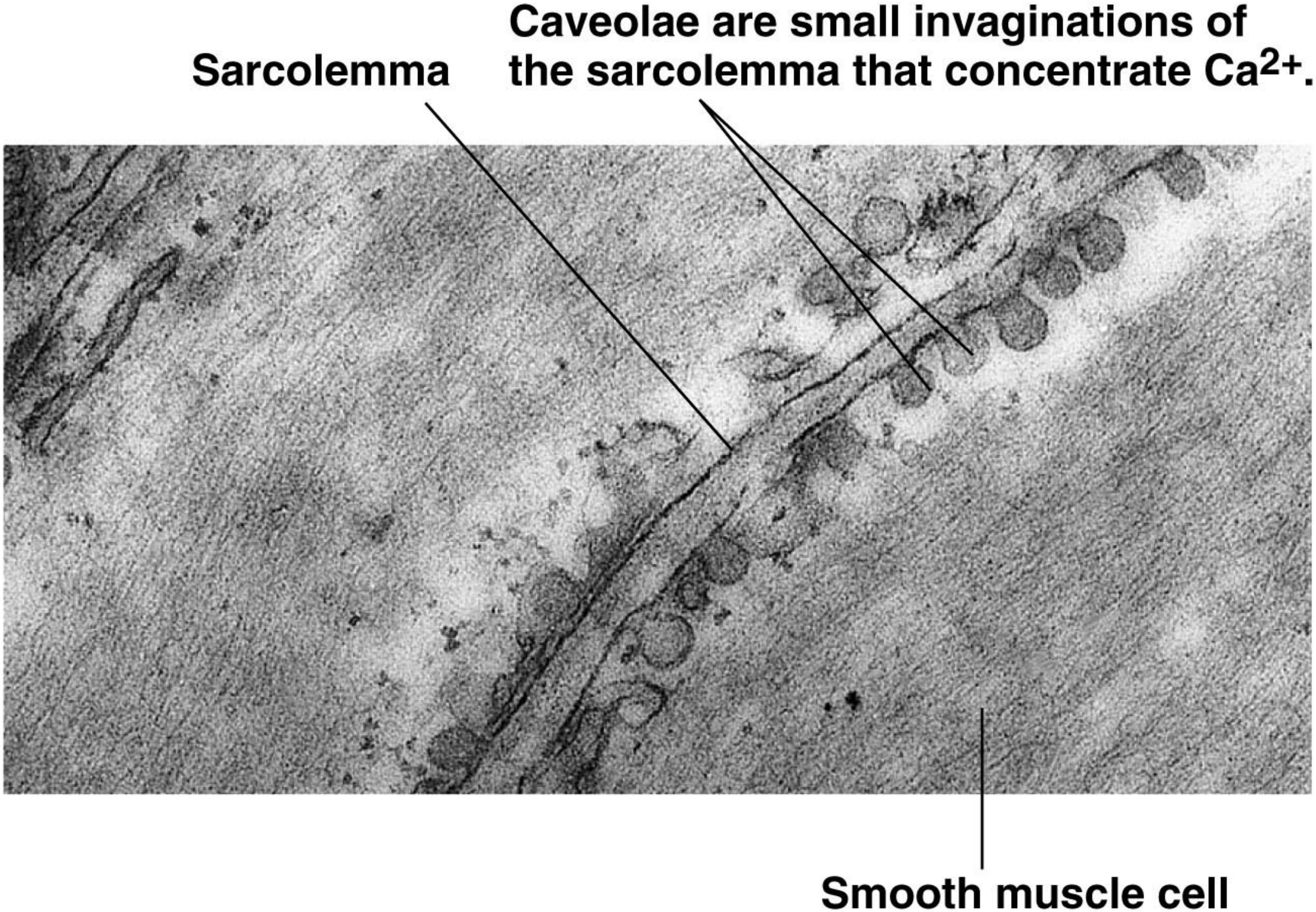
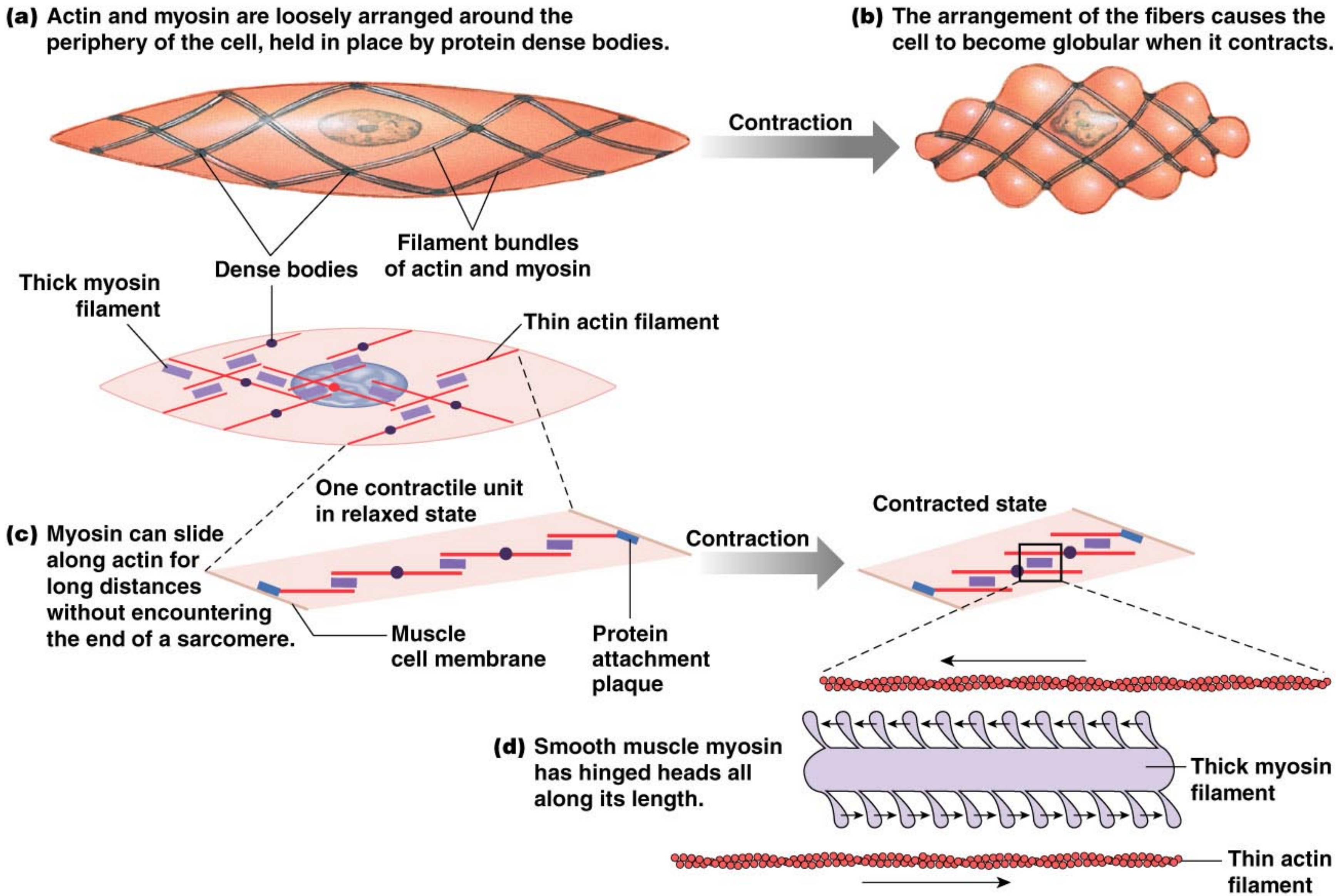


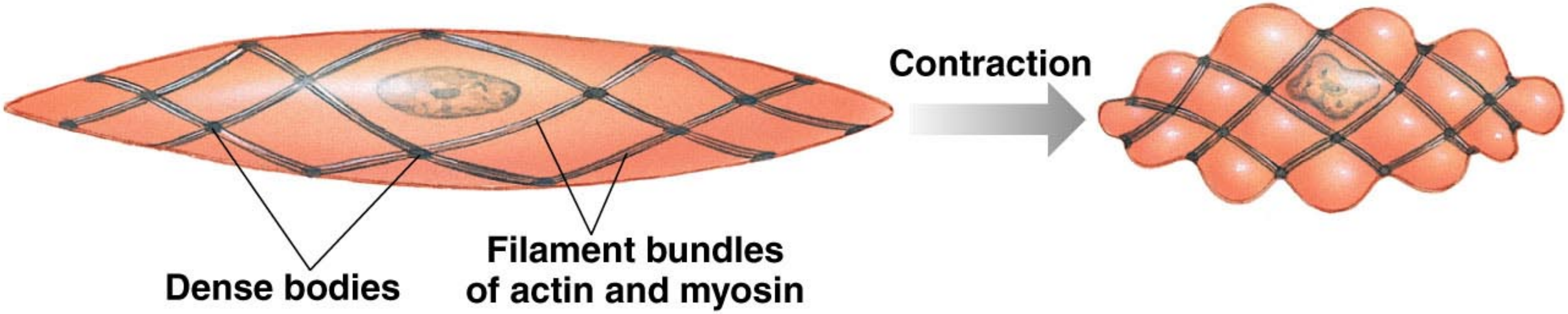
Figure 12-25b

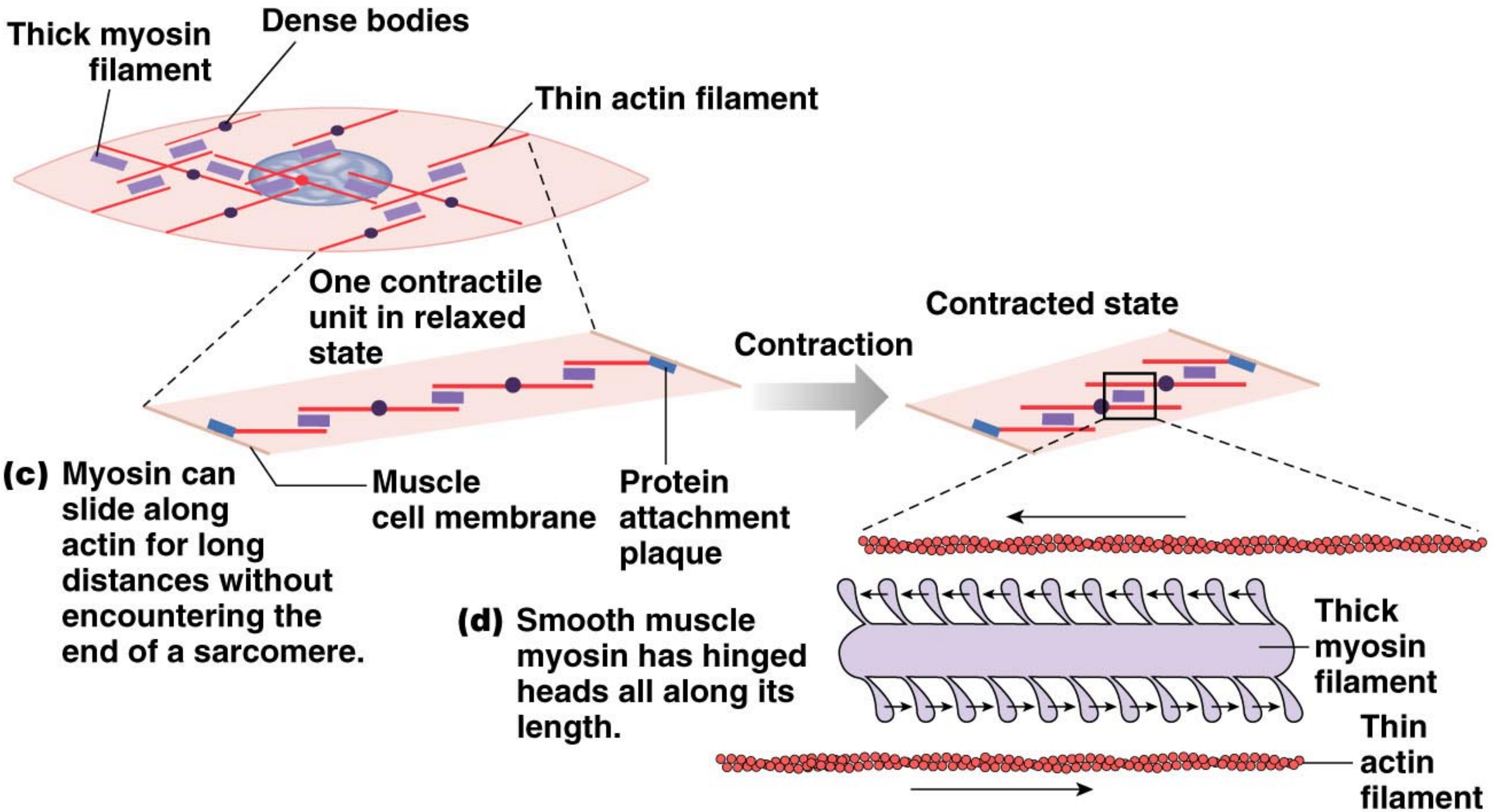

Sarcolemma
Caveolae are small invaginations of the sarcolemma that concentrate Ca^{2+}.
Smooth muscle cell


(a) Actin and myosin are loosely arranged around the periphery of the cell, held in place by protein dense bodies.
(b) The arrangement of the fibers causes the cell to become globular when it contracts.
Contraction
Dense bodies
Filament bundles of actin and myosin
Thick myosin filament
Thin actin filament
One contractile unit in relaxed state
Contracted state
Contraction
(c) Myosin can slide along actin for long distances without encountering the end of a sarcomere.
Muscle cell membrane
Protein attachment plaque
(d) Smooth muscle myosin has hinged heads all along its length.
Thick myosin filament
Thin actin filament

(a) Actin and myosin are loosely arranged around the periphery of the cell, held in place by protein dense bodies.

(b) The arrangement of the fibers causes the cell to become globular when it contracts.

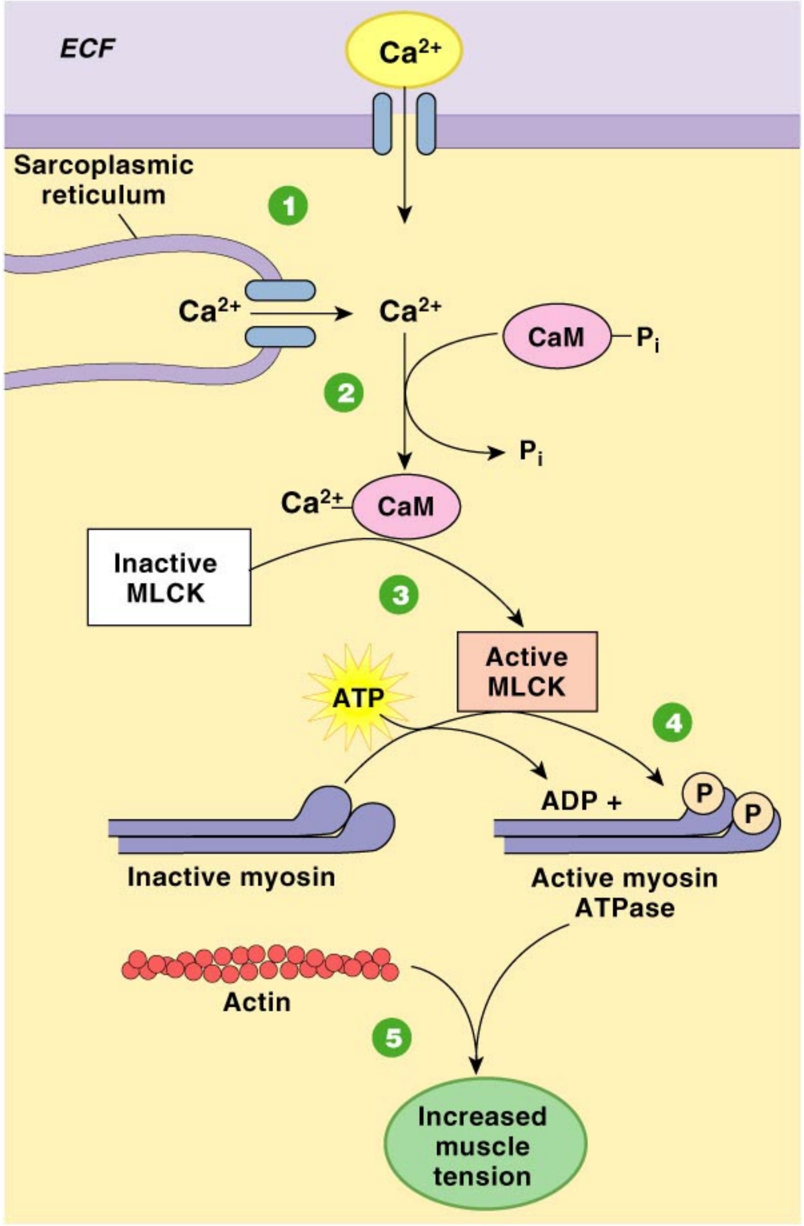




(c) Myosin can slide along actin for long distances without encountering the end of a sarcomere.

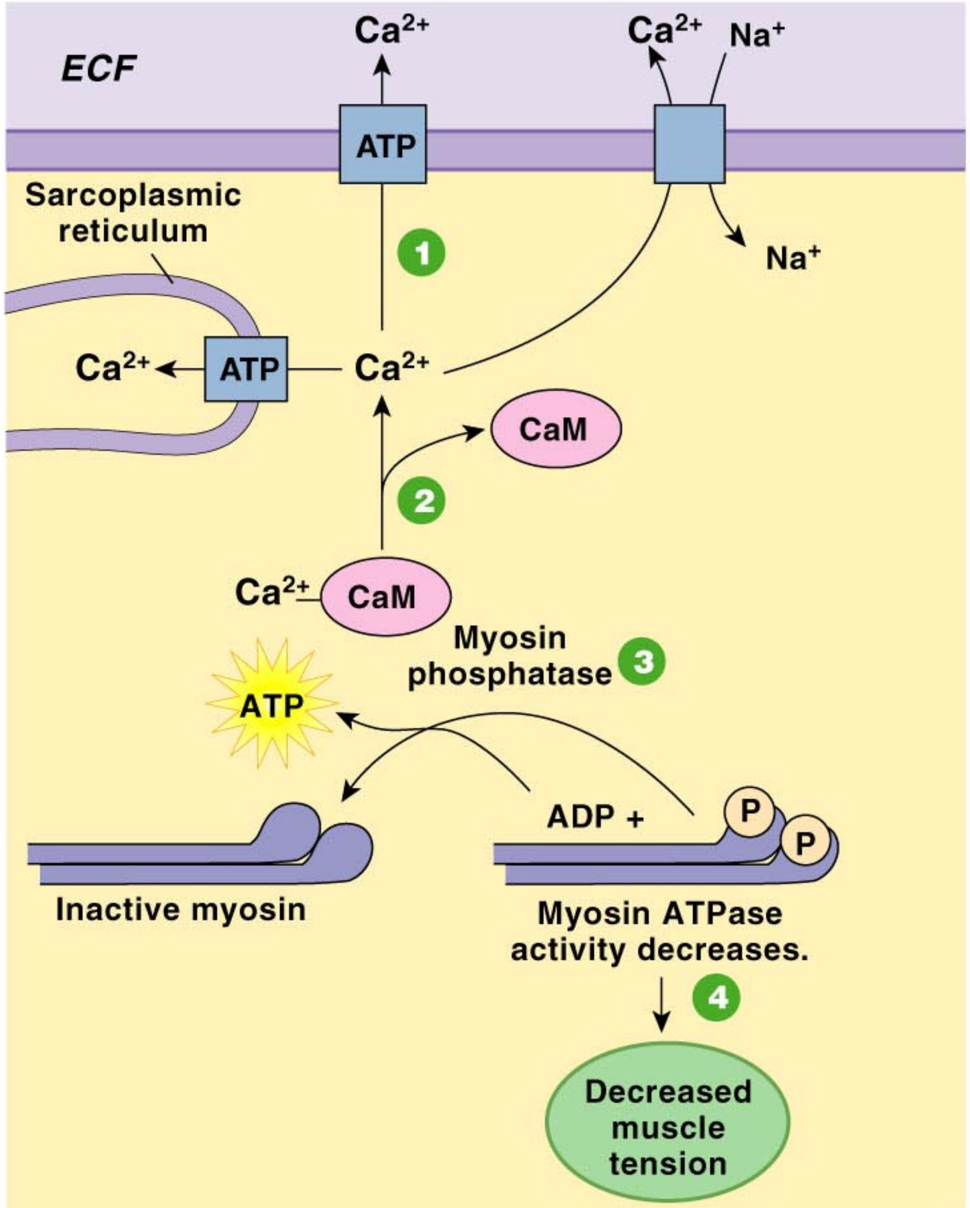
(d) Smooth muscle myosin has hinged heads all along its length.

Figure 12-27c-d



1. Intracellular Ca^{2+} concentrations increase when Ca^{2+} enters cell and is released from sarcoplasmic reticulum.
2. Ca^{2+} binds to calmodulin (CaM).
3. Ca^{2+}–calmodulin activates myosin light chain kinase (MLCK).
4. MLCK phosphorylates light chains in myosin heads and increases myosin ATPase activity.
5. Active myosin crossbridges slide along actin and create muscle tension.

Figure 12-28



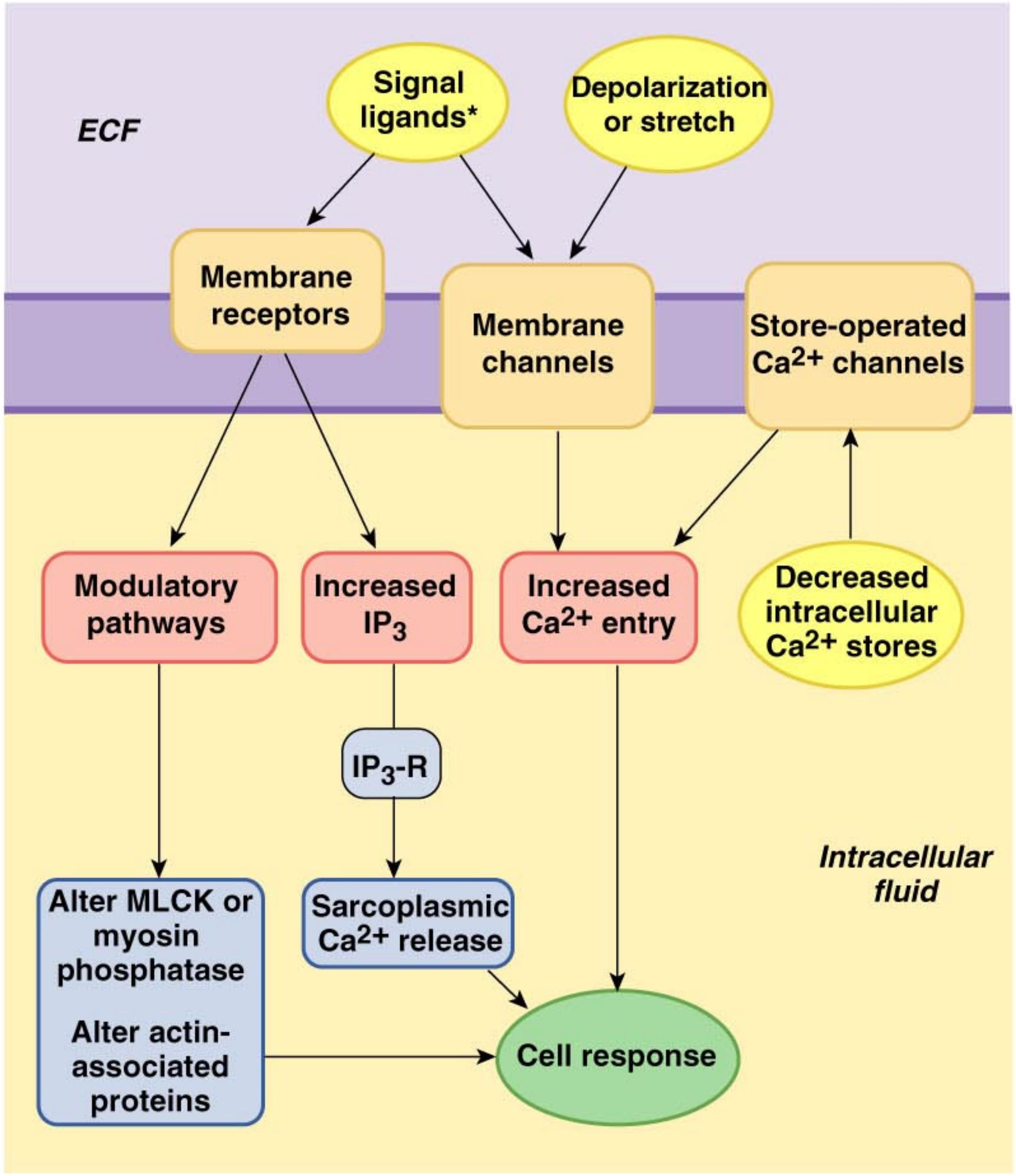
1. Free Ca^{2+} in cytosol decreases when Ca^{2+} is pumped out of the cell or back into the sarcoplasmic reticulum.

2. Ca^{2+} unbinds from calmodulin (CaM).

3. Myosin phosphatase removes phosphate from myosin, which decreases myosin ATPase activity.

4. Less myosin ATPase results in decreased muscle tension.

Figure 12-29



KEY

IP_3–R = IP_3–activated receptor–channel

* Ligands include norepinephrine, ACh, other neurotransmitters, hormones, and paracrines.

Figure 12-30

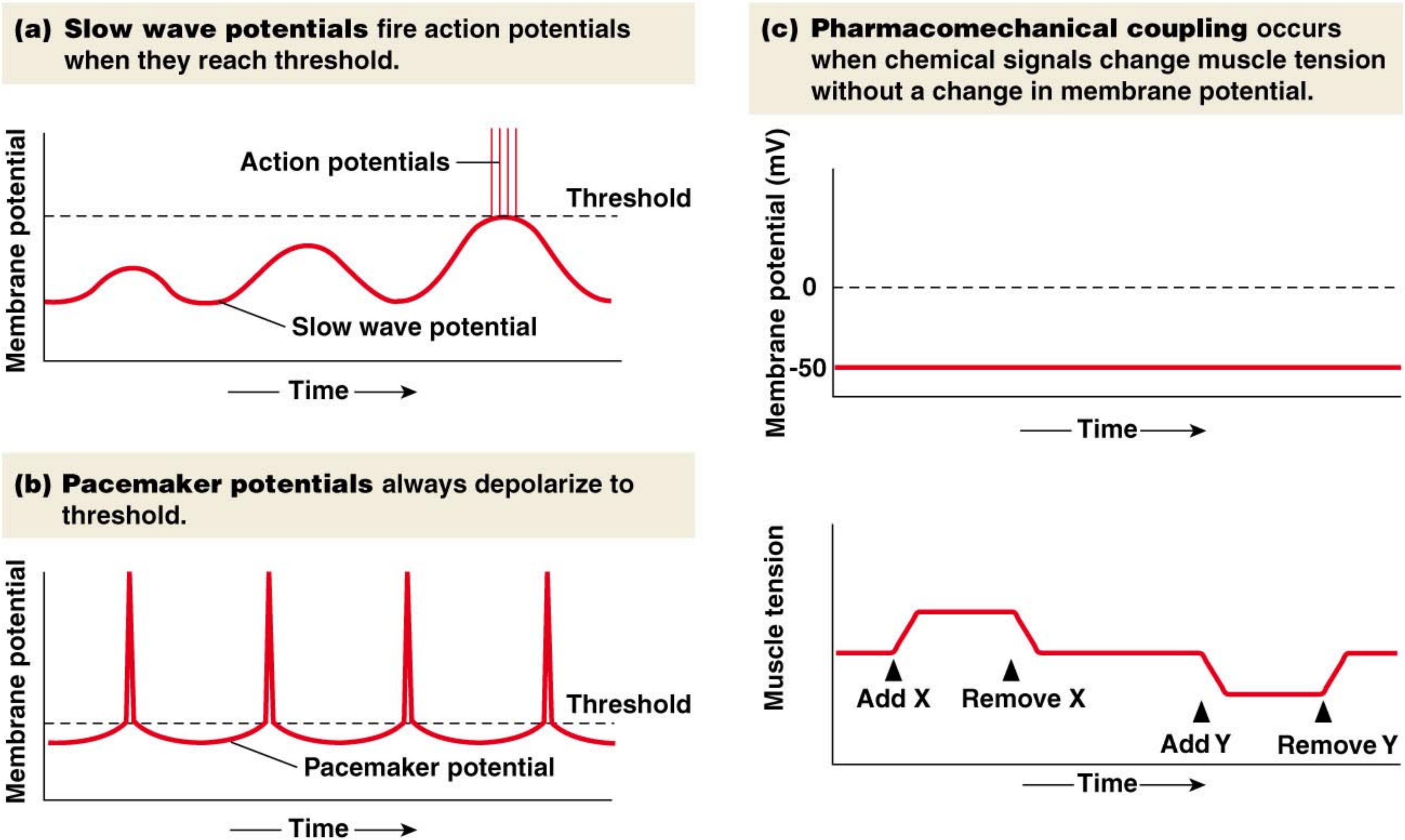


Figure 12-31 Overview

(a) Slow wave potentials fire action potentials when they reach threshold.

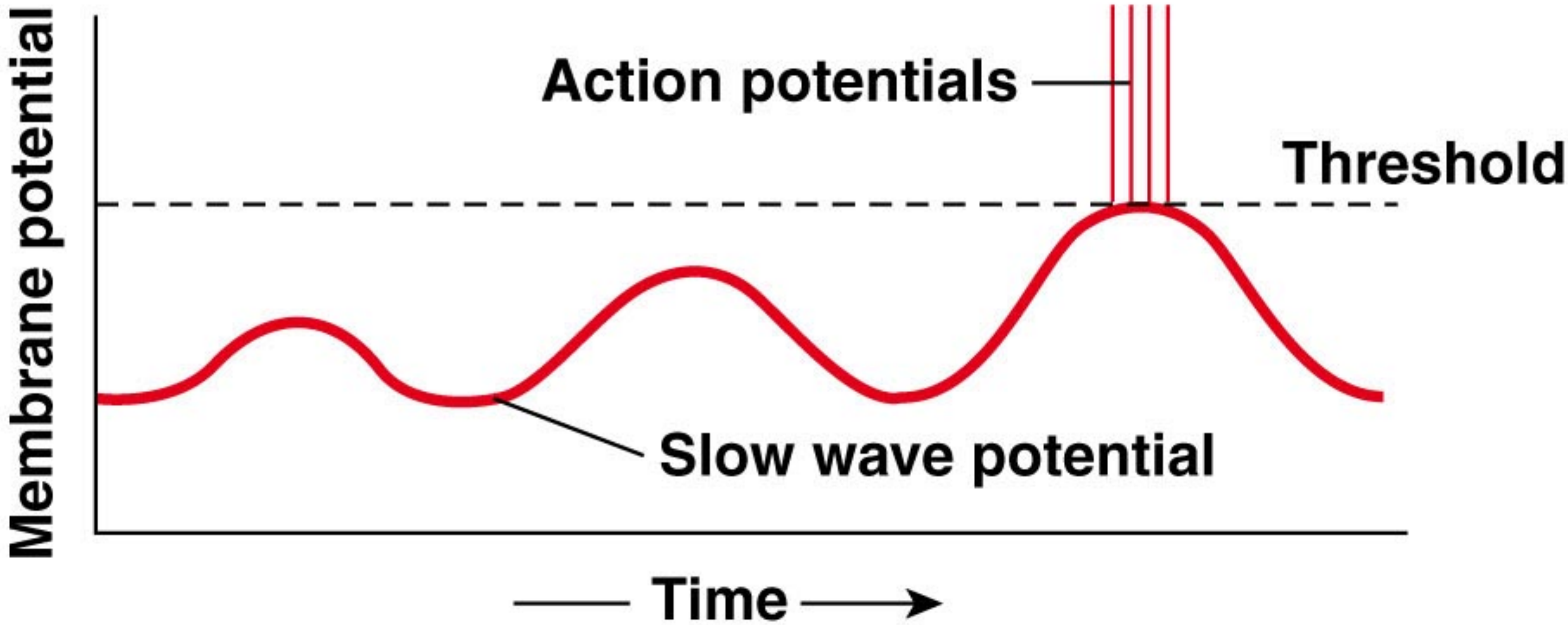


Figure 12-31a

(b) Pacemaker potentials always depolarize to threshold.

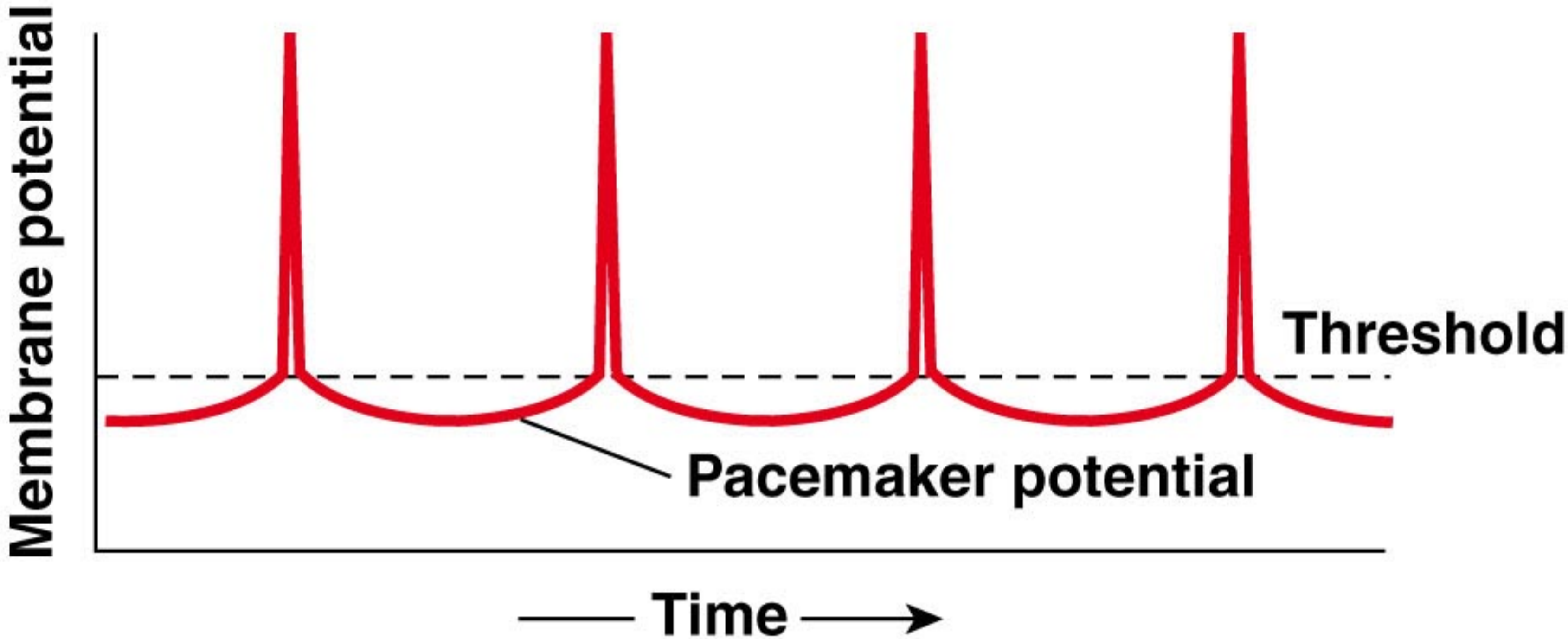


Figure 12-31b

(c) Pharmacomechanical coupling occurs when chemical signals change muscle tension without a change in membrane potential.

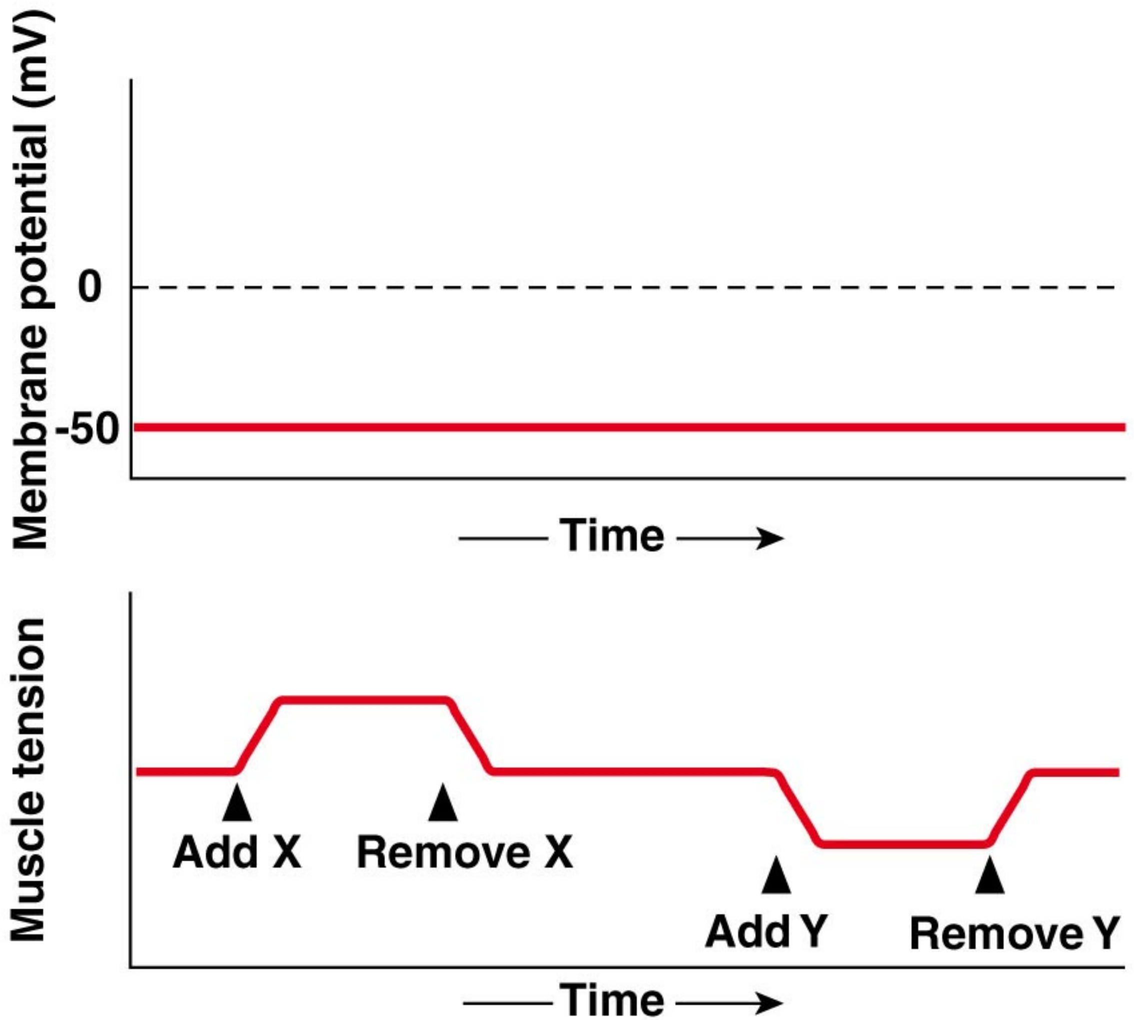


Figure 12-31c

TABLE 12-3 Comparison of the Three Muscle Types

	SKELETAL	SMOOTH	CARDIAC
Appearance under light microscope	Striated	Smooth	Striated
Fiber arrangement	Sarcomeres	Oblique bundles	Sarcomeres
Fiber proteins	Actin, myosin; troponin and tropomyosin	Actin, myosin, tropomyosin	Actin, myosin; troponin and tropomyosin
Control	• Voluntary • Ca^{2+} and troponin • Fibers independent of one another	• Involuntary • Ca^{2+} and calmodulin • Fibers electrically linked via gap junctions	• Involuntary • Ca^{2+} and troponin • Fibers electrically linked via gap junctions
Nervous control	Somatic motor neuron	Autonomic neurons	Autonomic neurons
Hormonal influence	None	Multiple hormones	Epinephrine
Location	Attached to bones; a few sphincters close off hollow organs	Forms the walls of hollow organs and tubes; some sphincters	Heart muscle
Morphology	Multinucleate; large, cylindrical fibers	Uninucleate; small spindle-shaped fibers	Uninucleate; shorter branching fibers
Internal structure	T-tubule and sarcoplasmic reticulum	No t-tubules; sarcoplasmic reticulum reduced or absent	T-tubule and sarcoplasmic reticulum
Contraction speed	Fastest	Slowest	Intermediate
Contraction force of single fiber twitch	All-or-none	Graded	Graded
Initiation of contraction	Requires input from motor neuron	Can be autorhythmic	Autorhythmic

Table 12-3