Sistem Gerak dan Lokomosi

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Sistem Gerak dan Lokomosi

- Sistem Saraf Motorik
- Otot rangka
- Tulang
- Sendi

NERVOUS SYSTEM/SISTEM SARAF

- Central nervous system (CNS)/Sistem Saraf Pusat (SSP) : otak & med spinalis, dan
- Peripheral nervous system (PNS) 12 ps s. cranial & 31 ps s.spinal
- PNS :
- Afferent division (sensorik dan *"Panca indera"*) &
- Efferen Division (motorik)

Sistem saraf

SS. Sensorik

- Mendeteksi perubahan lingkungan, mengirimkan info ke SS.Pusat untuk diinterpretasi

SS. Motorik

- Mengontrol, mengendalikan berbagai sistem dalam tubuh dengan mengirim perintah melalui serabut saraf motorik ke organ efektor : otot, jantung, kelenjar, dll

Divisions of the Peripheral Nervous System

I. Afferent division

II. Efferent division

A. Somatic nervous system

B. Autonomic nervous system

1. Sympathetic division
2. Parasympathetic division
3. Enteric division

Peripheral Nervous System: Somatic and Autonomic Divisions

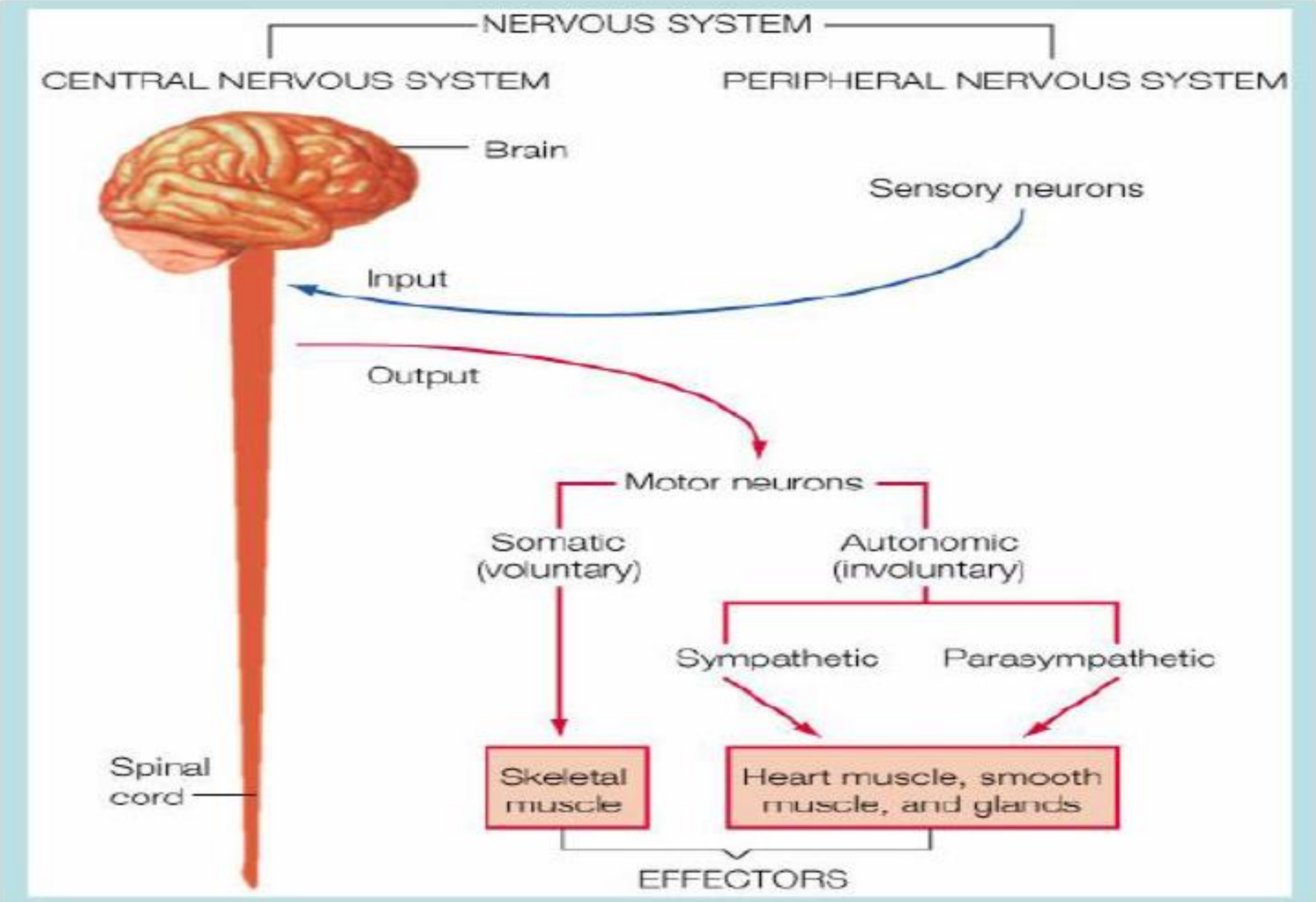
Somatic

1. Consists of a single neuron between central nervous system and skeletal-muscle cells
2. Innervates skeletal muscle
3. Can lead only to muscle excitation

Autonomic

1. Has two-neuron chain (connected by a synapse) between central nervous system and effector organ
2. Innervates smooth and cardiac muscle, glands, and GI neurons
3. Can be either excitatory or inhibitory

Organization of the human nervous system



Pengaturan sistem saraf motorik

- Korteks Serebri : pusat saraf penggerak (mengatur kekuatan gerak)
- Ganglia basalis (mengatur kecepatan gerak)
- Serebelum (mengatur keteraturan/akurasi gerak)
- Medula spinalis (mengatur tonus otot skelet)
- Saraf spinal (menghubungkan CNS (motorik) dengan efektor (otot skelet)

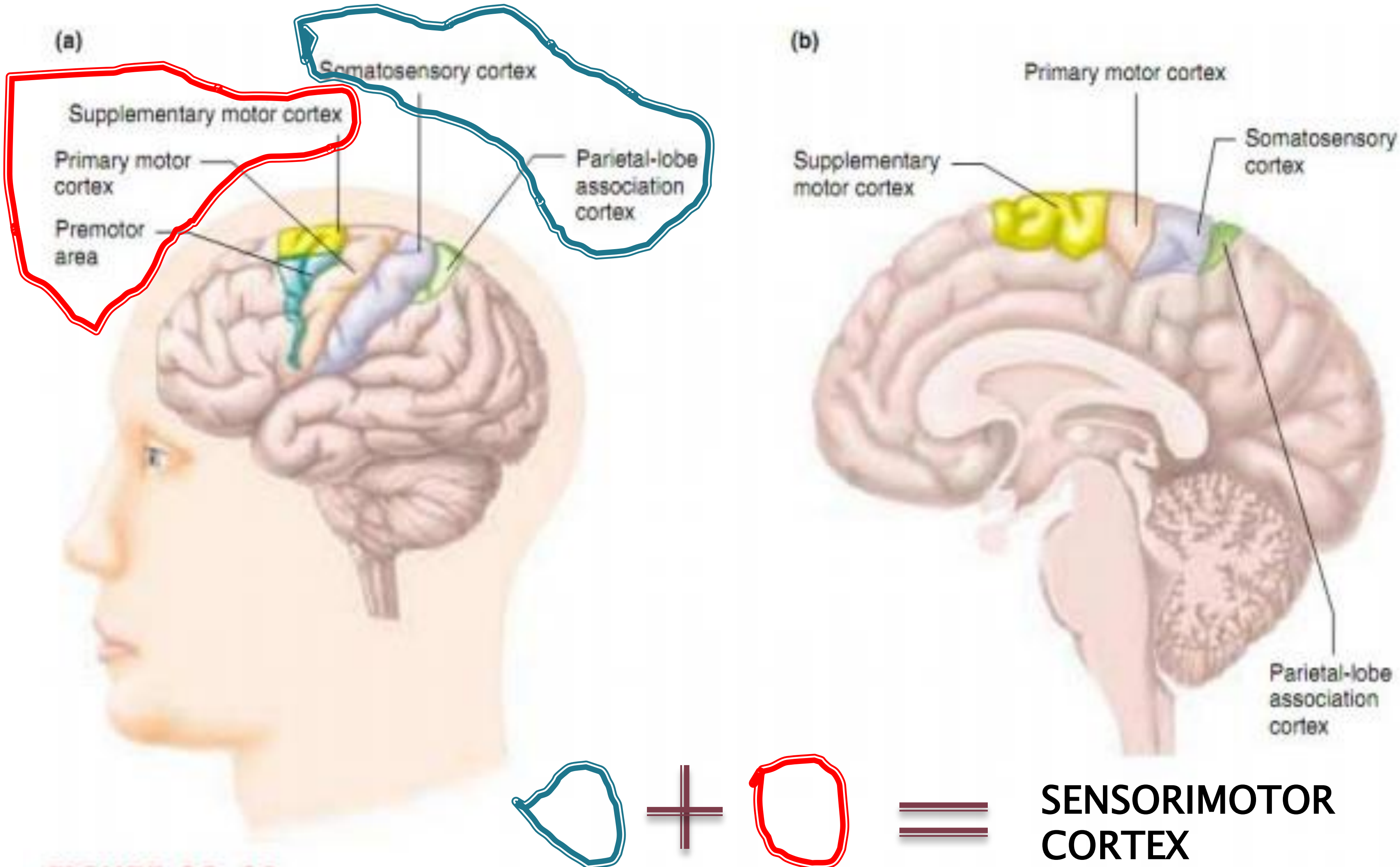
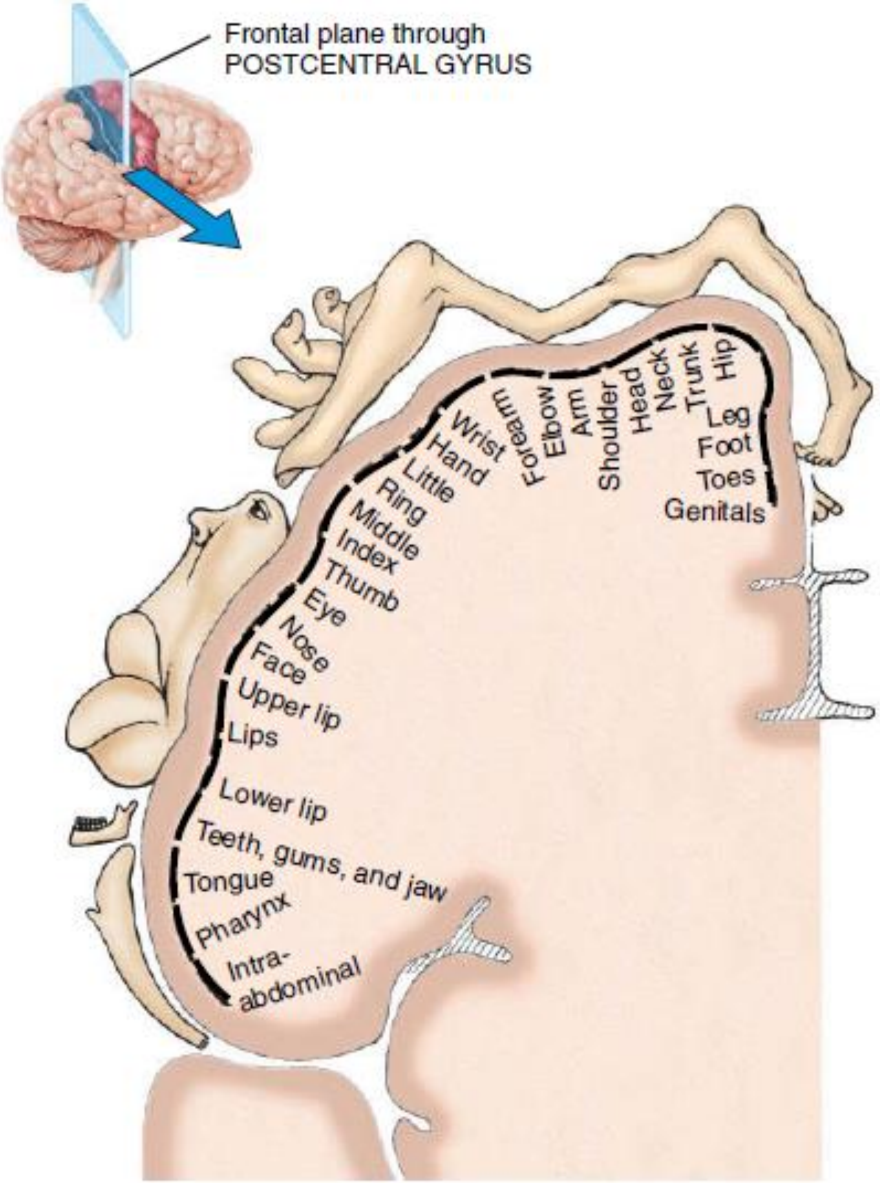


FIGURE 12–10

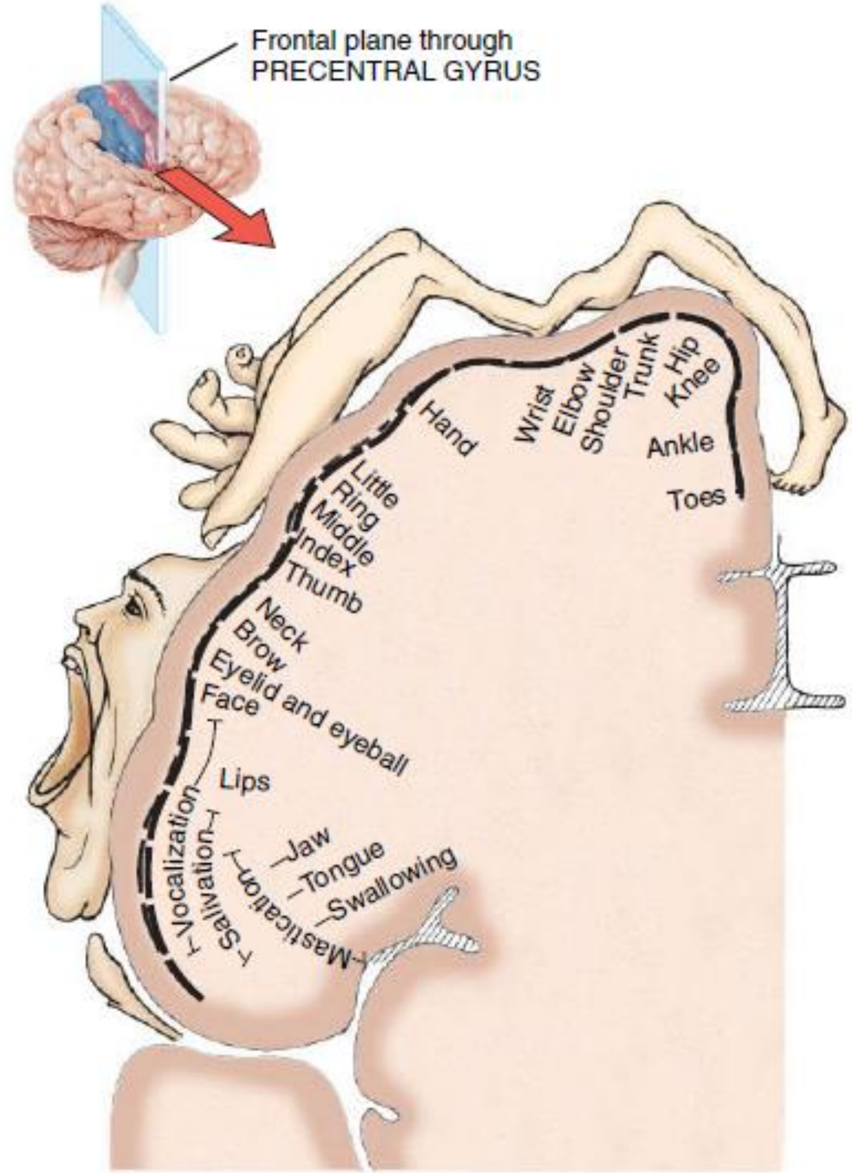
(a) The major motor areas of cerebral cortex. (b) Midline view of the brain showing the supplementary motor cortex, which lies in the part of the cerebral cortex that is folded down between the two cerebral hemispheres. Other cortical motor areas also extend onto this area. The premotor, supplementary motor, primary motor, somatosensory, and parietal-lobe association cortexes together make up the sensorimotor cortex.

Motor cortex

- Primary : girus presentralis lobus frontal → regio kontrol utama untuk pengaturan gerakan volunteer
- Area premotor (didekatnya) → memberikan akson-akson ke jalur descending.



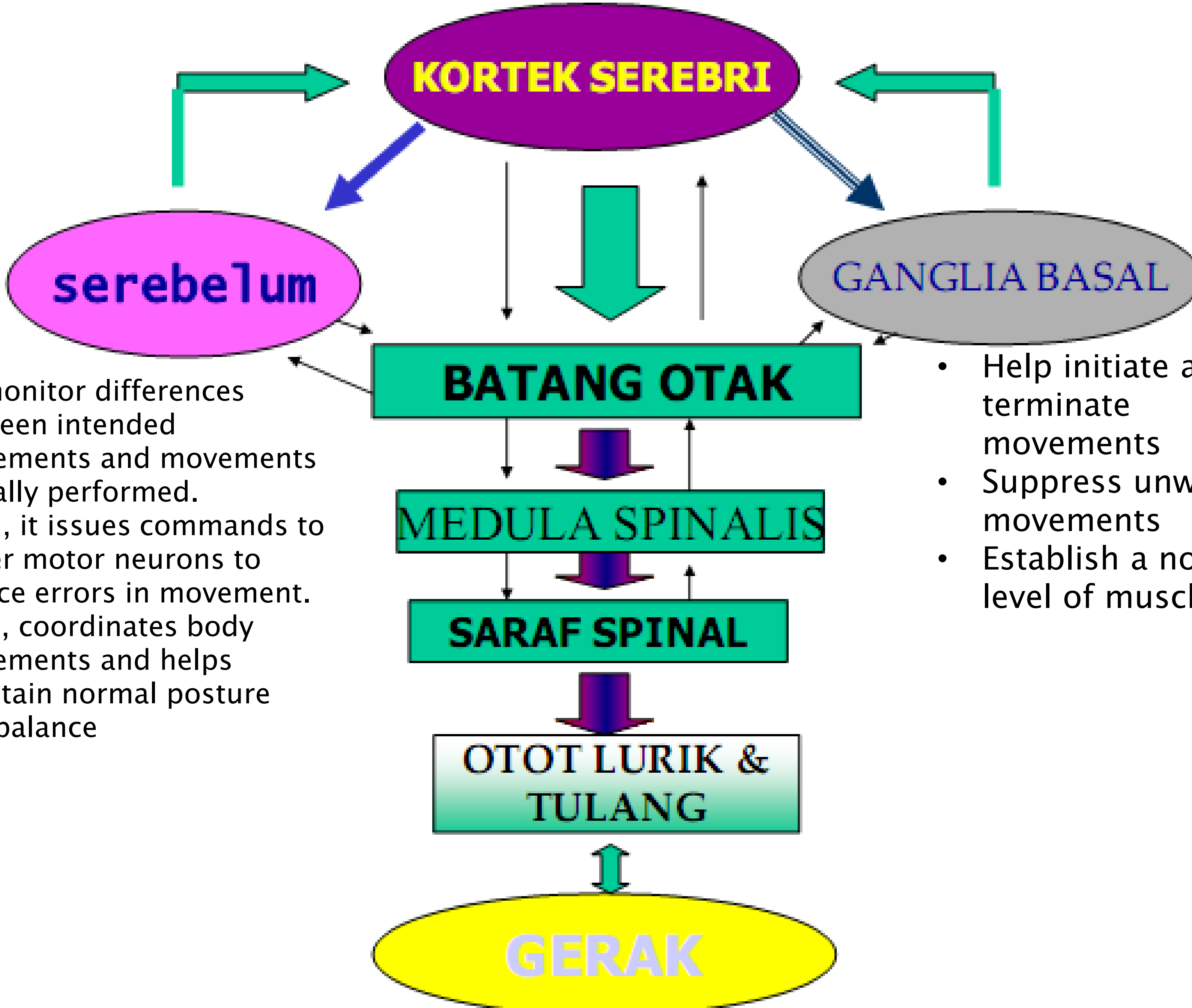
(a) Frontal section of primary somatosensory area in right cerebral hemisphere



(b) Frontal section of primary motor area in right cerebral hemisphere

Upper Motor Neuron pathway

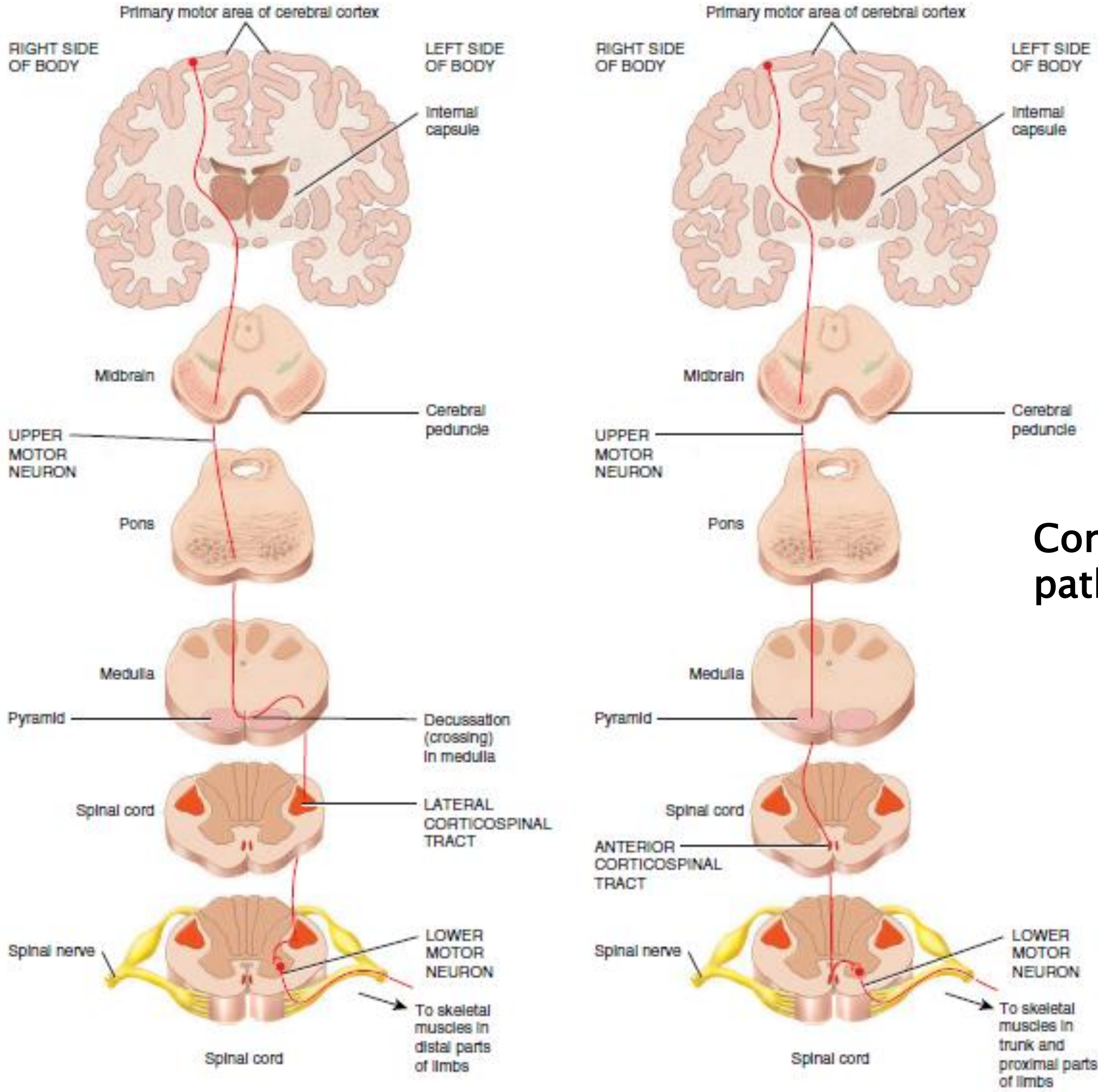
- Direct (jalur piramidal) , berasal dari area motorik primer (primary motor cortex dan area pre motor). Ada 2 traktus:
  - Corticospinal : cortex → M.S (lateral dan anterior)
  - Corticobulbar : cortex → badan sel N.craniales kec. I,II,VIII batang otak (impuls untuk mengontrol otot-otot di kepala)
- Indirect (jalur extrapiramidal), berasal dari jalur lain selain dari traktus piramidal, akson keluar dari nucleus di batang otak
  - Rubrospinal
  - Tectospinal
  - Vestibulo spinal
  - Lateral reticulospinal
  - Medial reticulospinal



- To monitor differences between intended movements and movements actually performed.
- Then, it issues commands to upper motor neurons to reduce errors in movement.
- Thus, coordinates body movements and helps maintain normal posture and balance

- Help initiate and terminate movements
- Suppress unwanted movements
- Establish a normal level of muscle tone

Corticospinal pathway



(a) The lateral corticospinal pathway

(b) The anterior corticospinal pathway

ORGANIZATION OF THE SPINAL CORD FOR MOTOR FUNCTIONS

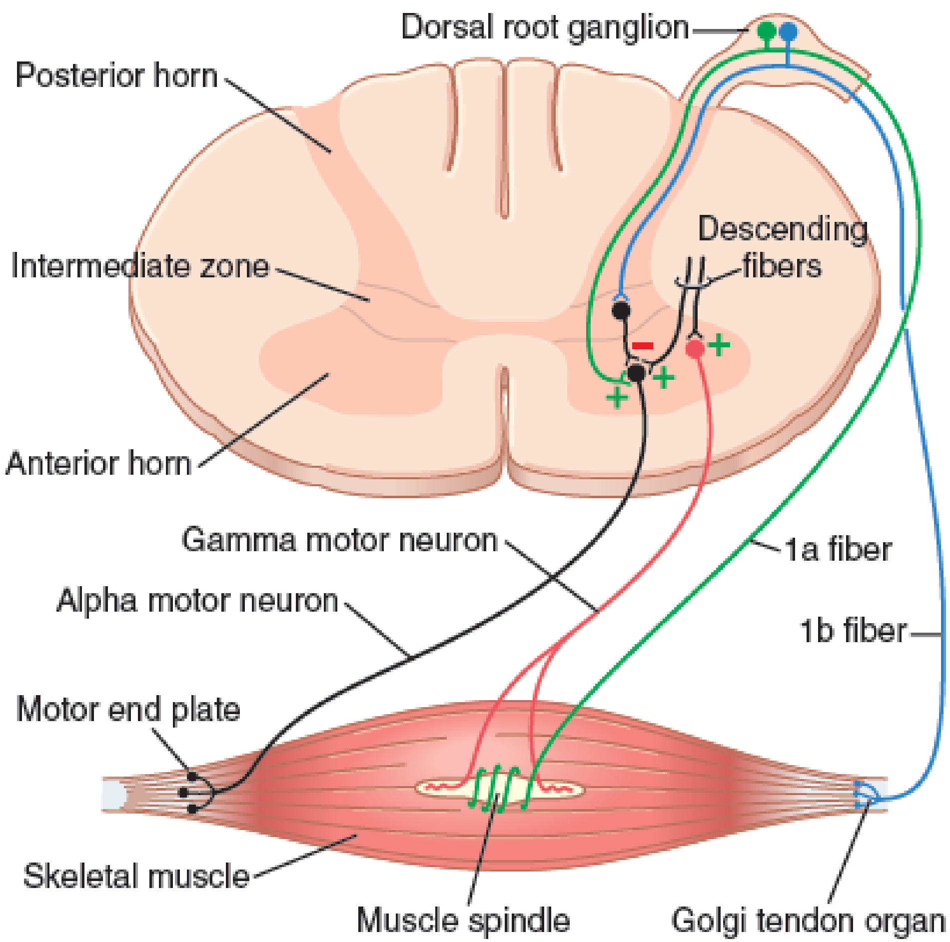


Figure 55-2. Peripheral sensory fibers and anterior motor neurons innervating skeletal muscle.

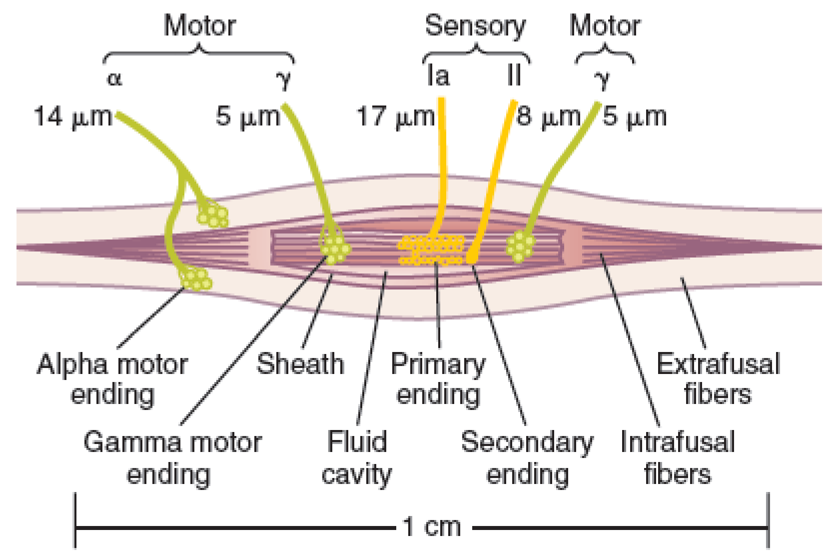


Figure 55-3. Muscle spindle, showing its relation to the large extrafusal skeletal muscle fibers. Note also both motor and sensory innervation of the muscle spindle.

Read more about nerve fiber classification in Guyton e-book ed.13th Unit IX page 599

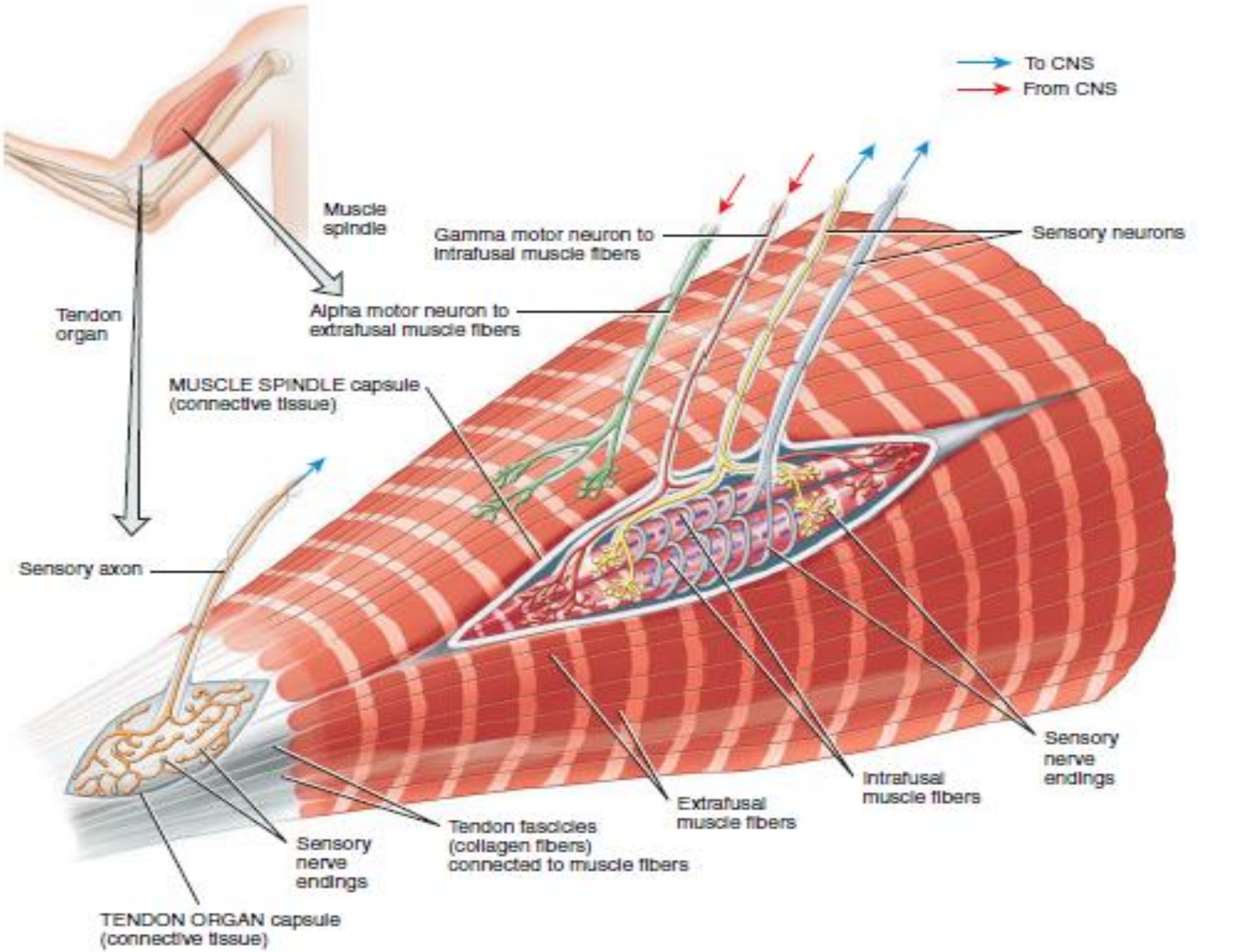
TIPE serabut saraf motorik

Alfa Motor neuron	Gamma Motor Neuron
Diameter serabut 14 μm	Diameter 5 μm
Bercabang banyak setelah memasuki otot (serabut ekstrafusal)	Menuju serabut otot rangka spesifik yang lebih kecil (serabut intrafusal)
Mensarafi serabut otot yang besar	
1 serabut alfa →cetuskan >300 serabut otot (motor unit)	Lokasi di muscle spindle

Reseptor Sensorik Otot Rangka

Muscle spindle	Badan Golgi / Golgi tendon
Membawa sinyal perubahan panjang serabut otot dan kecepatan perubahan otot, Fungsi : memonitor panjang otot / seberapa panjang otot meregang	Membawwa sinyal tension tendon dan kecepatan perubahan tension tendon Fungsi: mencegah over-tension/tegangan otot , mencegah tendon avulsi dari origo/insersionya
Berperan dalam reflek regang	Berperan dalam reflek tendon
Lokasi di serabut Intrafusal, yang juga mengandung motor neuron Gamma	Lokasi di Tendon

Proprioceptors provide information about body position and movement.



REFLEK SPINAL

- **Cutaneus reflexes :**

  withdrawal reflex, flexor reflek, pain reflex

- **Muscle reflexes :**

  stretch reflex

  reseptor : muscle spindle (serabut intrafusal)

  efektor : serabut ekstrafusal) extensor and flexor muscle

During the stretch reflex, impulses in muscle spindle sensory axons propagate into the spinal cord and brain stem and activate alpha motor neurons that connect to extrafusal muscle fibers in the same muscle. In this way, activation of its muscle spindles causes contraction of a skeletal muscle, which relieves the stretching.

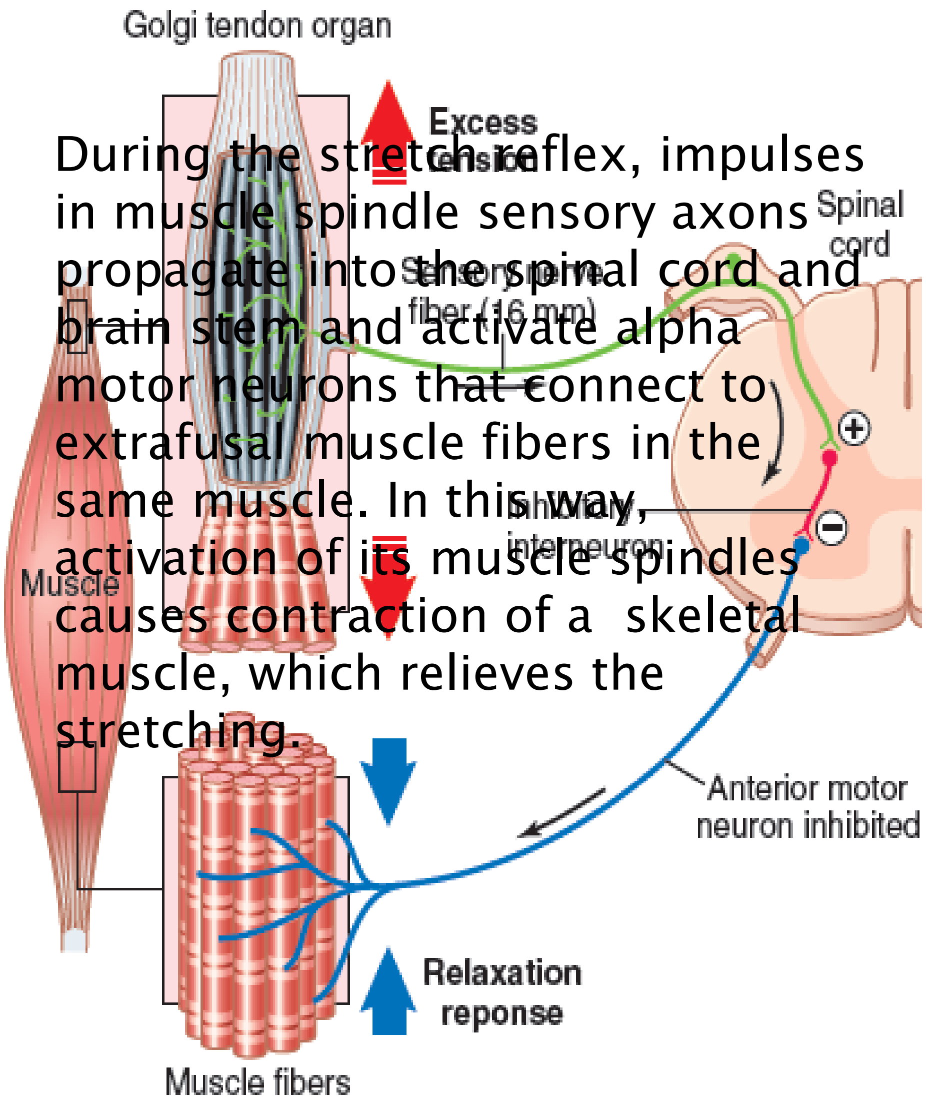


Figure 55-8. Golgi tendon reflex. Excessive tension of the muscle stimulates sensory receptors in the Golgi tendon organ. Signals from the receptors are transmitted through a sensory afferent nerve fiber that excites an inhibitory interneuron in the spinal cord, inhibiting anterior motor neuron activity, causing muscle relaxation, and protecting the muscle against excessive tension.

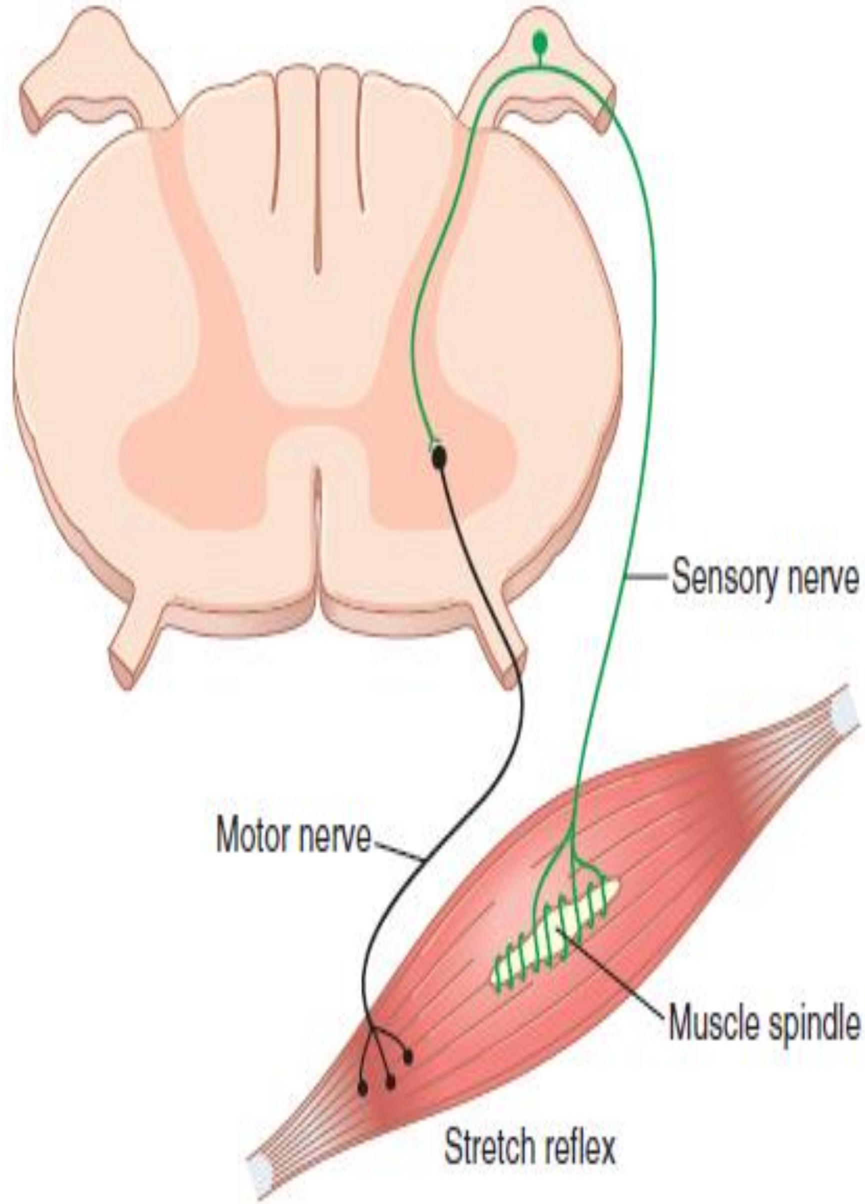


Figure 55-5. Neuronal circuit of the stretch reflex.

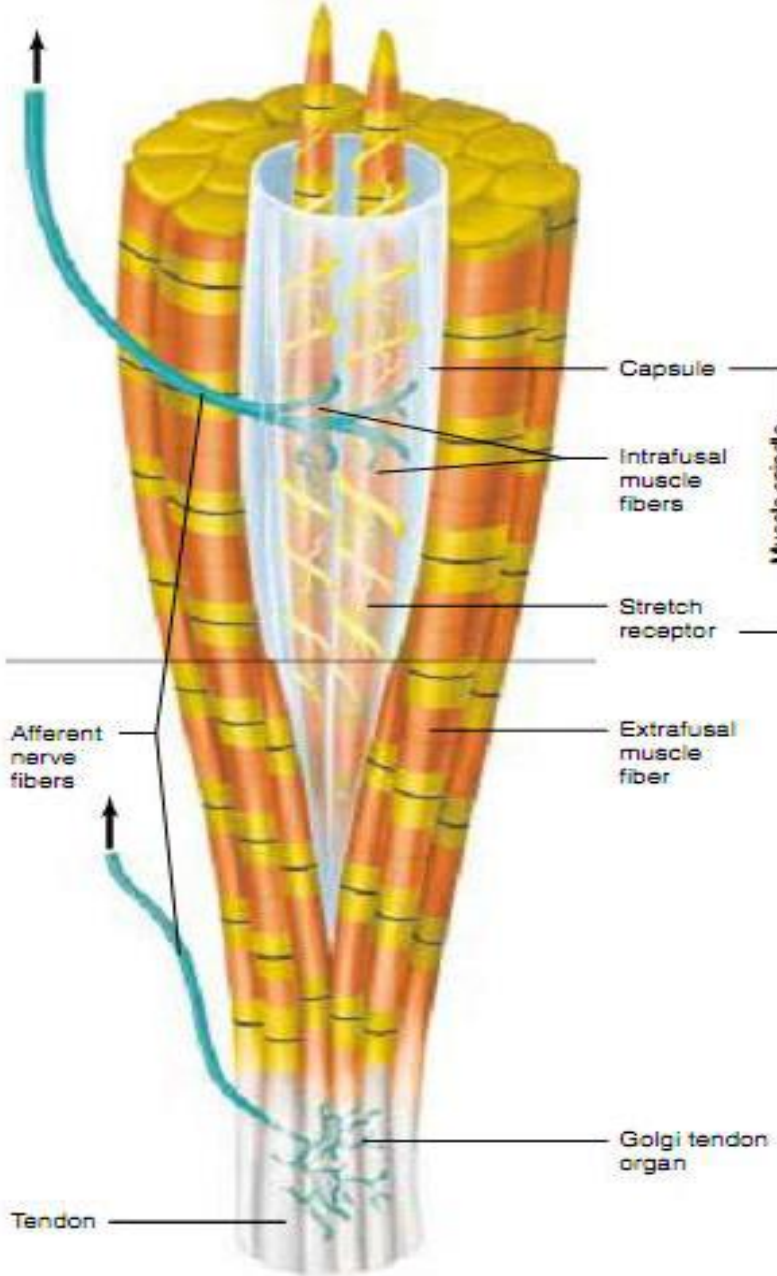


FIGURE 12–4
A muscle spindle and Golgi tendon organ. Note that the muscle spindle is parallel to the extrafusal muscle fibers. The Golgi tendon organ will be discussed later in the chapter.

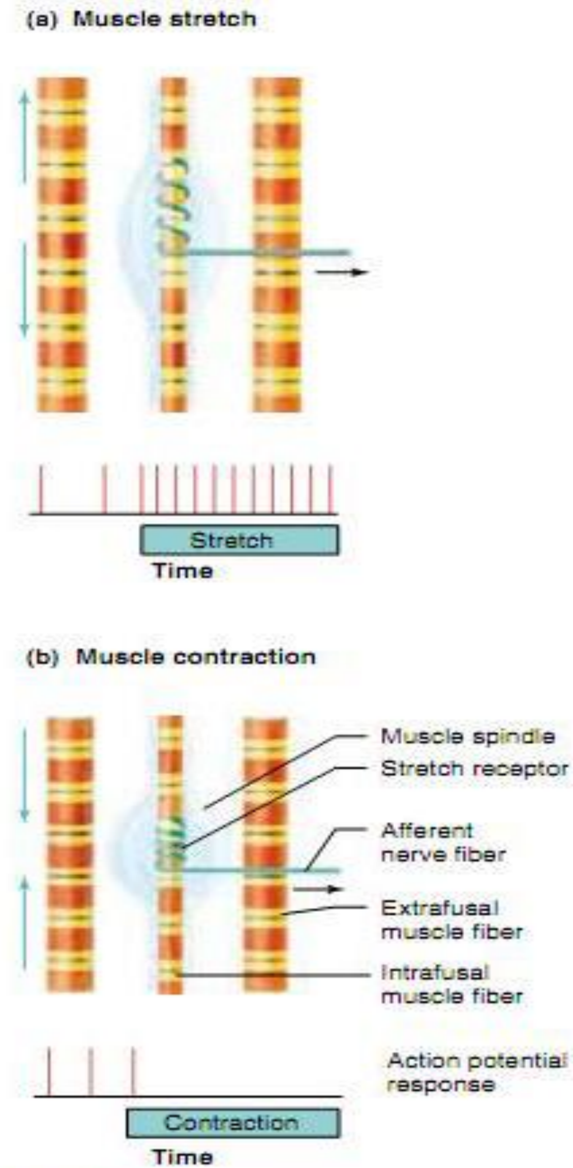


FIGURE 12–5
(a) Passive stretch of the muscle activates the spindle stretch receptors and causes an increased rate of action potentials in the afferent nerve. (b) Contraction of the extrafusal fibers removes tension on the stretch receptors and lowers the rate of action potential firing. Blue arrows indicate direction of force on the muscle spindles.

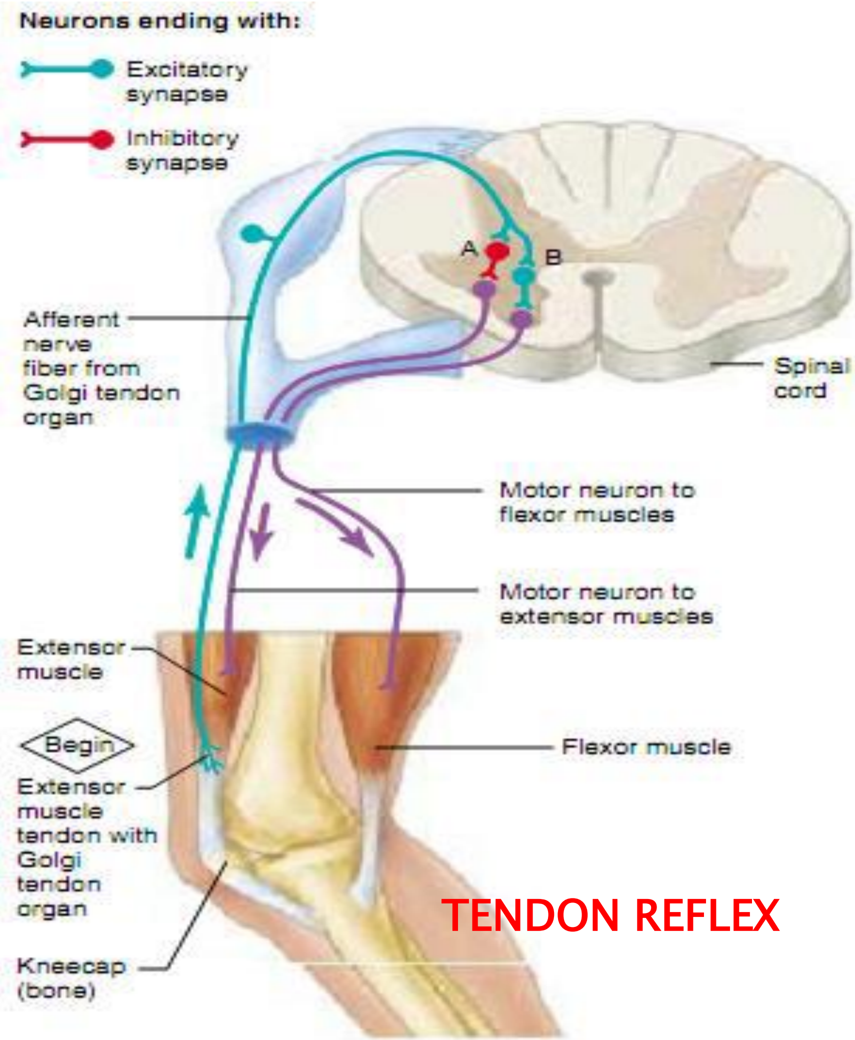
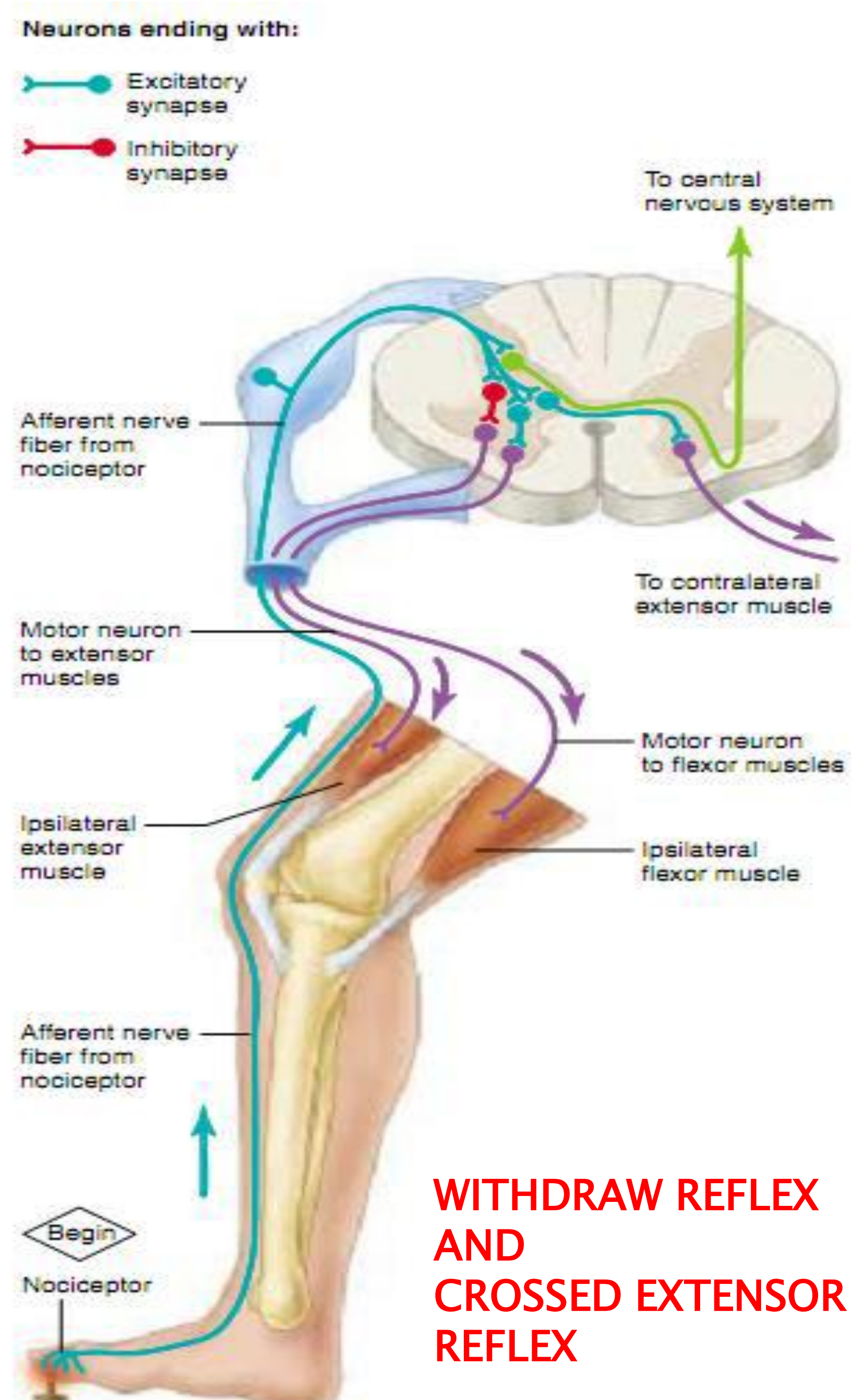
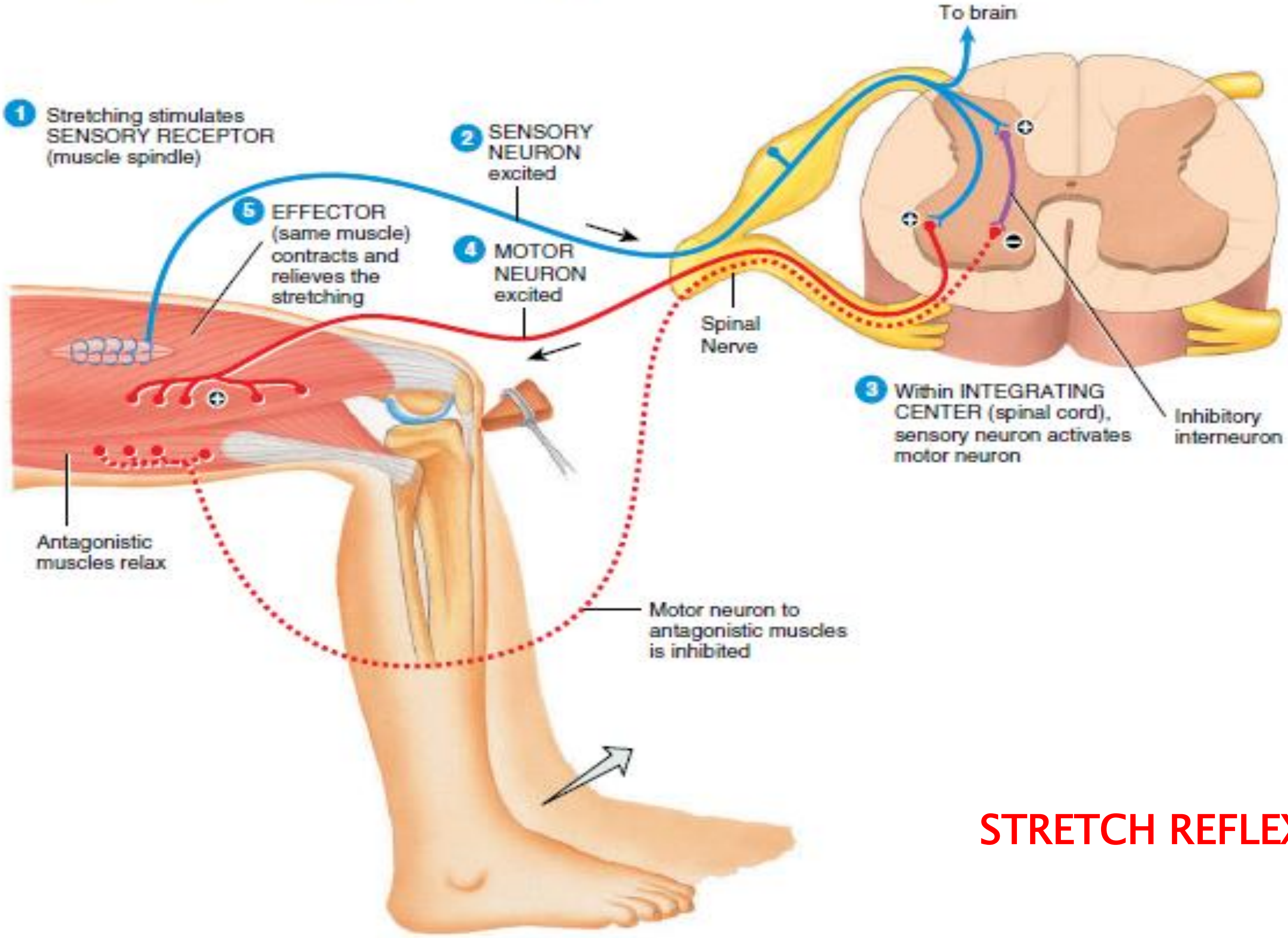


FIGURE 12–8
Neural pathways underlying the Golgi tendon organ component of the local control system. In this diagram, contraction of the extensor muscles causes tension in the Golgi tendon organ and increases the rate of action-potential firing in the afferent nerve fiber. By way of interneurons, this increased activity results in (path A) inhibition of the motor neuron of the extensor muscle and its synergists and (path B) excitation of flexor muscles' motor neurons. Arrows indicate direction of action-potential propagation.



The stretch reflex causes contraction of a muscle that has been stretched.



STRETCH REFLEX

Neurons (Nerve Cells)

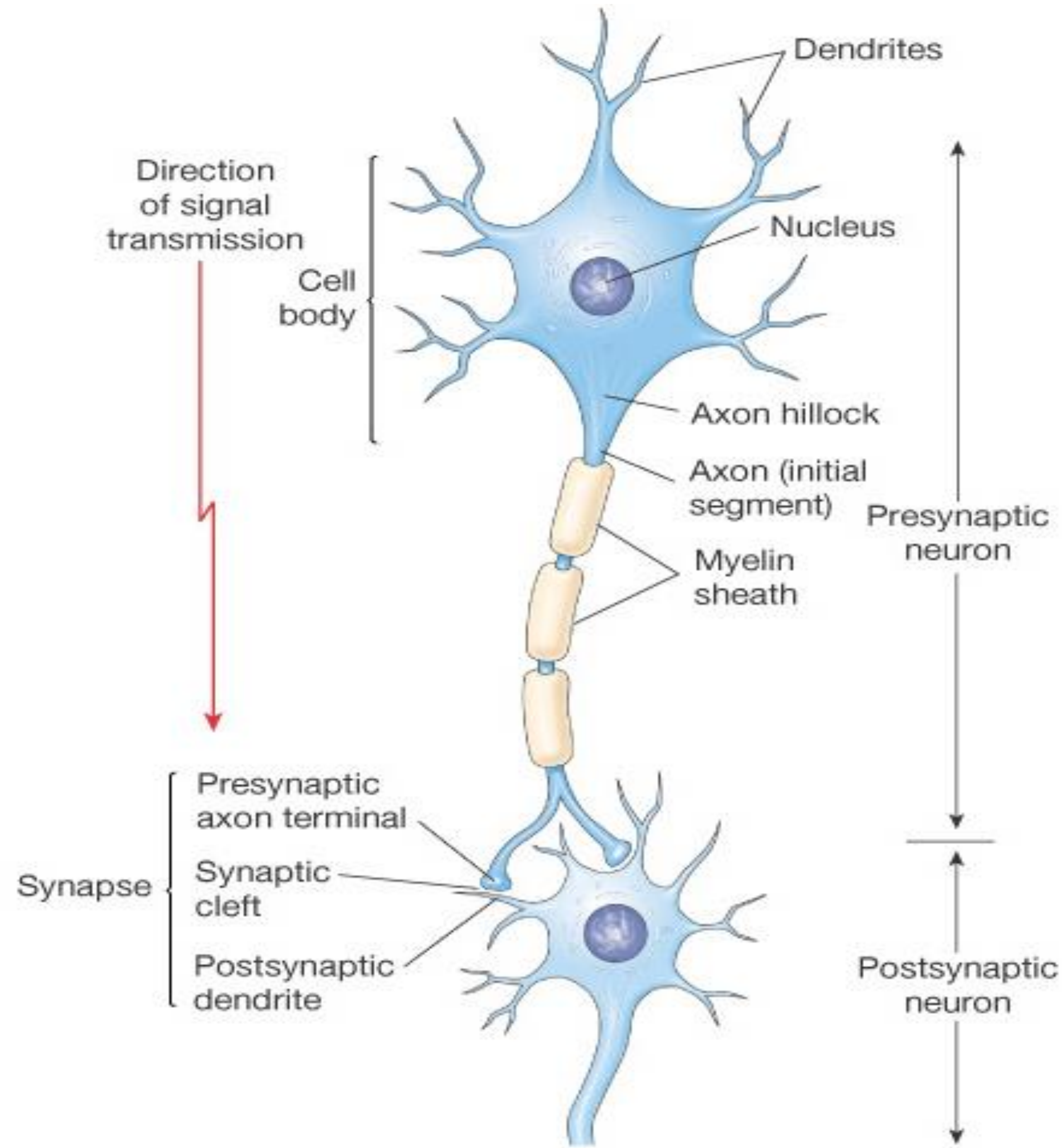
- Structural units of the nervous system
  - Composed of a body, axon, and dendrites
  - Long-lived, amitotic, and have a high metabolic rate
- Functions in:
  - Electrical signaling
  - Cell-to-cell signaling during development

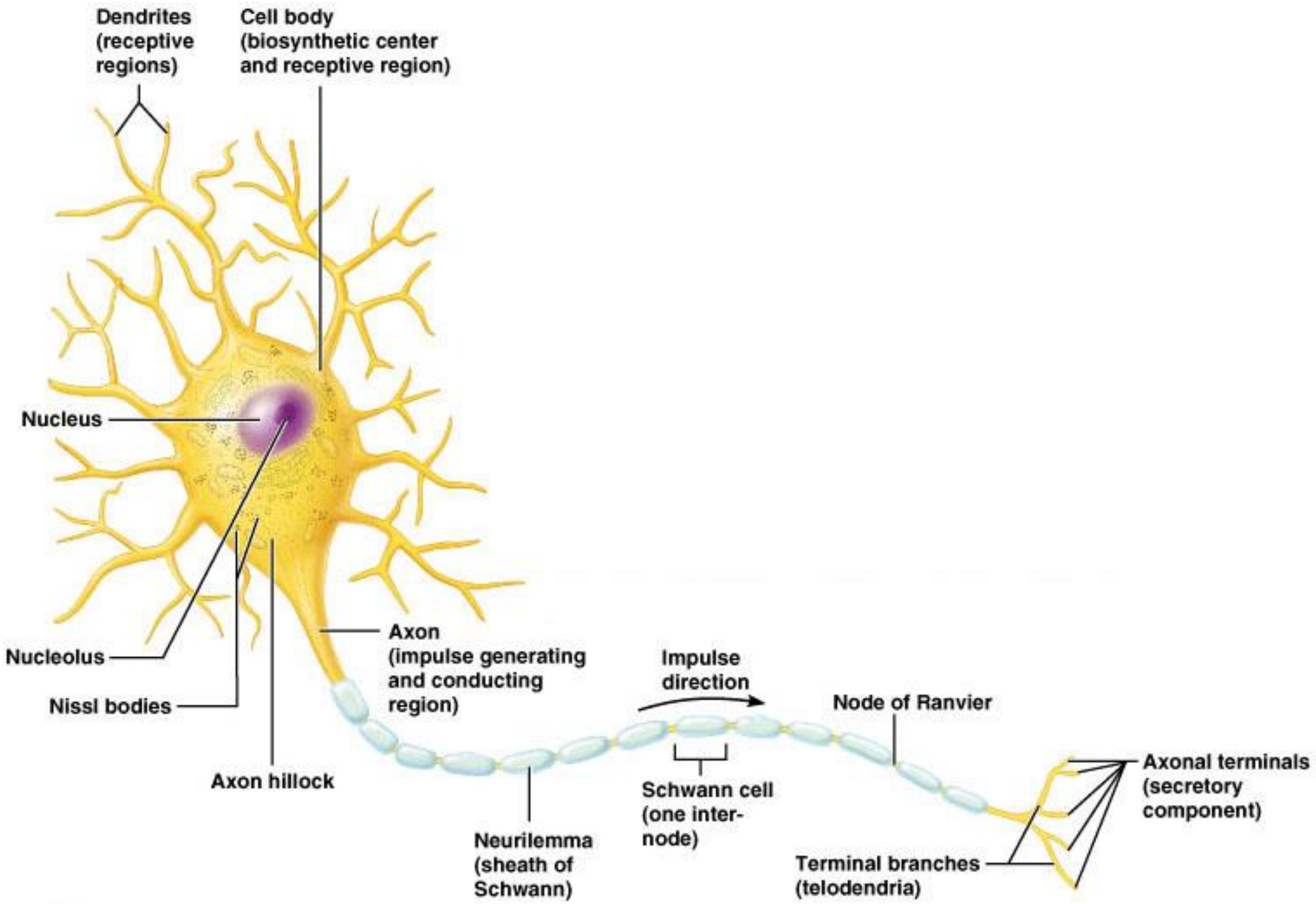
MOTOR UNIT

unit fungsional yang dikendalikan oleh sistem saraf motorik untuk menghasil kan gerakan

A Typical Neuron Overview

- Dendrites
- Cell Body
- Axon
- Terminal



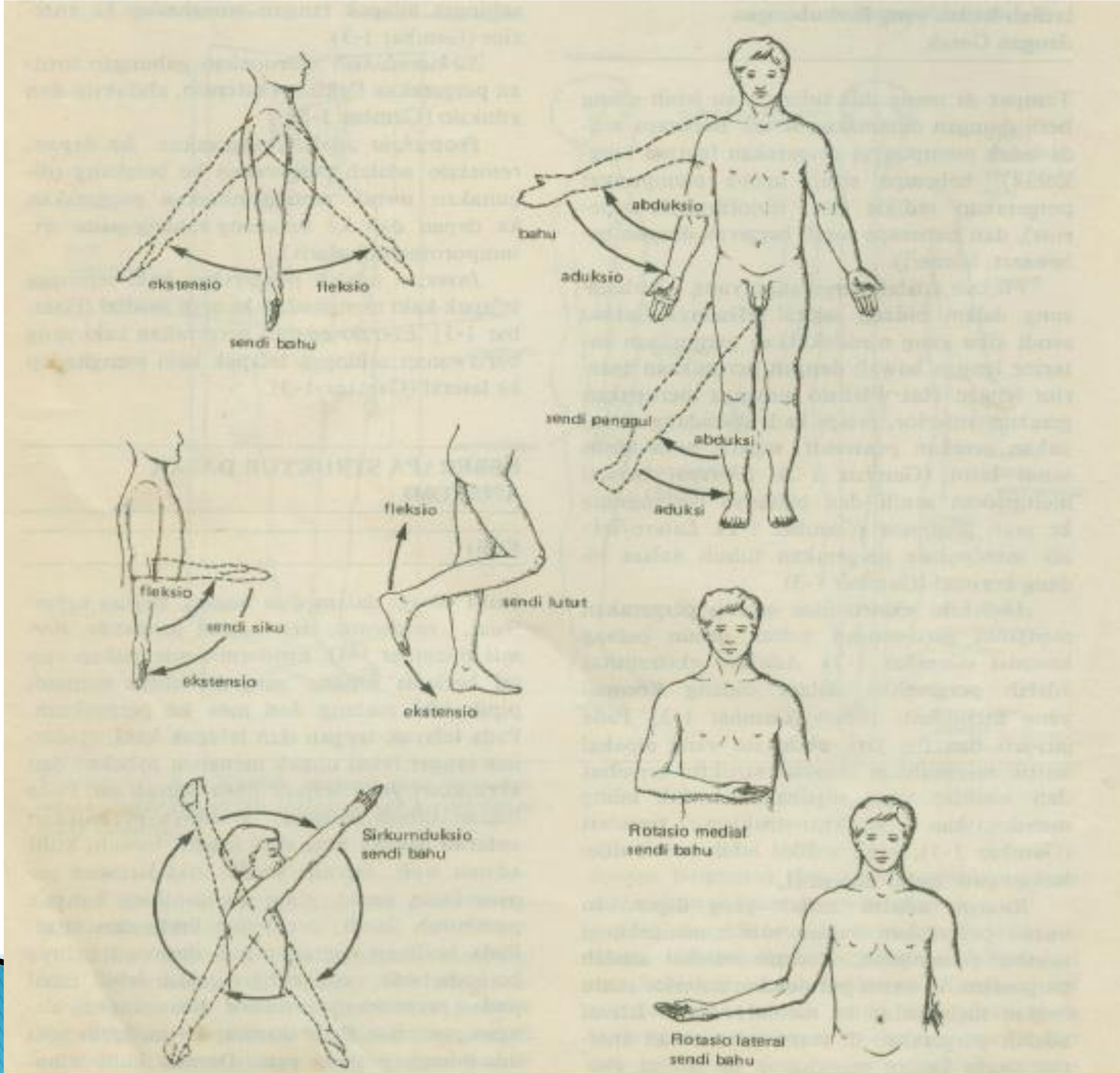

Dendrites (receptive regions)
Cell body (biosynthetic center and receptive region)
Nucleus
Nucleolus
Nissl bodies
Axon hillock
Axon (impulse generating and conducting region)
Impulse direction
Node of Ranvier
Neurilemma (sheath of Schwann)
Schwann cell (one inter-node)
Terminal branches (telodendria)
Axonal terminals (secretory component)

Macam macam gerak

- FLEKSI
- EKSTENSI
- ADDUKSI
- ABDUKSI
- ENDOROTASI
- EKSOROTASI
- SUPINASI
- PRONASI

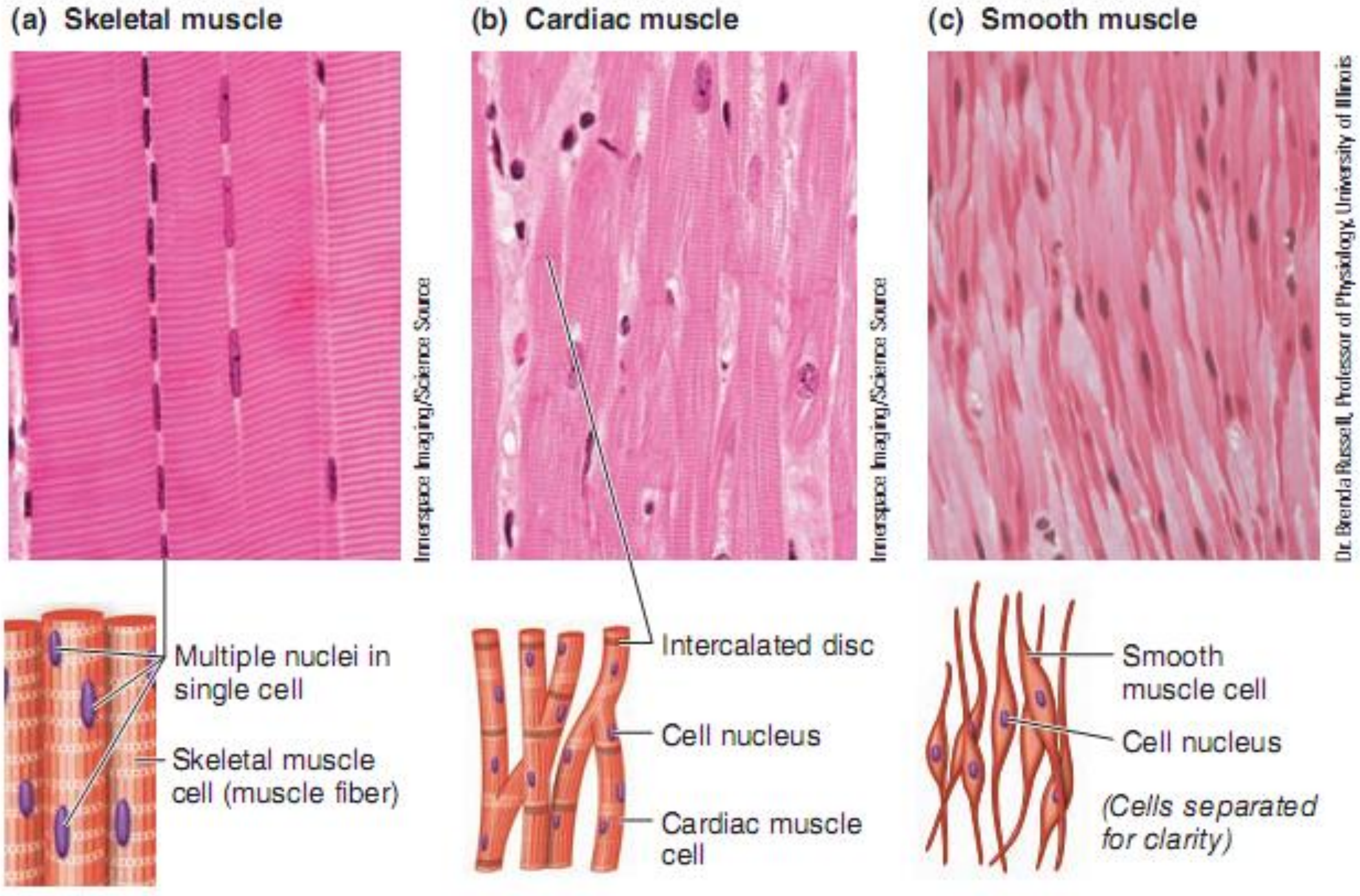
Macam macam gerak kolumna vertebralis

- Antefleksi
- Retrofleksi
- Laterofleksi kanan – kiri
- Rotasi kanan - kiri


ekstensio
fleksio
sendi bahu
abduksio
bahu
aduksio
sendi panggul
abduksi
aduksi
fleksio
sendi siku
ekstensio
fleksio
sendi lutut
ekstensio
Sirkumduksio
sendi bahu
Rotasio medial
sendi bahu
Rotasio lateral
sendi bahu

Muscle

- Secara umum dibagi 2 : otot **serat lintang** (otot rangka dan otot jantung) dan otot tak berserat/**polos** , berdasarkan ada/tidaknya striae (serat) di bawah mikroskop
- Berdasarkan persarafannya dibagi 2 : otot **volunter** (otot rangka) dipersarafi oleh serabut saraf somatik dan otot **involunter** (otot jantung dan otot polos) dipersarafi oleh serabut saraf otonom.
- Otot rangka → volunter krn secara sadar dapat dikontrol, tapi kebanyakan aktivitas otot rangka juga subconsious dan diregulasi secara tidak sadar, misal ketika berkaitan dengan perubahan postur, keseimbangan, dan ritme gerak ketika berjalan.

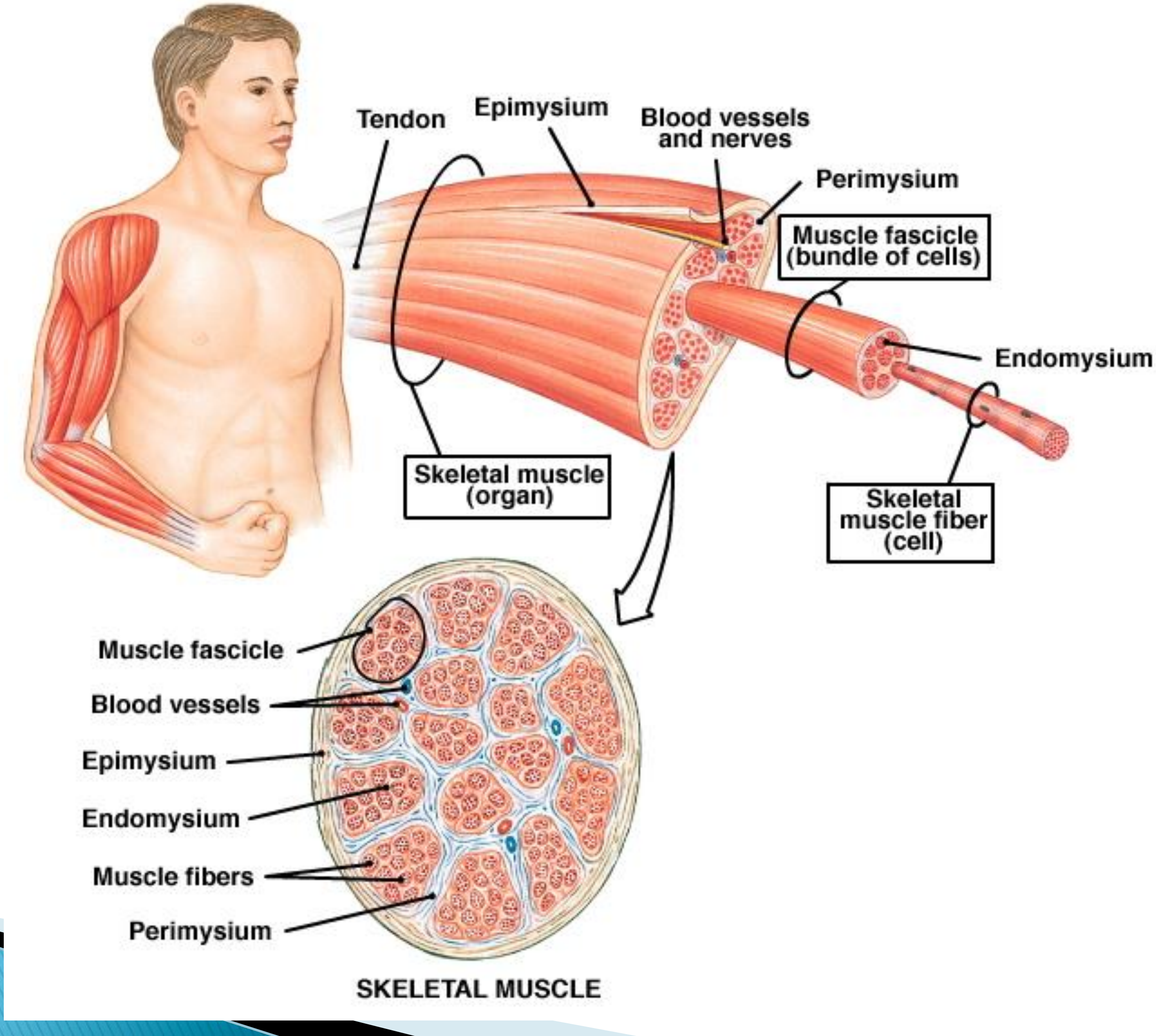

(a) Skeletal muscle
Innerspace Imaging/Science Source
Multiple nuclei in single cell
Skeletal muscle cell (muscle fiber)
(b) Cardiac muscle
Innerspace Imaging/Science Source
Intercalated disc
Cell nucleus
Cardiac muscle cell
(c) Smooth muscle
Dr. Brenda Russell, Professor of Physiology, University of Illinois
Smooth muscle cell
Cell nucleus
(Cells separated for clarity)

Otot Rangka

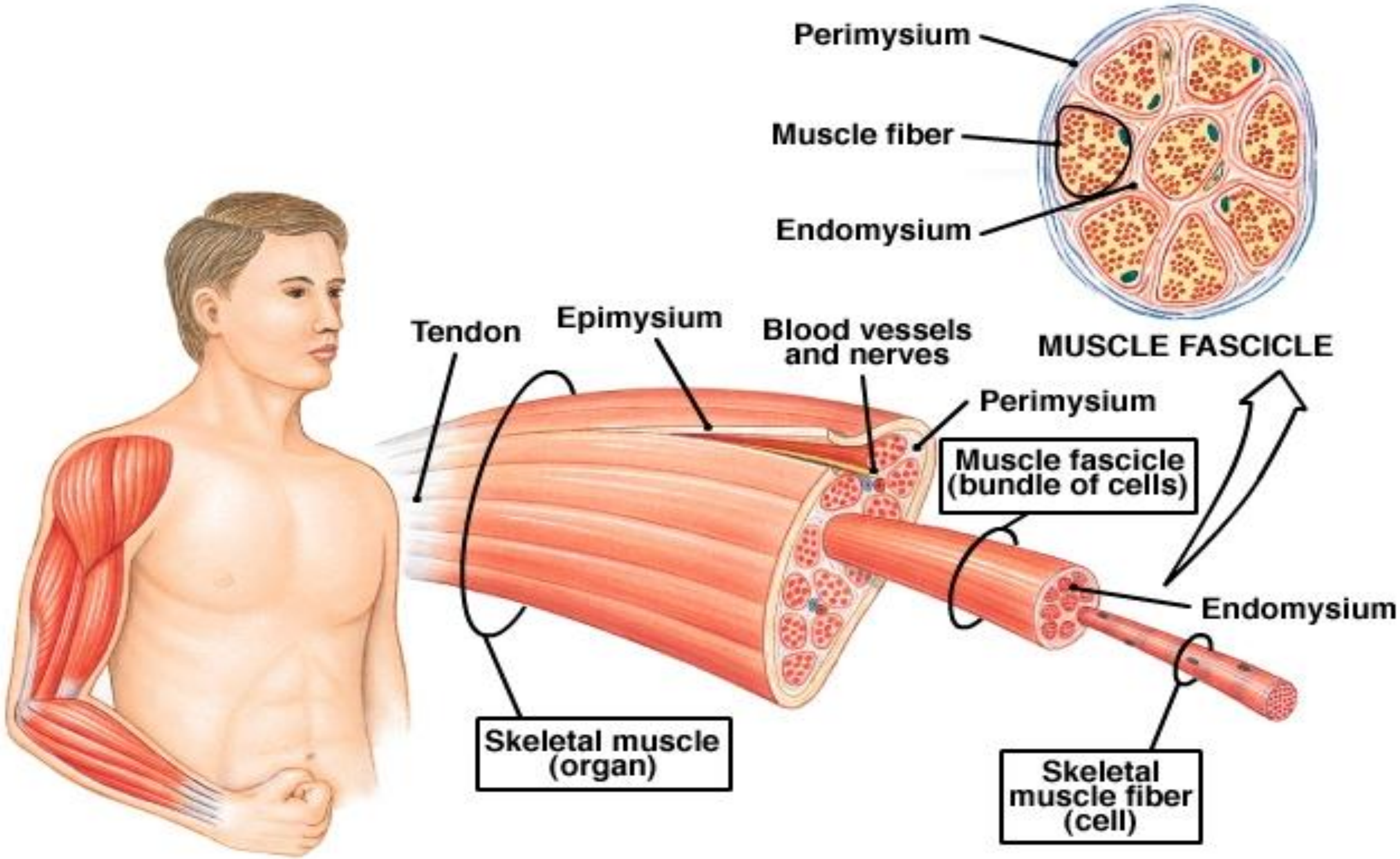
- 40% penyusun tubuh (laki-laki), 32% pada wanita, 10% sisanya adalah otot polos dan otot jantung

Whole muscle	→	muscle fiber	→	myofibril	→	thick and thin filament	→	myosin and actin
(an organ)		(a cell)		(a specialized intracellular structure)		(cytoskeletal elements)		(protein molecules)

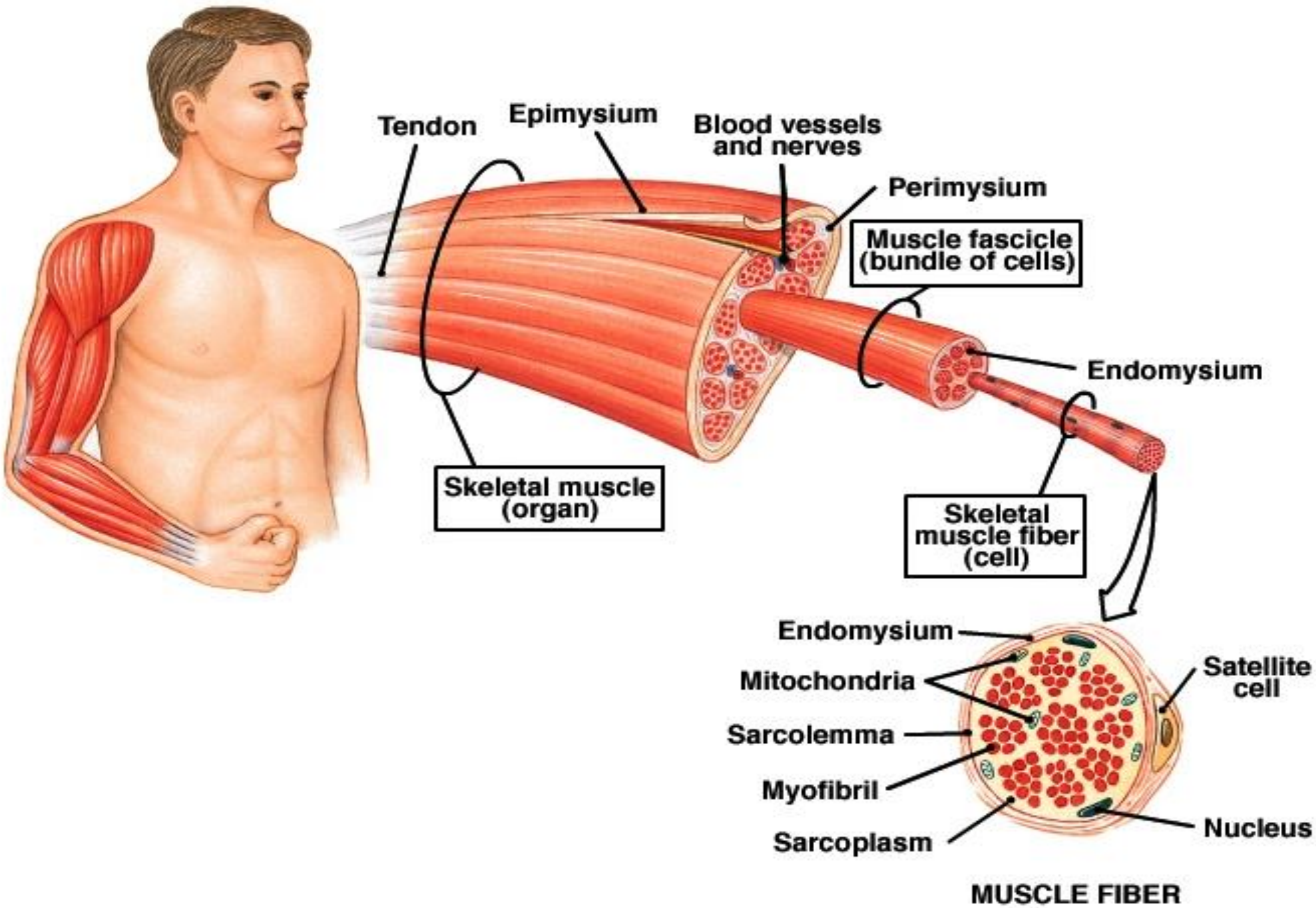
Organization I



Organization II



Organization III



Skeletal Muscle

- Muscle fibers are wrapped and held together by connective tissue sheaths that support each cell, reinforce the muscle as a whole (preventing bulging muscles during strong contractions)

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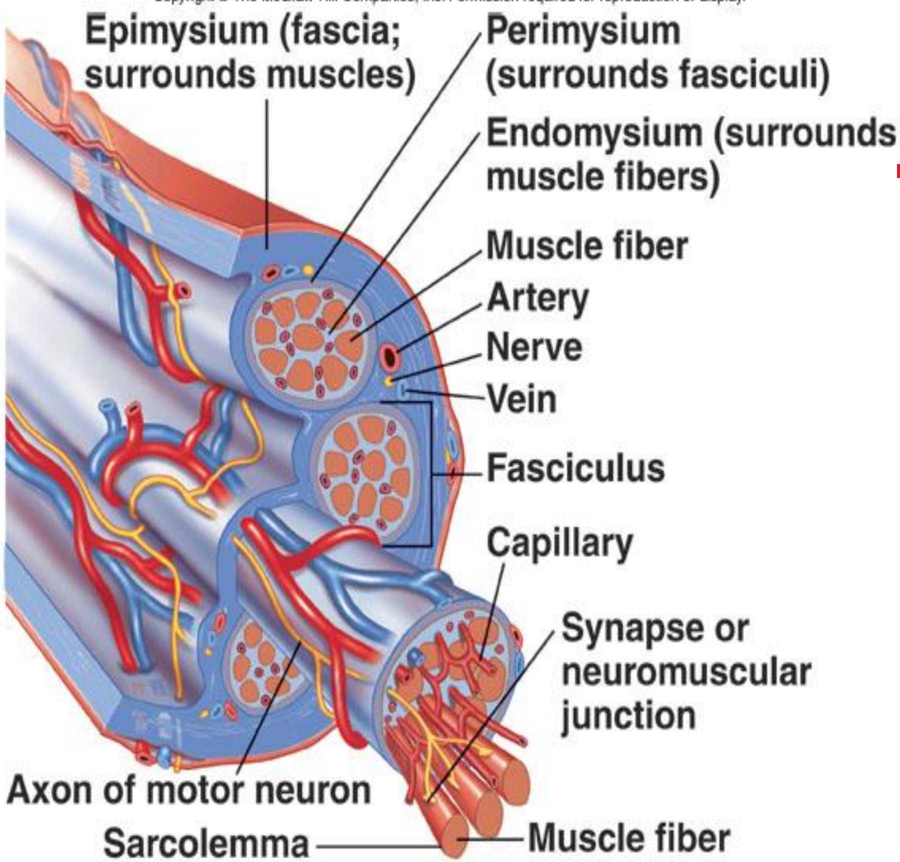


- The three connective tissue are:
  - Endomysium – fine sheath of connective tissue composed of reticular fibers surrounding each muscle fiber
  - Perimysium – fibrous connective tissue that surrounds groups of muscle fibers called fascicles
  - Epimysium – an overcoat of dense regular connective tissue that surrounds the entire muscle

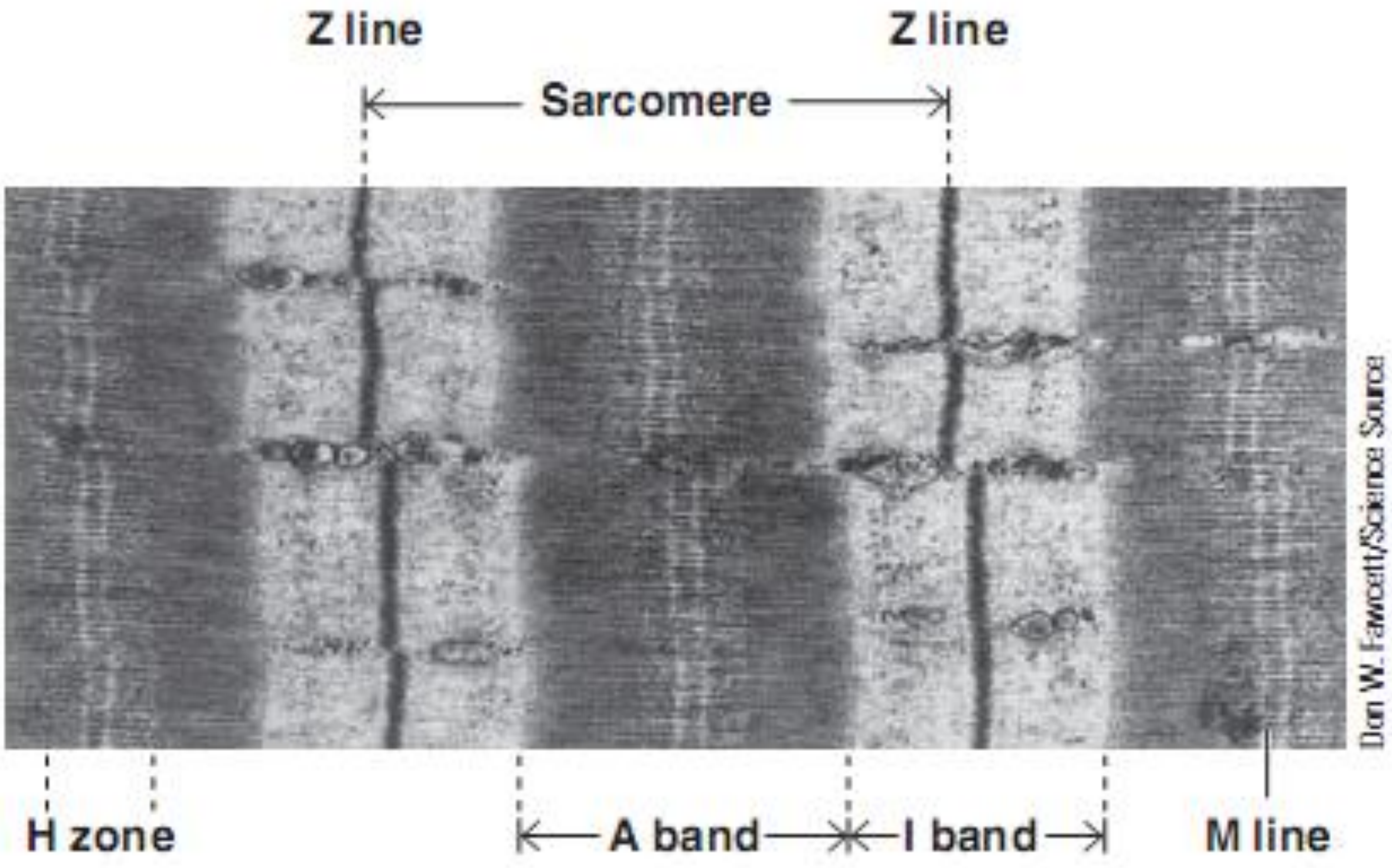
Skeletal Muscle: Nerve and Blood Supply

- Each muscle is served by one nerve, an artery, and one or more veins
- Each skeletal muscle fiber is supplied with a **nerve ending** that controls contraction
- Contracting fibers require continuous delivery of oxygen and nutrients via arteries
- Wastes must be removed via veins

Skeletal Muscle: Attachments

- Most skeletal muscles span joints and are attached to bone in at least two places
- Origo (otot melekat pada tulang yang tidak bisa digerakan), Insertio (otot melekat pada tulang yang bergerak)
- Muscles attach:
  - Directly – epimysium of the muscle is fused to the periosteum of a bone or perichondrium of a cartilage
  - Indirectly – connective tissue wrappings extend beyond the muscle as a tendon or aponeurosis (more common than direct attachment)

Myofibril



Z line
Z line
Sarcomere
H zone
A band
I band
M line
Don W. Fawcett/Science Source

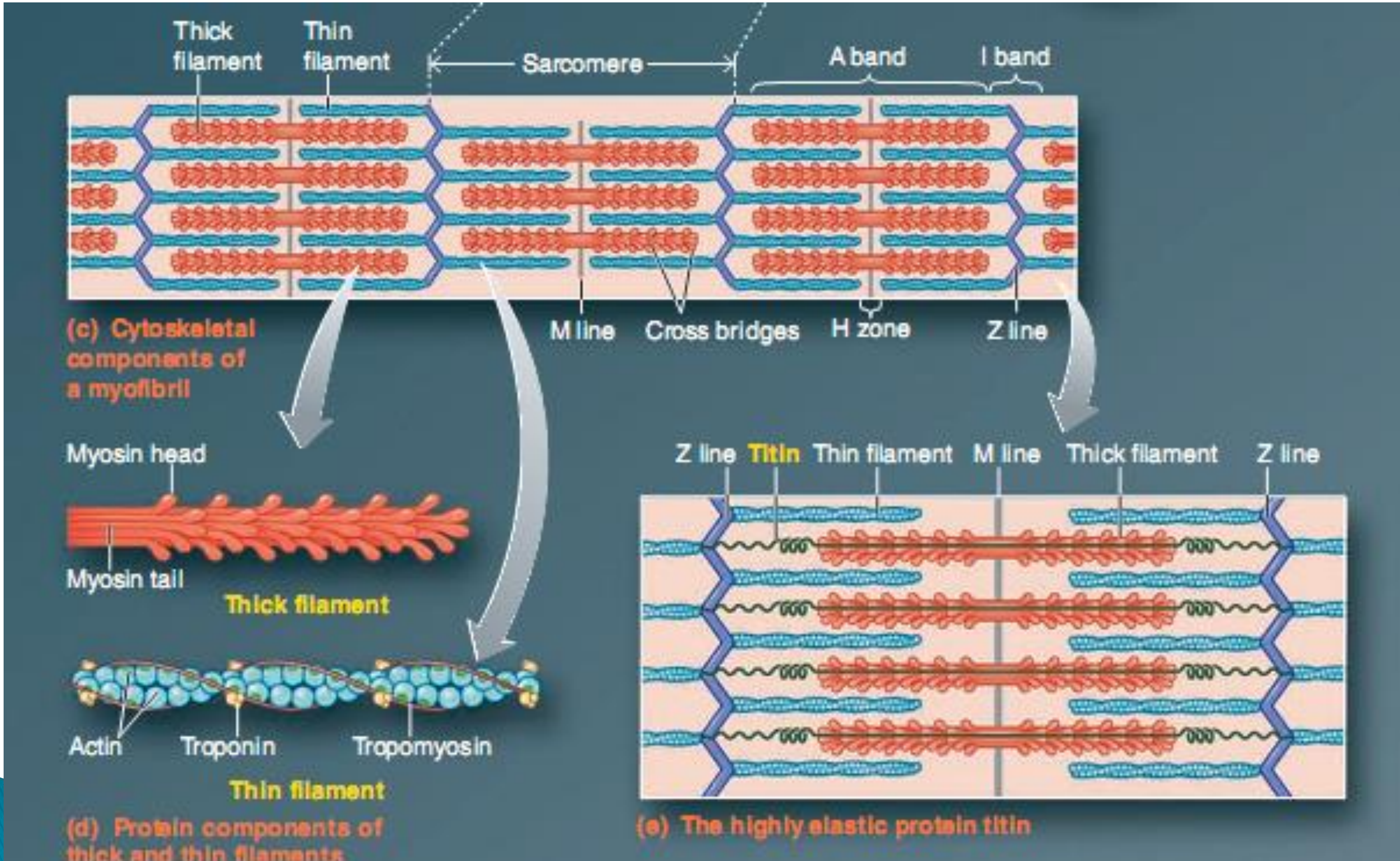
Myofibril

- Secara **fungsional** tiap myofibril → filamen **tebal** dan filamin **tipis** yang masing-masing terdiri dari protein kontraktil (aktin, myosin, troponin, tropomyosin)
- Filamen **tebal/Filamen myosin** (terbentang sepanjang PITA A): tersusun oleh myosin. Ditengahnya ada pita H
- Filamen **tipis/filamen aktin** (PITA I) : tersusun oleh aktin, troponin dan tropomyosin. Ditengahnya ada garis Z. Antara garis Z sampai Z lainnya disebut sarkomer.
- Filamen **titin** → menjaga agar filamen tebal dan tipis tetap pada tempatnya.

Protein otot lainnya

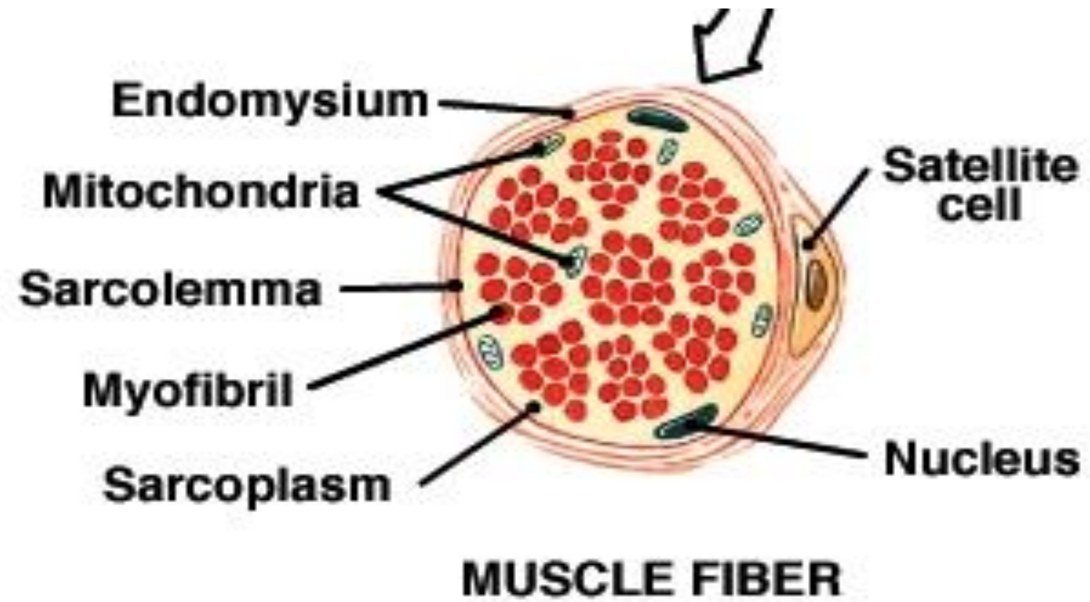
- Titin : stabilkan filamen tebal
- Alfa-actinin: material padat di disc Z, berikatan dengan actin dan titin
- Myomesin: membentuk garis M (M line), berikatan dg titin dan menghubungkan filamen tebal yang berdekatan
- Nebulin: protein non-elastik yang panjang, membungkus keseluruhan filamen tipis, menancapkan filamen tipis ke disc Z
- Dystropin: menghubungkan filamen tipis sarkomer ke membran protein integral sarkolema, memperkuat sarkolema dan membantu mentransmisikan tension yang dipicu ole sarkomer ke tendon

Organisasi otot rangka (V)



Sarkolema

- Suatu membran tipis yang melapisi serabut otot rangka
- Tersusun atas membran plasma
- Berfusi dengan serabut tendon di tiap akhir serabut otot



Sarkoplasma

- Merupakan cairan intraseluler antara myofibril
- Didalamnya banyak terkandung magnesium, potasium, fosfat, dan mitokondria yang mensuplai ATP sebagai sumber energi kontraksi myofibril

- RETIKULUM SARKOPLASMA
  - Merupakan RE yang khusus untuk otot rangka
  - Berada dalam sarkoplasma
  - Penting dalam regulasi *storage, release, and reuptake* **Kalsium**.

Karakter molekuler filamen kontraktil (Myosin)

- The protruding arms and heads together are called crossbridges.
- Each cross bridge has two sites crucial to the contractile process: (1) an actin-binding site and (2) a myosin ATPase (ATP-splitting) site.

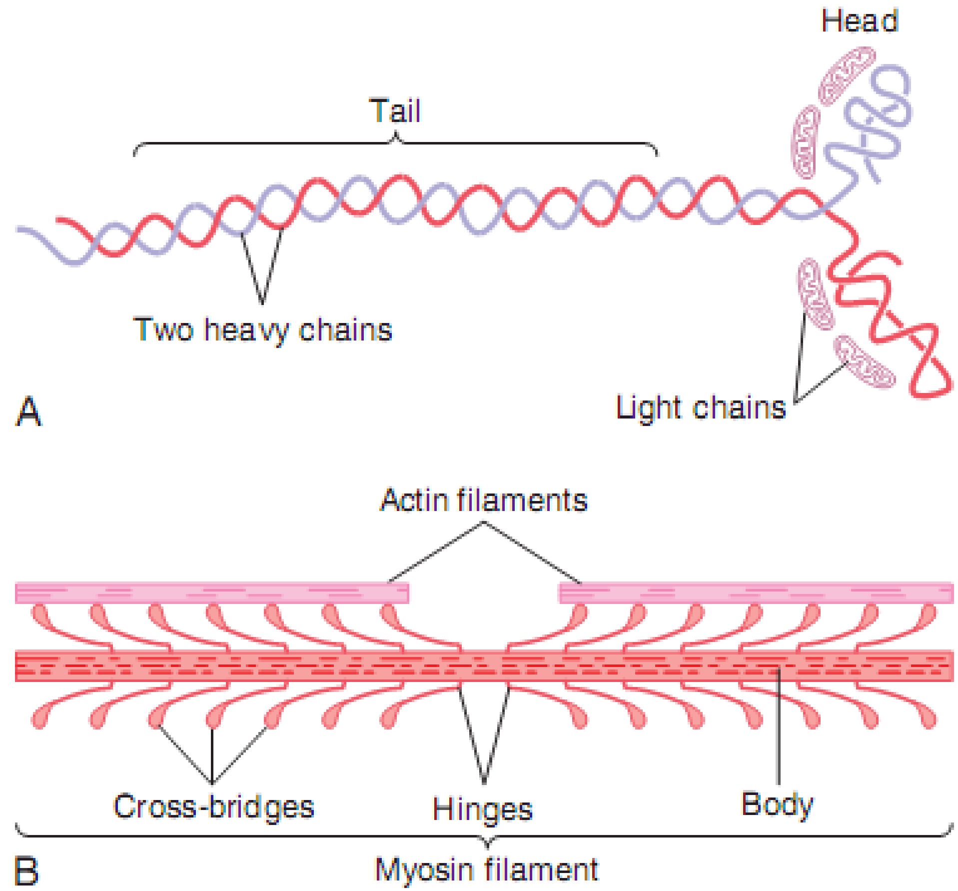
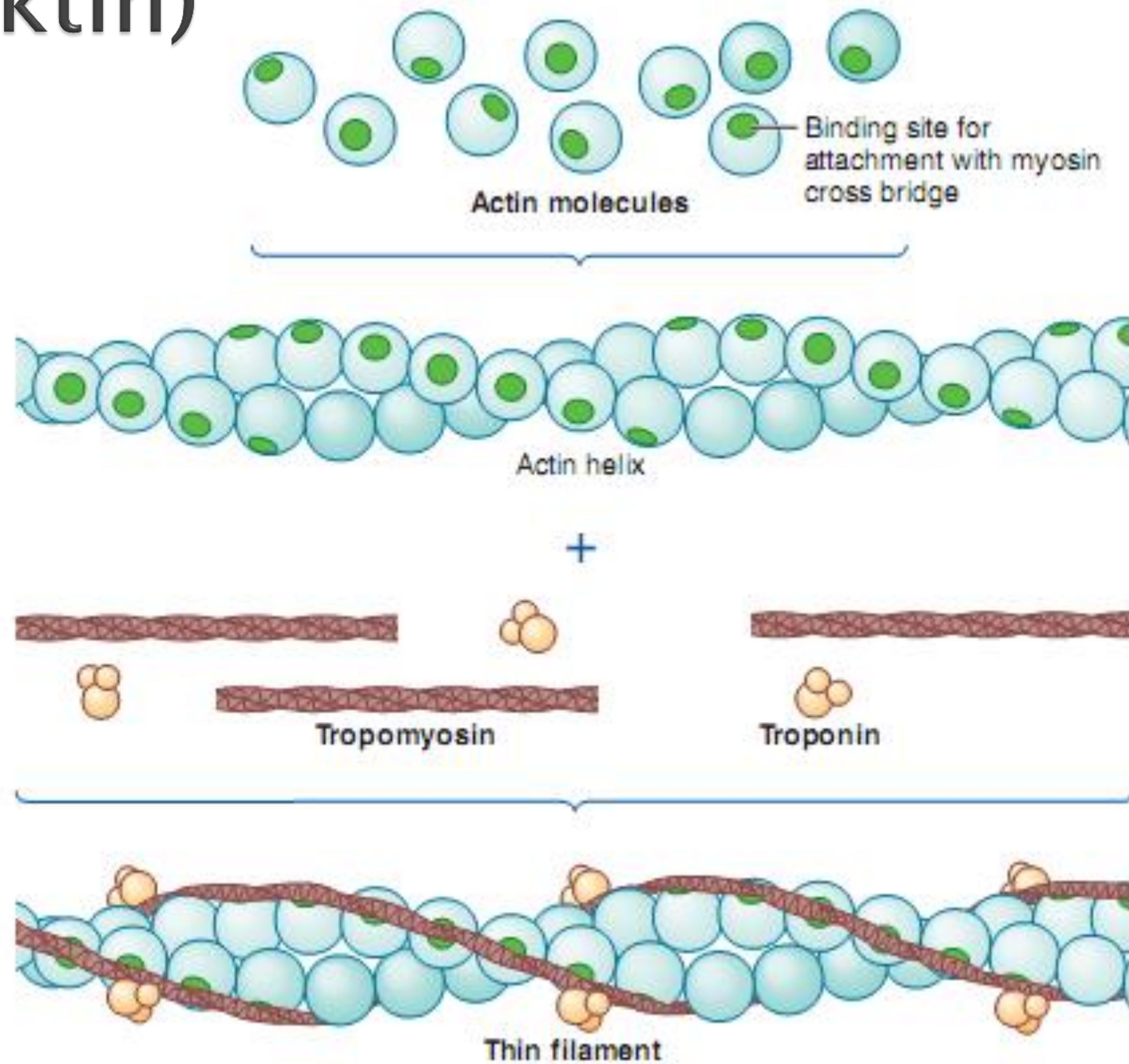


Figure 6-6. A, Myosin molecule. **B,** Combination of many myosin molecules to form a myosin filament. Also shown are thousands of myosin *cross-bridges* and interaction between the *heads* of the cross-bridges with adjacent actin filaments.

Karakter molekuler filamen kontraktil (Aktin)

- Actin as the backbone
- Tropomyosin covers the actin sites that bind with the cross bridges, blocking the interaction that leads to muscle contraction.
- Troponin is a protein complex made of three polypeptide units: one **binds to tropomyosin (T)**, one **binds to actin (I)**, and a third can **bind Ca^{2+} (C)**



Mekanisme Kontraksi Otot

- AP berjalan di nervus motorik → NMJ → keluarkan Ach.
- Ach bekerja di sekitar serabut otot untuk membuka *"acetylcholine gated" cation channels* melalui molekul protein yang ada dalam membran.
- Terbukanya *acetylcholine-gated channels* → Na^{+} berdifusi masuk ke membran serabut otot → **depolarisasi** → terbukanya *voltage-gated sodium channels* → mengawali aksi potensial membran.
- AP berjalan sepanjang membran serabut otot sama seperti pada AP neuron.
- AP mendepolarisasi membran otot, kebanyakan menjalar melalui sentral serabut otot → dari sini menyebabkan retikulum sarkoplasma mengeluarkan ion Ca^{2+} simpanannya.

- Ca^{2+} mengawali tarik–menarik antara filamen aktin dan myosin → *sliding filament mechanism,* merupakan proses kontraksi.
- Setelah beberapa detik, ion Ca^{2+} dipompa kembali masuk ke retikulum sarkoplasma oleh suatu Ca^{2+} *membrane pump* dan disimpan dalam retikulum sampai AP yang baru muncul
- Hilangnya Ca^{2+} dari myofibril → kontraksi hilang

Sliding Filament Mechanism

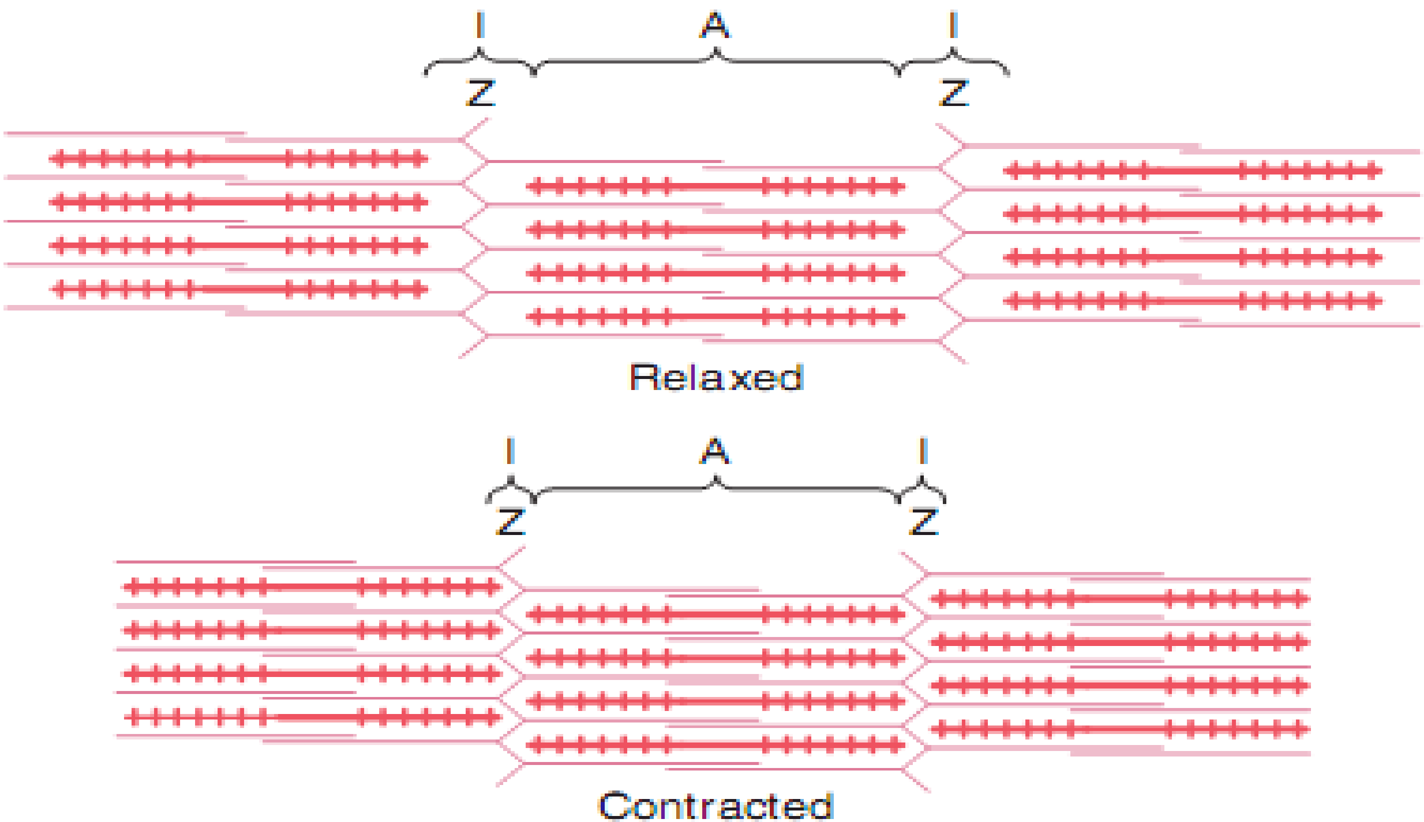
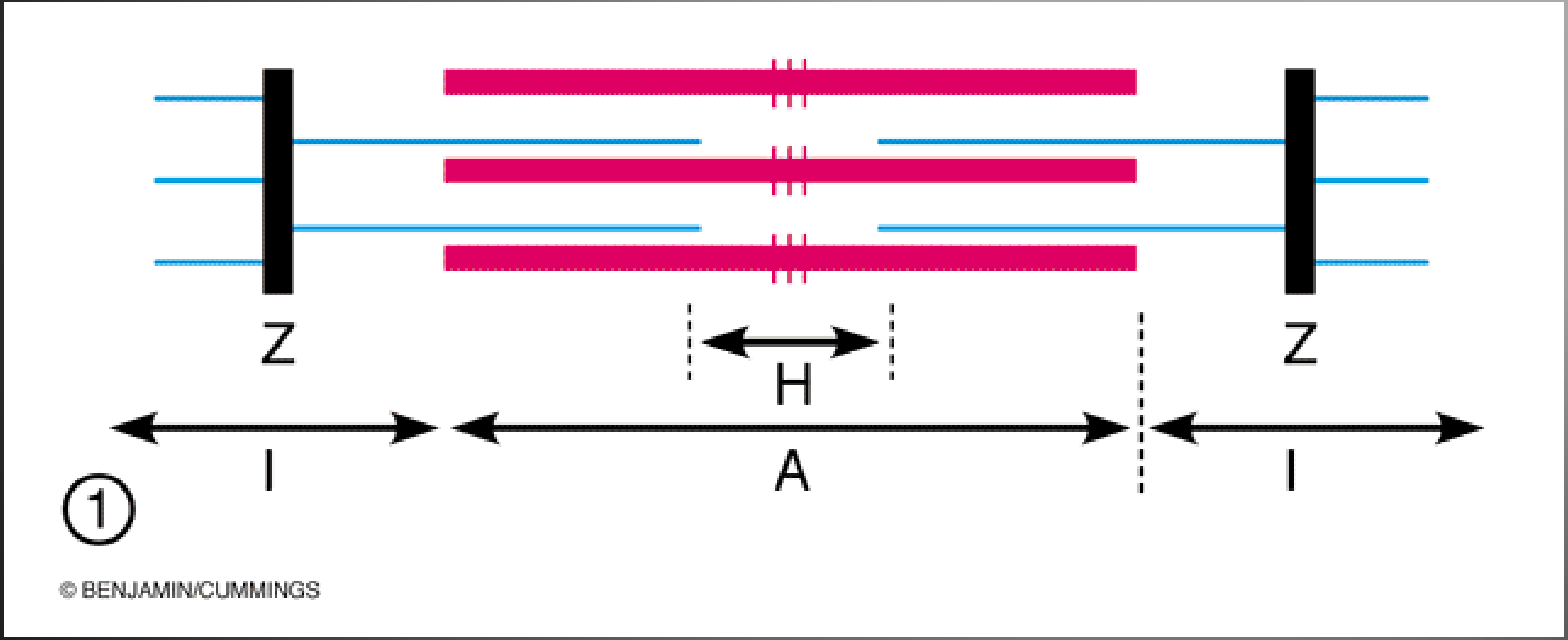
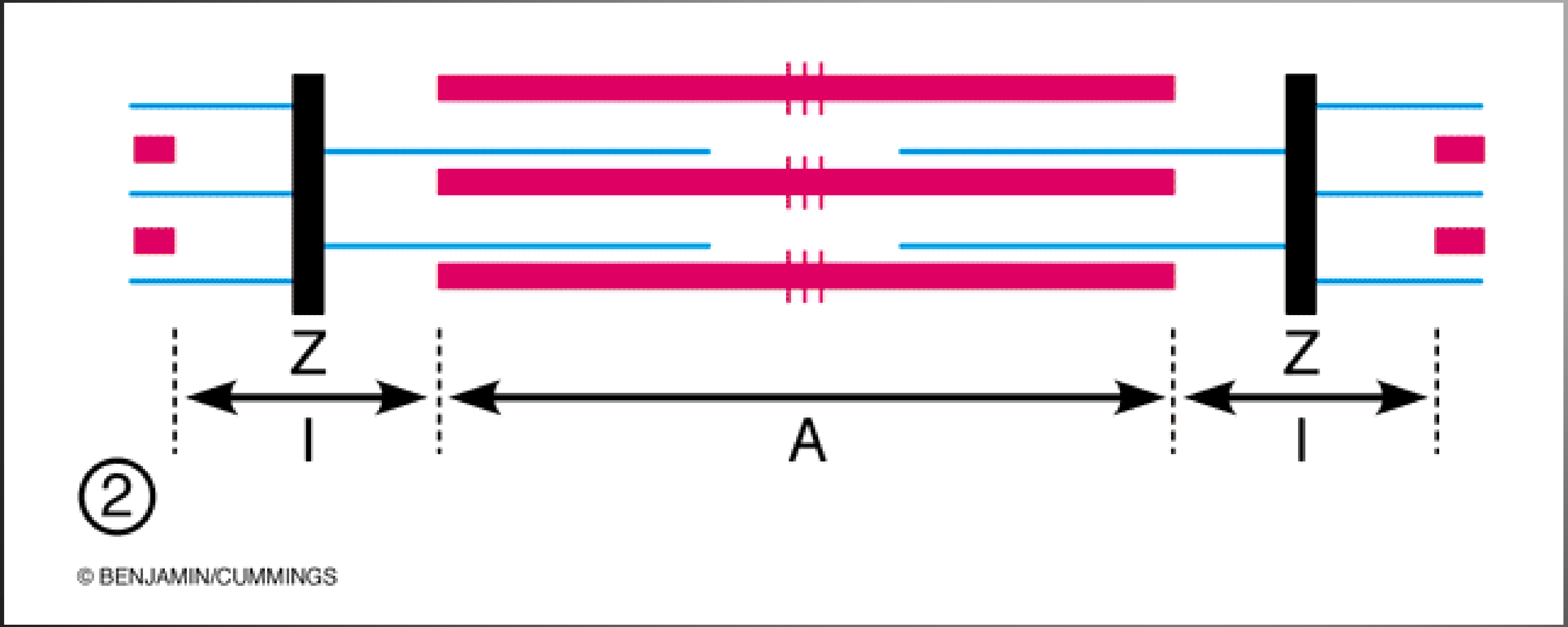


Figure 6-5. Relaxed and contracted states of a myofibril showing (*top*) sliding of the actin filaments (*pink*) into the spaces between the myosin filaments (*red*) and (*bottom*) pulling of the Z membranes toward each other.

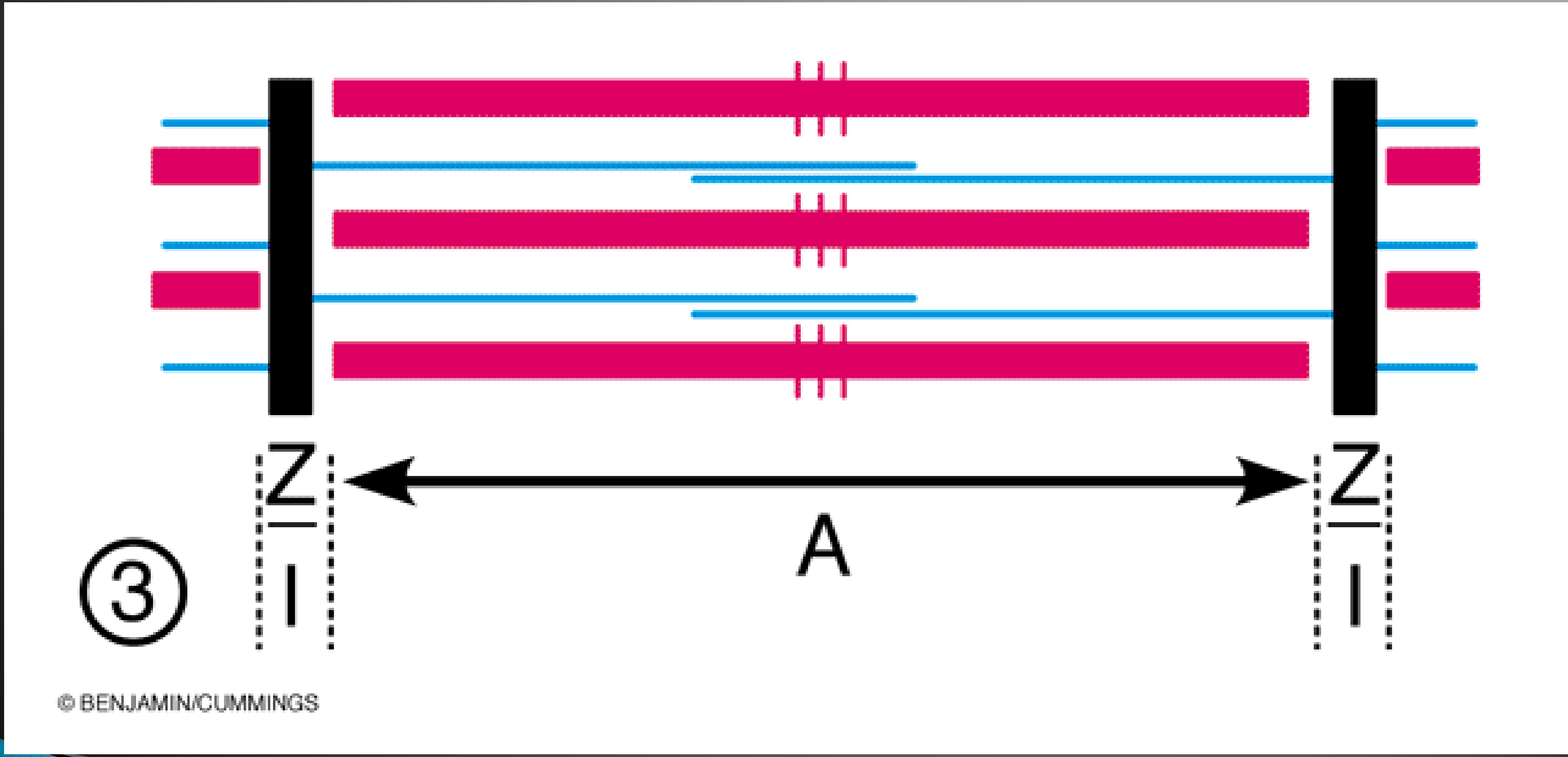
Sarcomere Relaxed



Sarcomere Partially Contracted



Sarcomere Completely Contracted



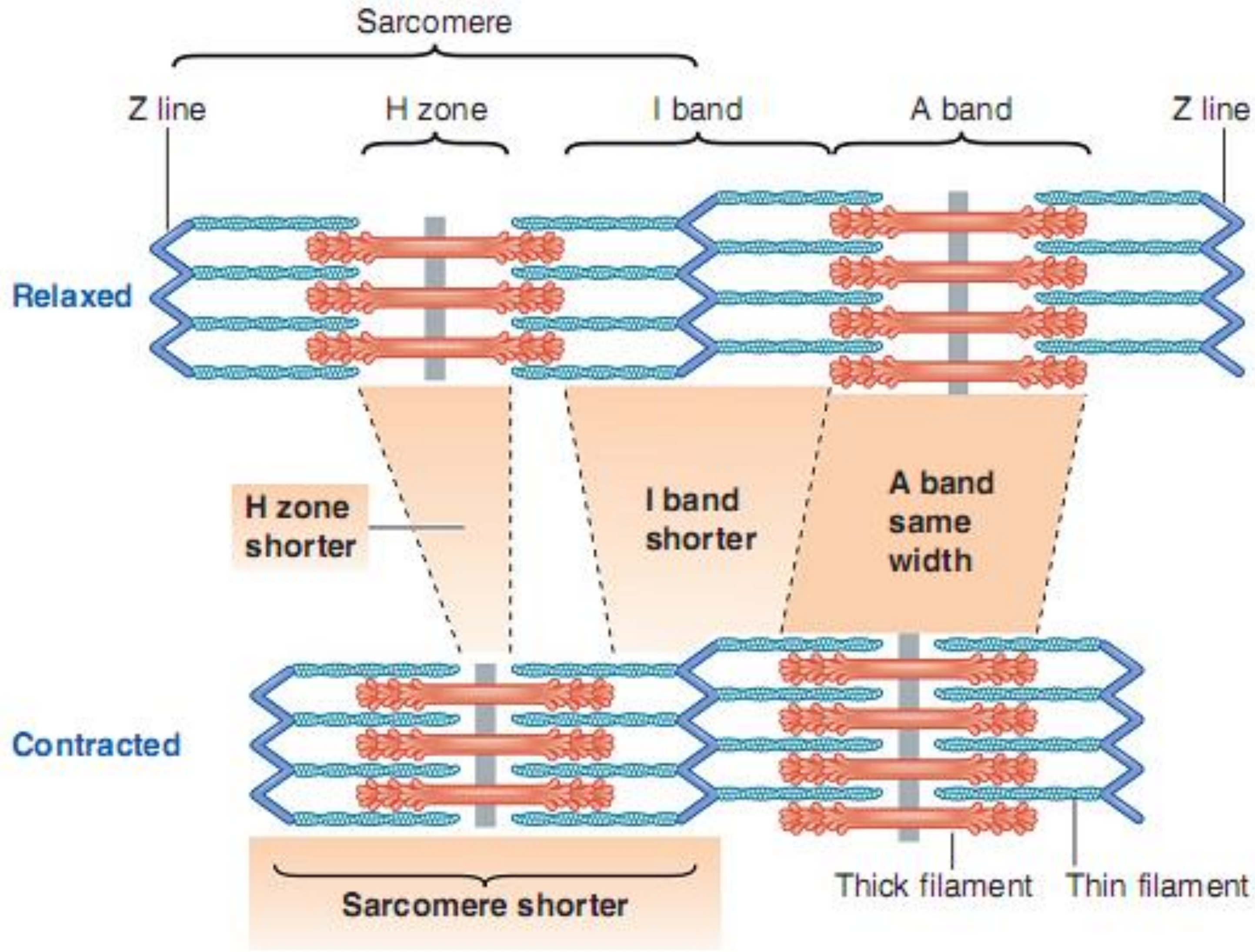
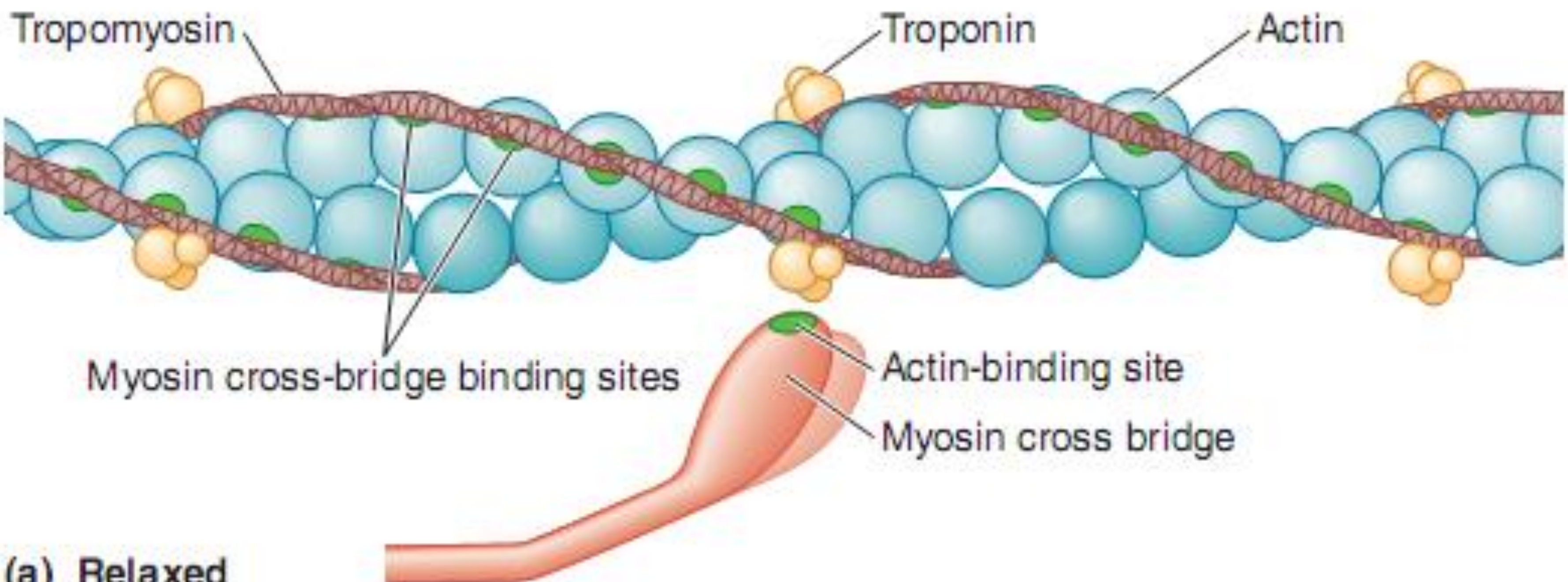


Figure 8-7 Changes in banding pattern during shortening. During muscle contraction, each sarcomere shortens as the thin filaments slide closer together between the thick filaments so that the Z lines are pulled closer together. The width of the A bands does not change as a muscle fiber shortens, but the I bands and H zones become shorter.

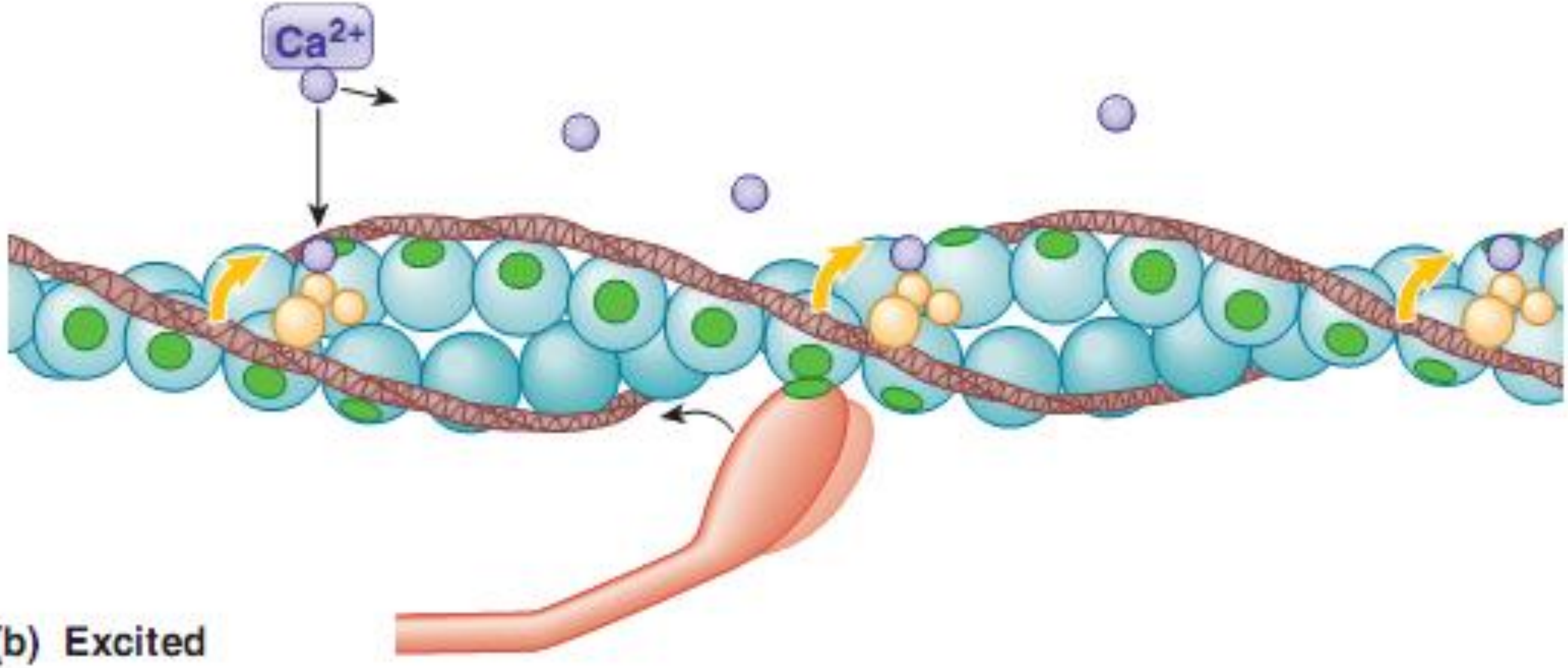


(a) Relaxed

1 No excitation.

2 No cross-bridge binding because cross-bridge binding site on actin is physically covered by troponin–tropomyosin complex.

3 Muscle fiber is relaxed.



(b) **Excited**

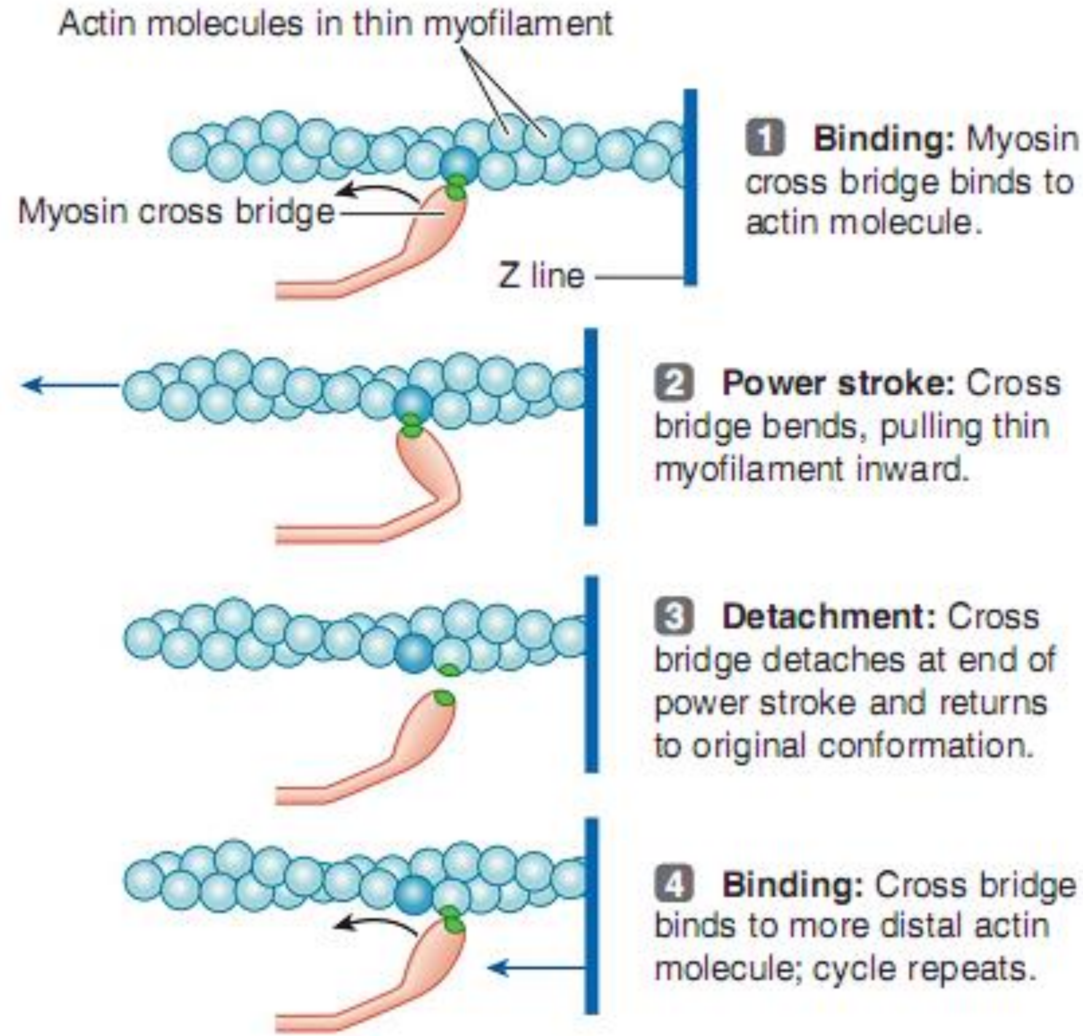
1 Muscle fiber is excited and Ca^{2+} is released.

2 Released Ca^{2+} binds with troponin, pulling troponin–tropomyosin complex aside to expose cross-bridge binding site.

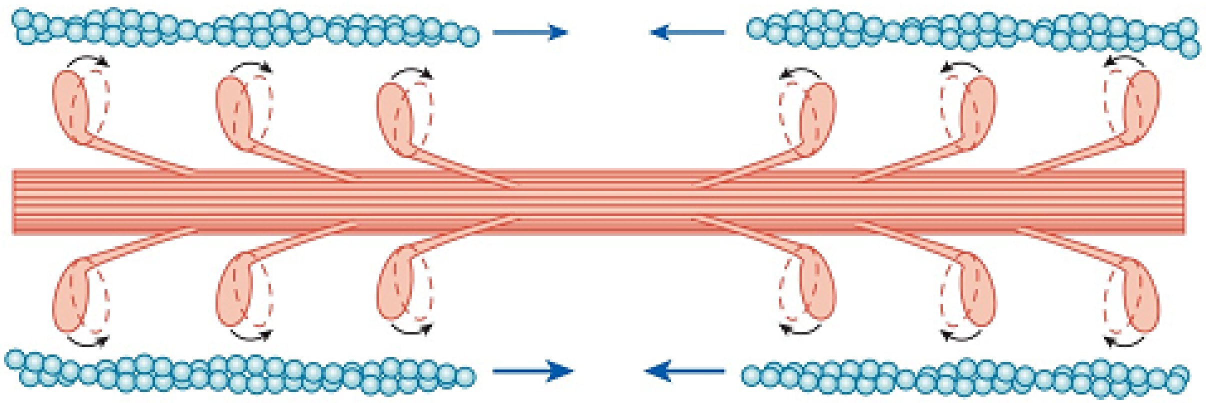
3 Cross-bridge binding occurs.

4 Binding of actin and myosin cross bridge triggers power stroke that pulls thin filament inward during contraction.

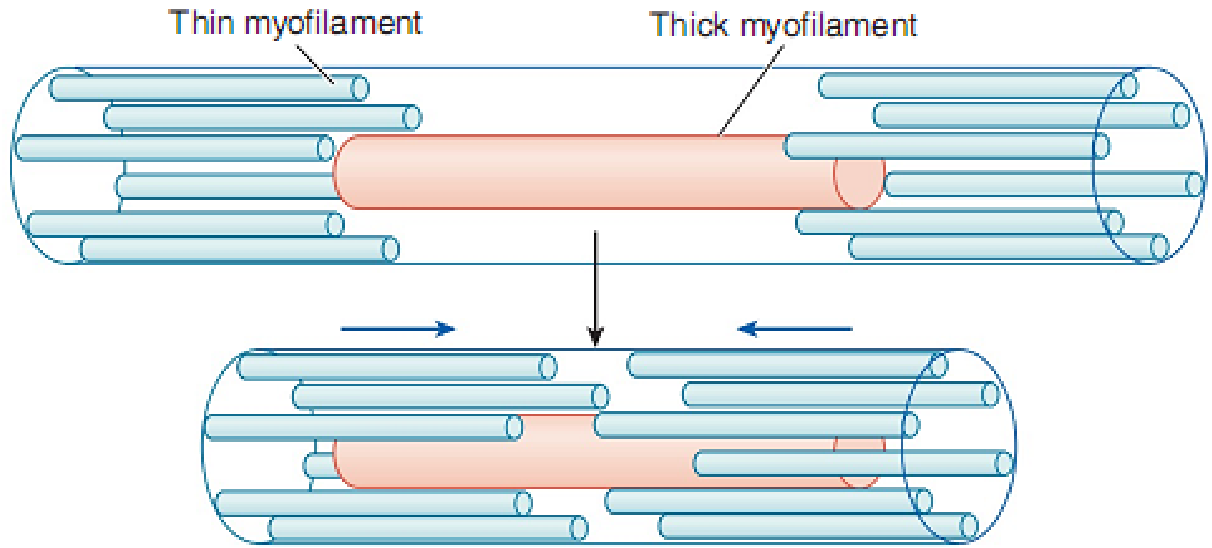
Cross bridge activity



(a) Single cross-bridge cycle



(b) All cross-bridge stroking directed toward center of thick filament



(c) Simultaneous pulling inward of all six thin filaments surrounding a thick filament

Excitation-contraction coupling

- Di sarcolema, terdapat 2 struktur membran yang penting dalam **menghubungkan eksitasi menjadi kontraksi**, yaitu tubulus tranversus (T) dan retikulum sarcoplasma
- AP menyebar dari permukaan membran menuruni tubulus T sehingga AP menyebar masuk ke dalam serabut otot.
- Adanya AP lokal di tubulus T → perubahan permeabilitas dalam jaringan membran yang terpisah diantara retikulum sarcoplasma serabut otot.

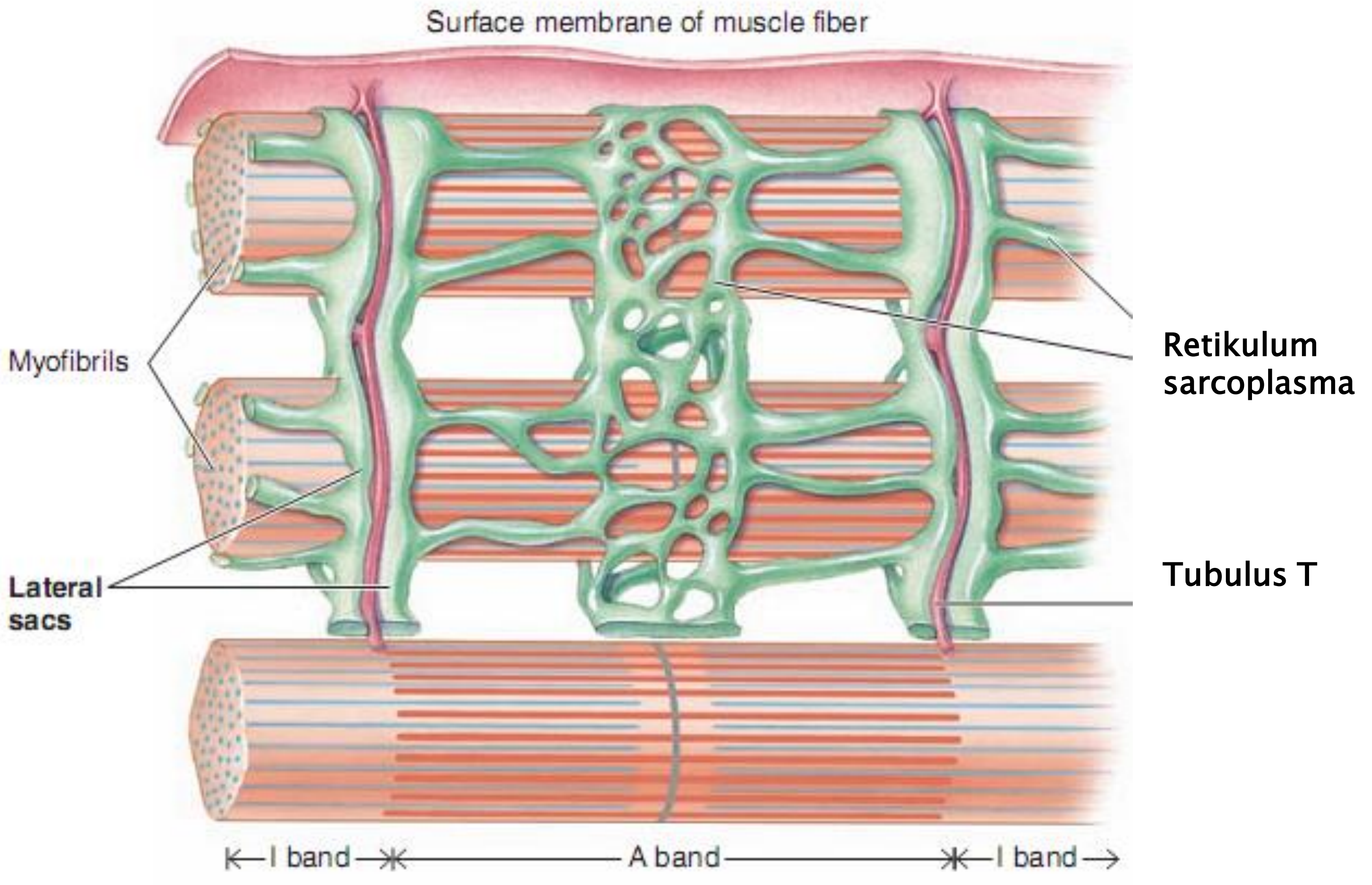
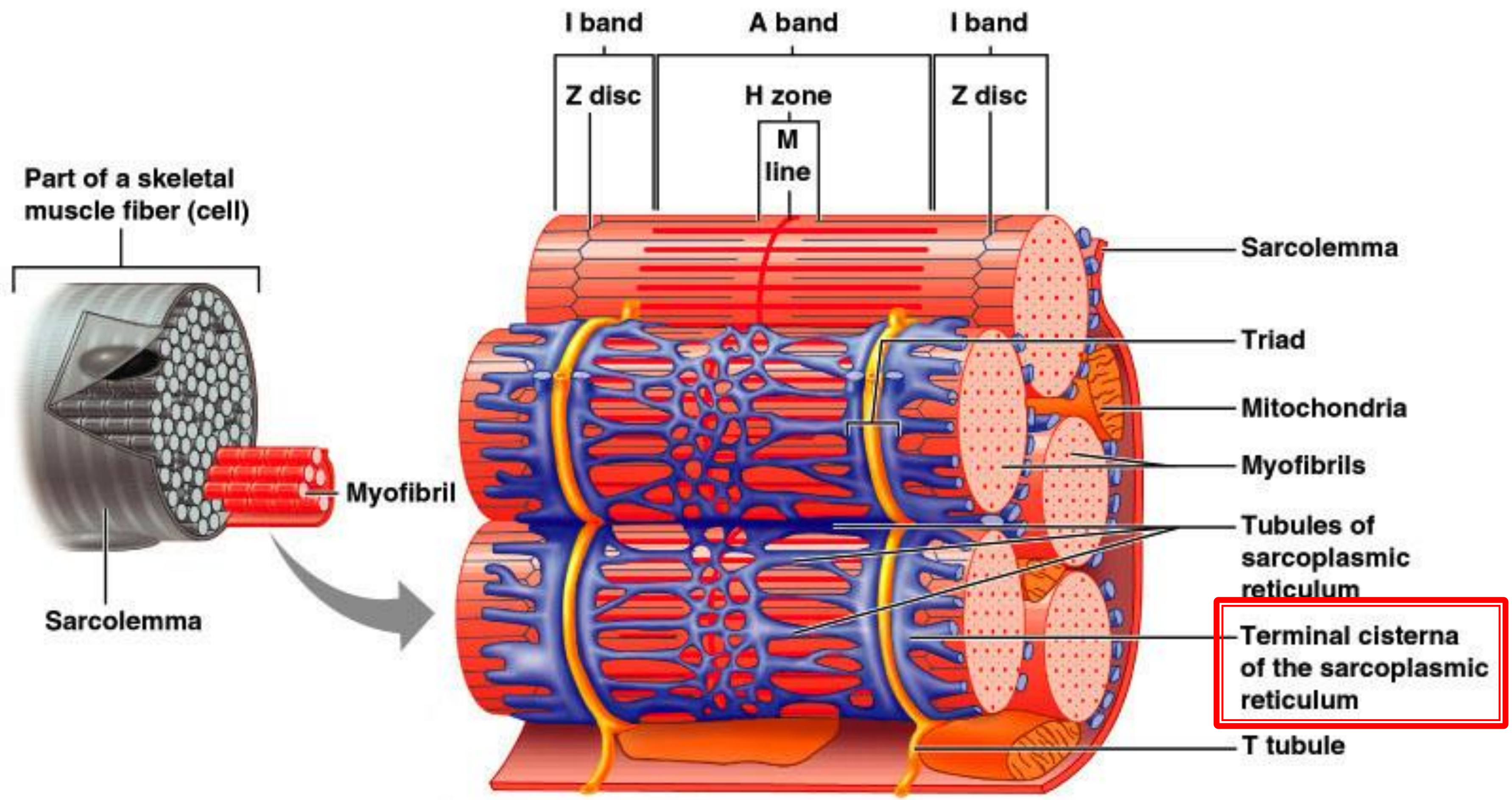


Figure 8-9 The T tubules and sarcoplasmic reticulum in relationship to the myofibrils. The transverse (T) tubules are membranous, perpendicular extensions of the surface membrane that dip deep into the muscle fiber at the junctions between the A and I bands of the myofibrils. The sarcoplasmic reticulum (SR) is a fine, membranous network that runs longitudinally and surrounds each myofibril, with separate segments encircling each A band and I band. The ends of each segment are expanded to form lateral sacs that lie next to the adjacent T tubules.

Retikulum Sarkoplasma



Calsium menghubungkan eksitasi-kontraksi

- Segmen retikulum sarkoplasma melingkupi sekitar band A dan band I. Ujung dari masing-masing segmen meluas untuk membentuk regio sakus, i.e **sakus lateralis** (dikenal dg **sisterna terminal**), yang terpisah dari tubulus T sekitarnya oleh gap sempit. Sakus lateralis menyimpan Ca^{2+}
- AP yang menyebar menuruni tubulus T memicu retikulum sarkoplasma untuk mengeluarkan Ca^{2+} ke dalam sitosol

- Membran protein tubulus T memiliki reseptor dihydropyridine sebagai sensor voltase AP.
- Depolarisasi tubulus T aktifkan reseptor dihydropyridine → mengaktifkan reseptor ryanodine/Ca^{2+} *release channel* pada retikulum sarkoplasma (sakus lateralis)
- Disebut reseptor ryanodine because they are locked in the open position by the plant chemical ryanodine.

- Ketika channel Ca^{2+} dibuka oleh AP di tubulus T, Ca^{2+} dikeluarkan ke sitosol dari sakus lateralis
- Adanya Ca^{2+} di sitosol berikatan dg tropomyosin dan mengubah posisi myosin sehingga *cross bridging site* aktif dan mengikat aktin → *sliding filament mechanism*

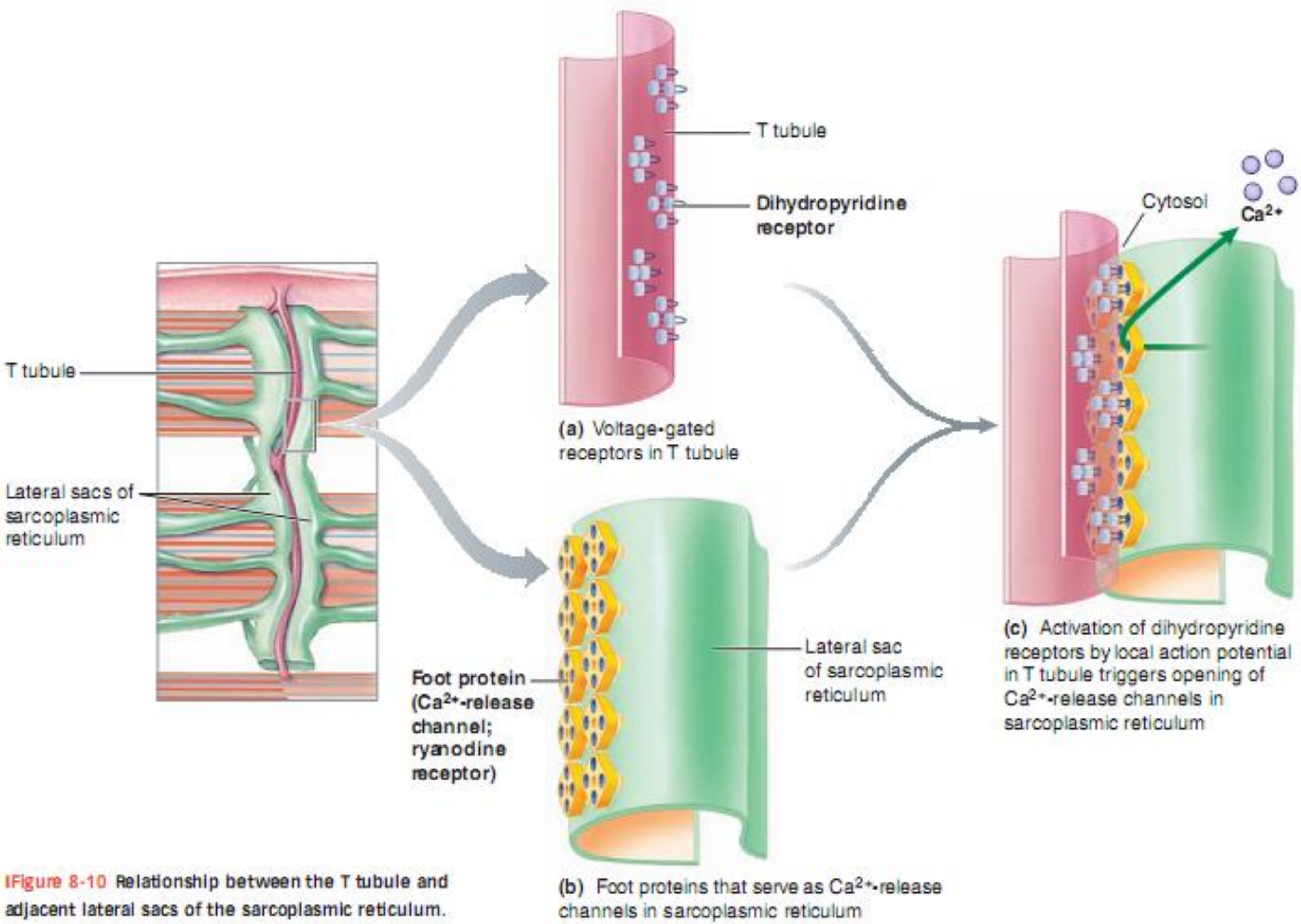


Figure 8-10 Relationship between the T tubule and adjacent lateral sacs of the sarcoplasmic reticulum.

Neuromuscular Junction

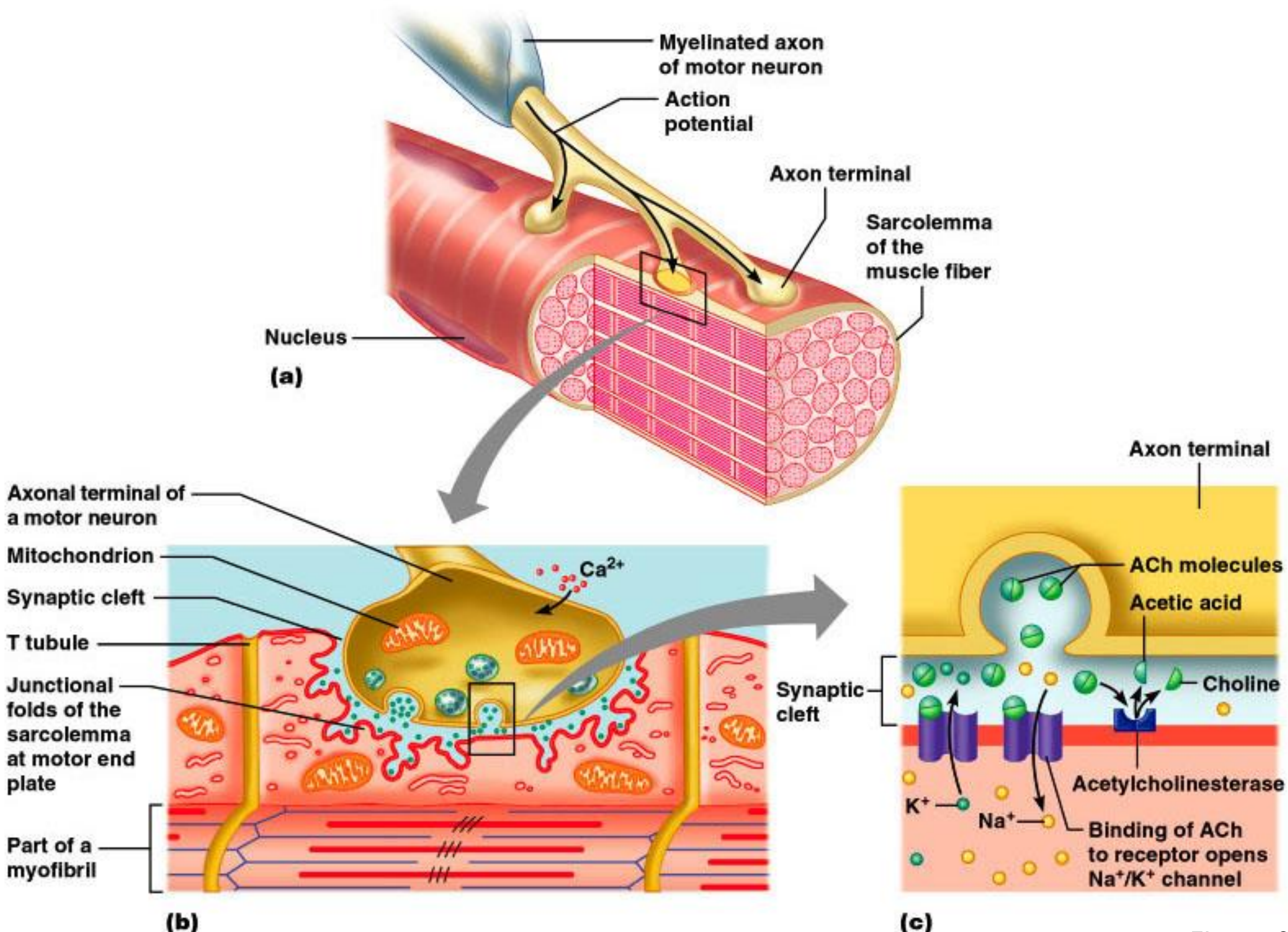


Figure 9.7 (a–c)

Neuromuscular Junction

- When a nerve impulse reaches the end of an axon at the neuromuscular junction:
  - ACh release into the synaptic cleft via exocytosis
  - ACh diffuses across the synaptic cleft to ACh receptors on the sarcolemma
  - Binding of ACh to its receptors initiates an action potential in the muscle

Destruction of Acetylcholine

- ACh bound to ACh receptors is quickly destroyed by the enzyme acetylcholinesterase
- This destruction prevents continued muscle fiber contraction in the absence of additional stimuli

Role of Acetylcholine (Ach)

- ACh binds its receptors at the motor end plate
- Binding opens chemically (ligand) gated channels
- Na^+ and K^+ diffuse out and the interior of the sarcolemma becomes less negative
- This event is called depolarization

Neuromuscular junction diseases

- Toxin C. Botulinum : Blocking the release of A Ch. Dari motor end plate

  Mati o/k gagal nafas
- Curare : berikatan dg reseptor A Ch. (reversibel)

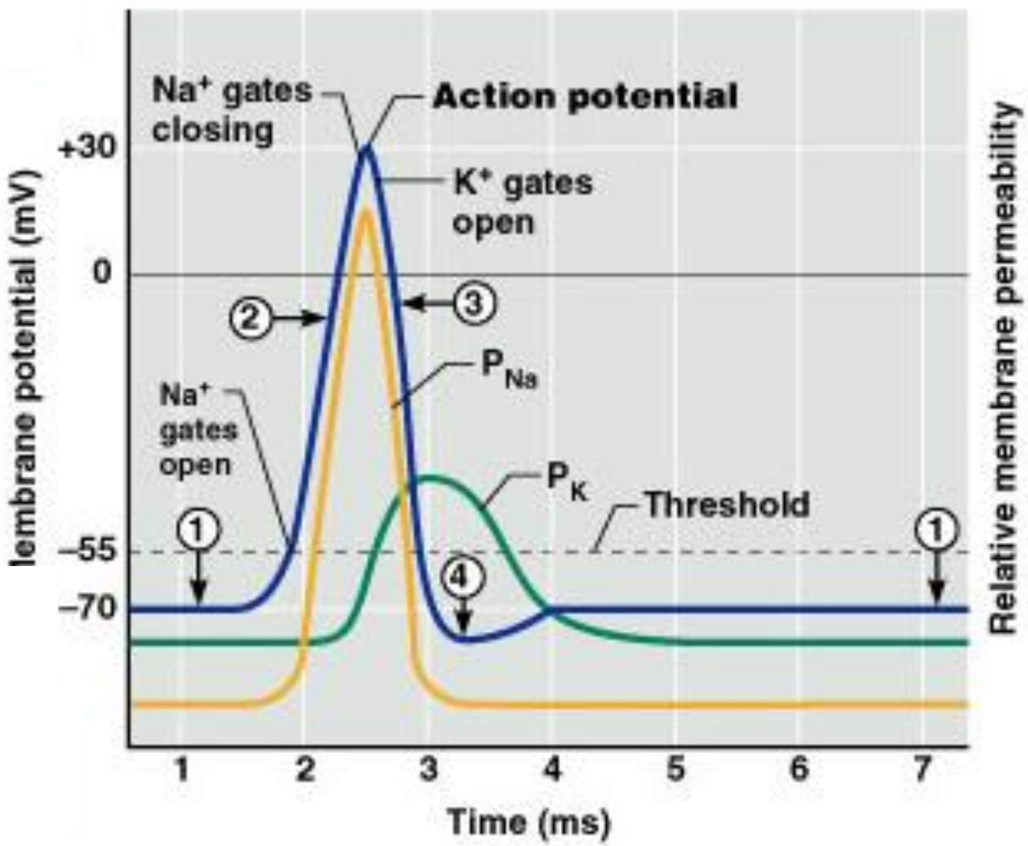
  Mati o/k respiratory paralysis
- Organofospat : hambat Ach (ireversibel)
- Myastenia gravis : kelemahan otot o/k tubuh membentuk antibodi yang merusak reseptor ACh

Action Potential

- Suatu rangkaian depolarisasi sementara yang melibatkan perubahan polaritas dari sarcolema atau membran sel saraf dan penjalaran aksi potensial sepanjang membran.

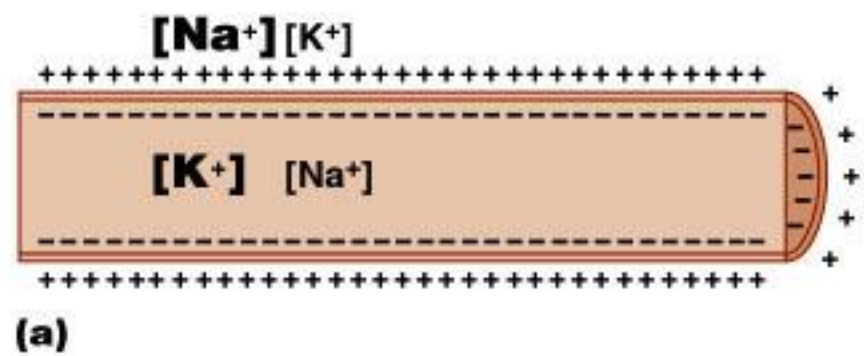
Phases of the Action Potential

- 1 – resting state
- 2 – depolarization phase
- 3 – repolarization phase
- 4 – hyperpolarization



Action Potential: Electrical Conditions of a Polarized Sarcolemma

- The predominant extracellular ion is Na^+
- The predominant intracellular ion is K^+
- The sarcolemma is relatively impermeable to both ions

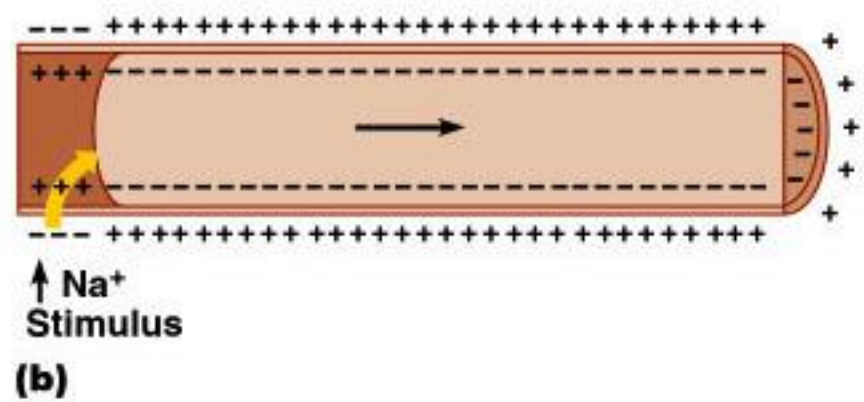


Resting Membran potensial

Figure 9.8 (a)

Action Potential: Depolarization and Generation of the Action Potential

- An axonal terminal of a motor neuron releases ACh and causes a patch of the sarcolemma to become permeable to Na^+ (sodium channels open)



Depolarisasi

Figure 9.8 (b)

Action Potential: Depolarization and Generation of the Action Potential

- Na^+ enters the cell, and the resting potential is decreased (depolarization occurs)
- If the stimulus is strong enough, an action potential is initiated

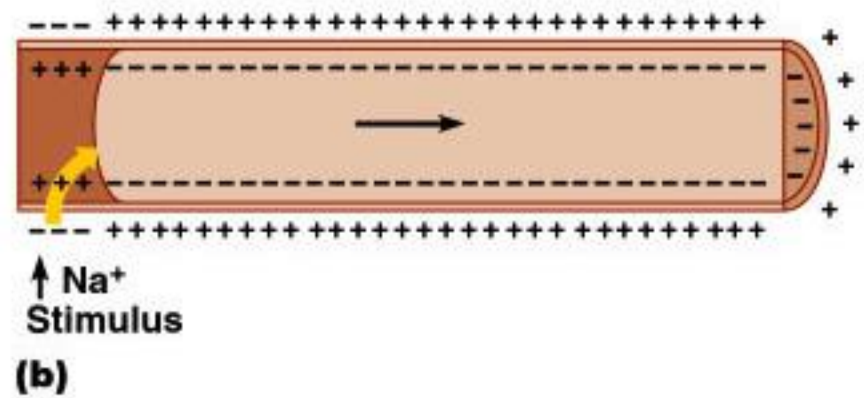
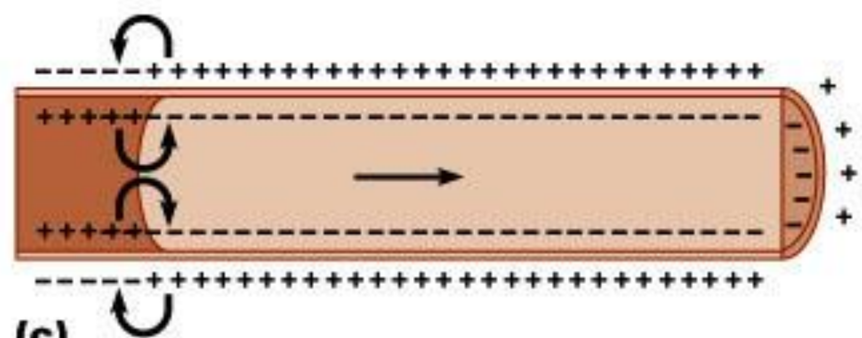


Figure 9.8 (b)

Action Potential: Propagation of the Action Potential

- Perubahan polaritas disisi awalnya sarkolema merubah permeabilitas membran didekatnya.
- *Voltage-regulated Na^+ channels* didekatnya terbuka → depolarisasi



(c)

Figure 9.8 (c)

Action Potential: Propagation of the Action Potential

- Sehingga, AP merambat secara cepat sepanjang sarkolema.
- Ketika terinisiasi, AP tidak dapat dihentikan, dan akhirnya menyebabkan kontraksi otot.

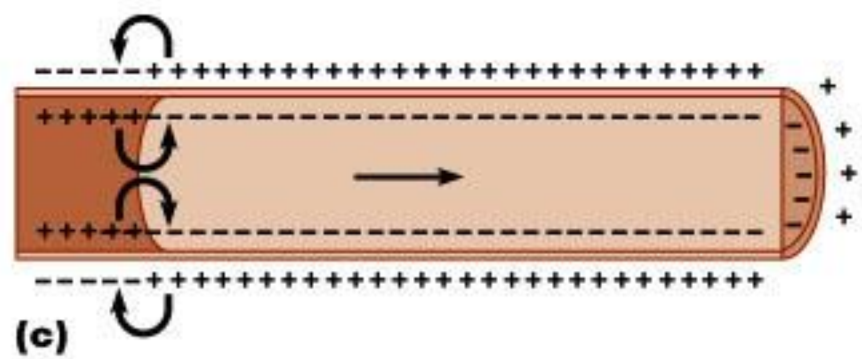


Figure 9.8 (c)

Action Potential: Repolarization

- Segera setelah gelombang depolarisasi berlalu, permeabilitas sarkolema berubah.
- Na^+ channels close and K^+ channels open
- K^+ berdifusi dari sel keluar → mengembalikan polaritas listrik di sarkolema menjadi lebih negatif

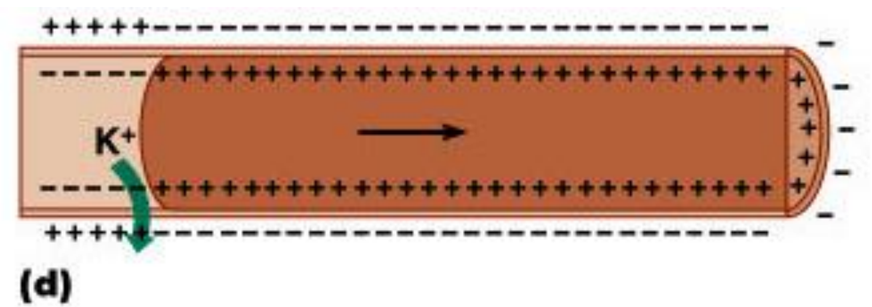


Figure 9.8 (d)

Action Potential: Repolarization

- Repolarisasi terjadi dengan arah yang sama seperti depolarisasi, dan harus terjadi sebelum otot dapat distimulasi lagi. (*refractory period*)
- The ionic concentration of the resting state is restored by the Na^+–K^+ pump

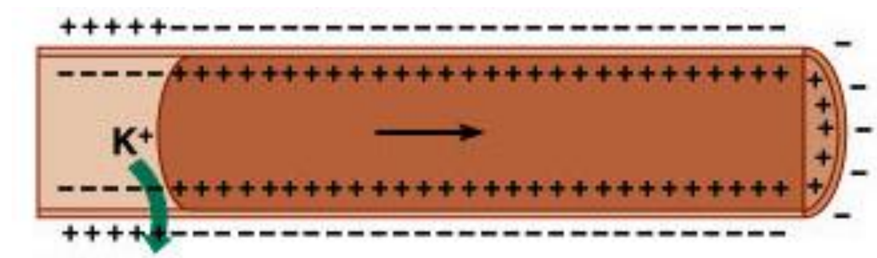
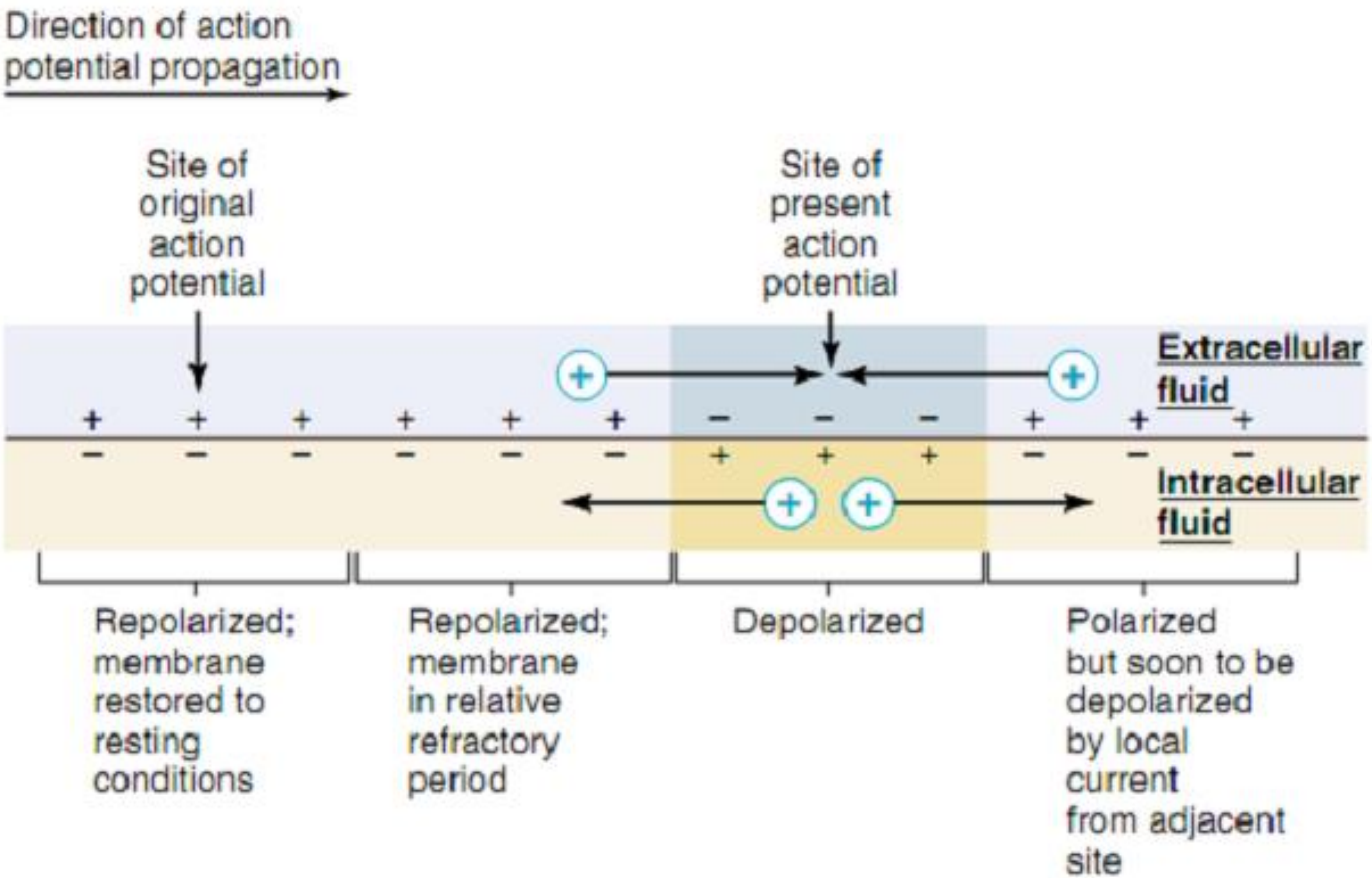


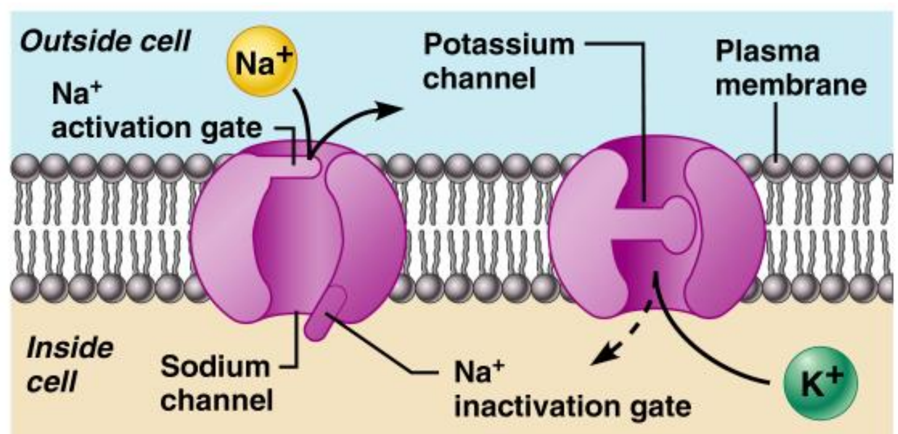
Figure 9.8 (d)

Propagation of an action potential along a plasma membrane.



Action Potential: Resting State

- Na^+ and K^+ channels are closed (voltage = −70mV)
- Leakage accounts for small movements of Na^+ and K^+
- Each Na^+ channel has two voltage-regulated gates
  - Activation gates – closed in the resting state
  - Inactivation gates – open in the resting state



① Resting state: All gated Na^+ and K^+ channels closed (Na^+ activation gates closed; inactivation gates open)

Figure 11.12.1

Action Potential: Depolarization Phase

- Na^+ permeability increases; membrane potential reverses
- Na^+ gates are opened; K^+ gates are closed
- Threshold – a critical level of depolarization (–55 to –50 mV)
- At threshold, depolarization becomes self-generating

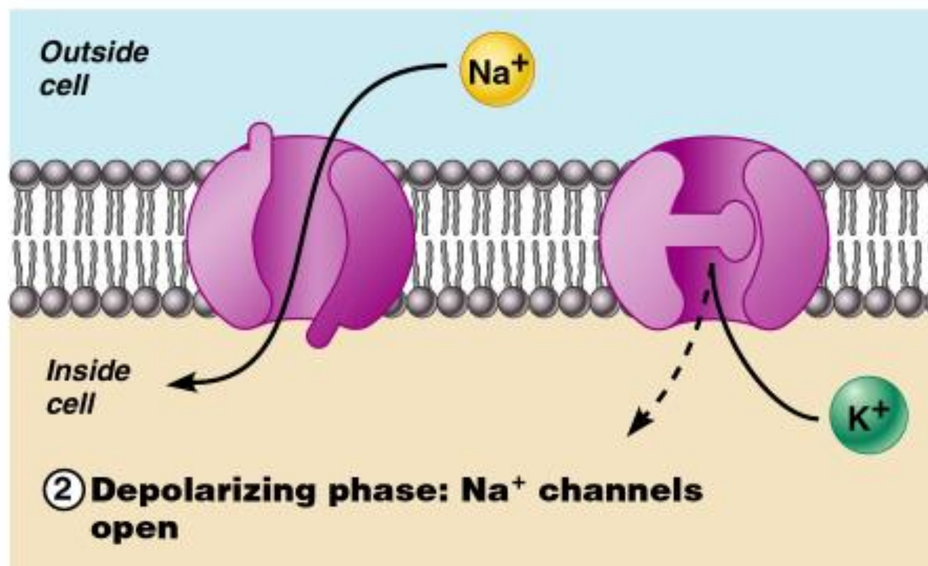


Figure 11.12.2

Action Potential: Repolarization Phase

- Sodium inactivation gates close
- Membrane permeability to Na^+ declines to resting levels
- As sodium gates close, voltage-sensitive K^+ gates open
- K^+ exits the cell and internal negativity of the resting neuron is restored

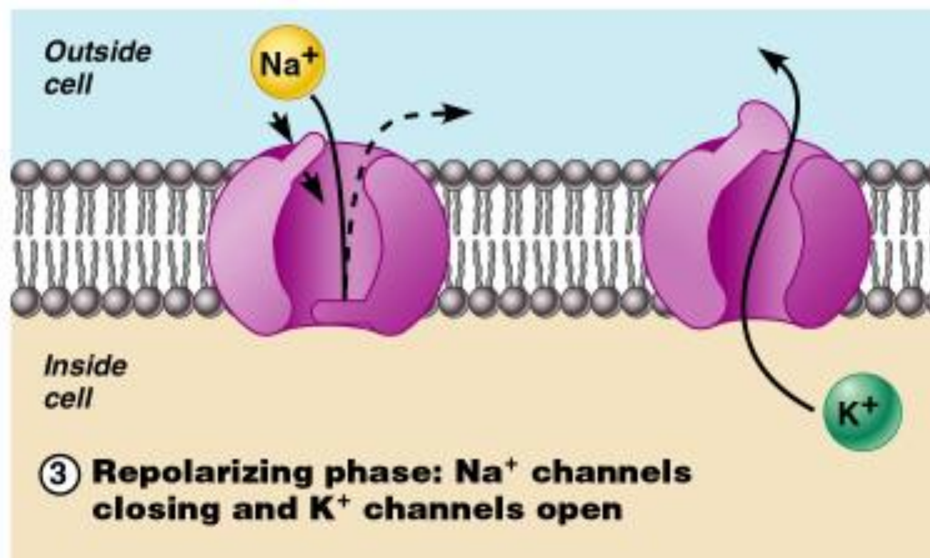


Figure 11.12.3

Action Potential: Hyperpolarization

- Potassium gates remain open, causing an excessive efflux of K^+
- This efflux causes hyperpolarization of the membrane (undershoot) → semakin (–)
- The neuron is insensitive to stimulus and depolarization during this time

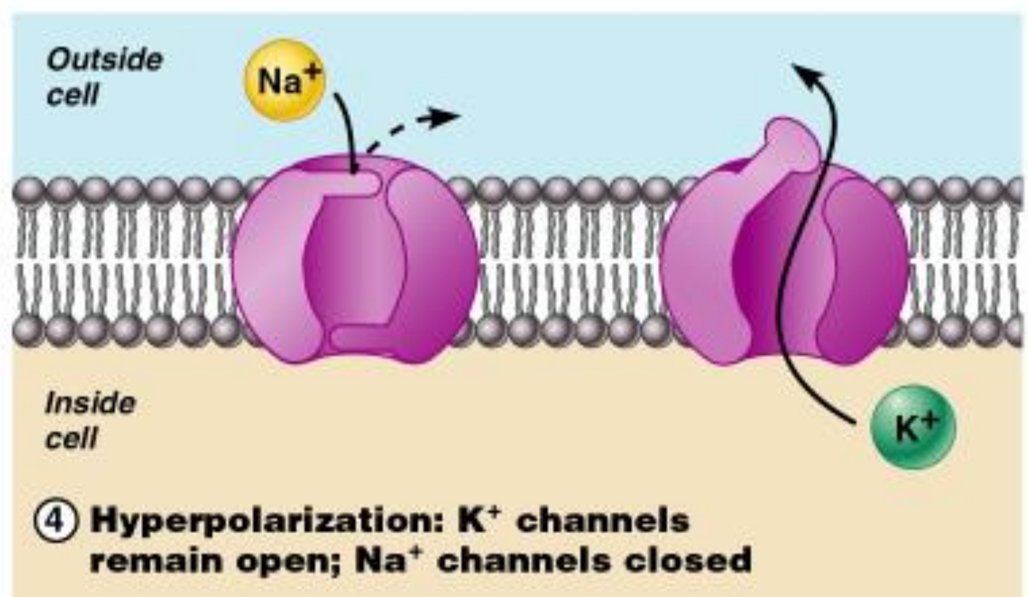
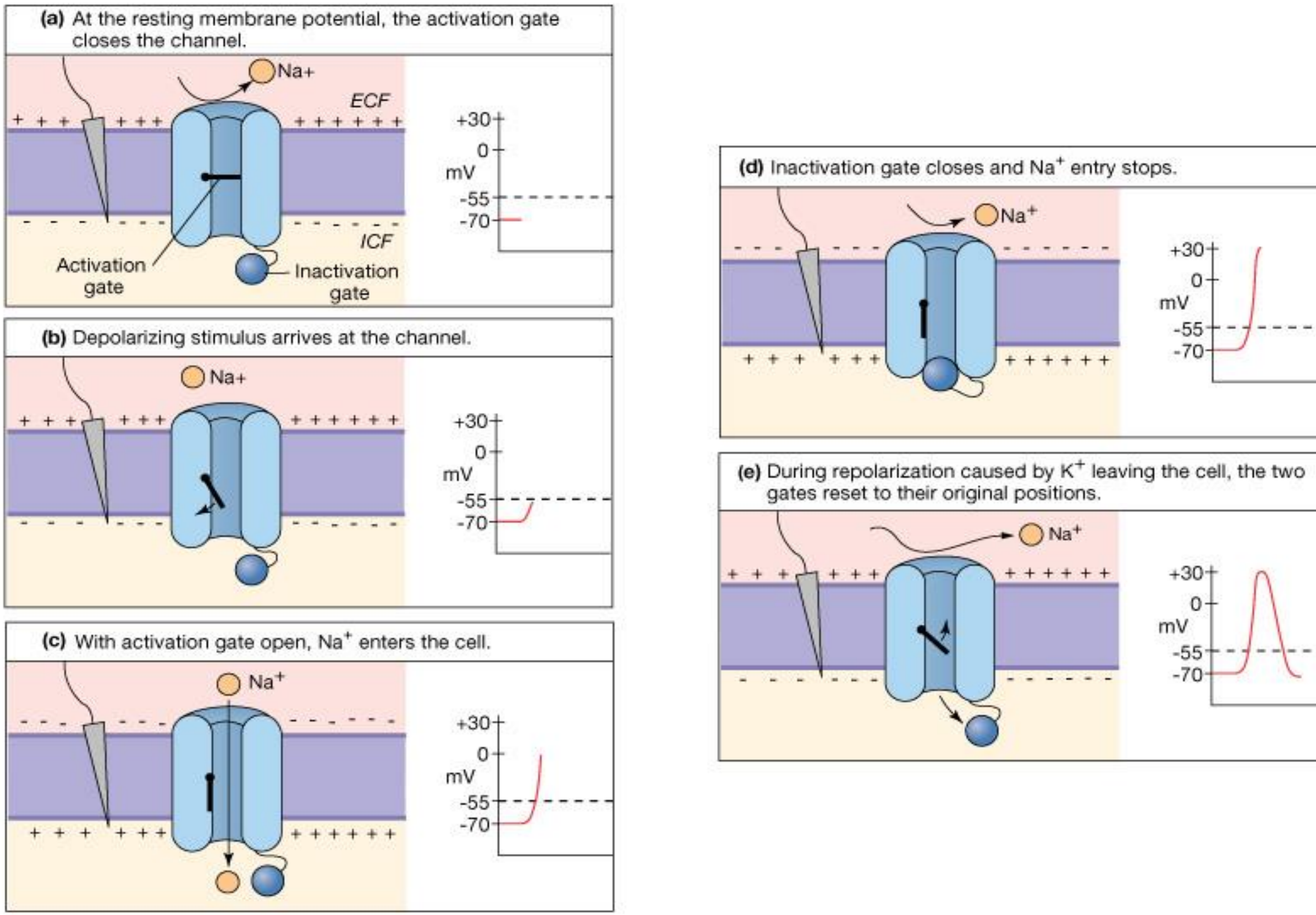


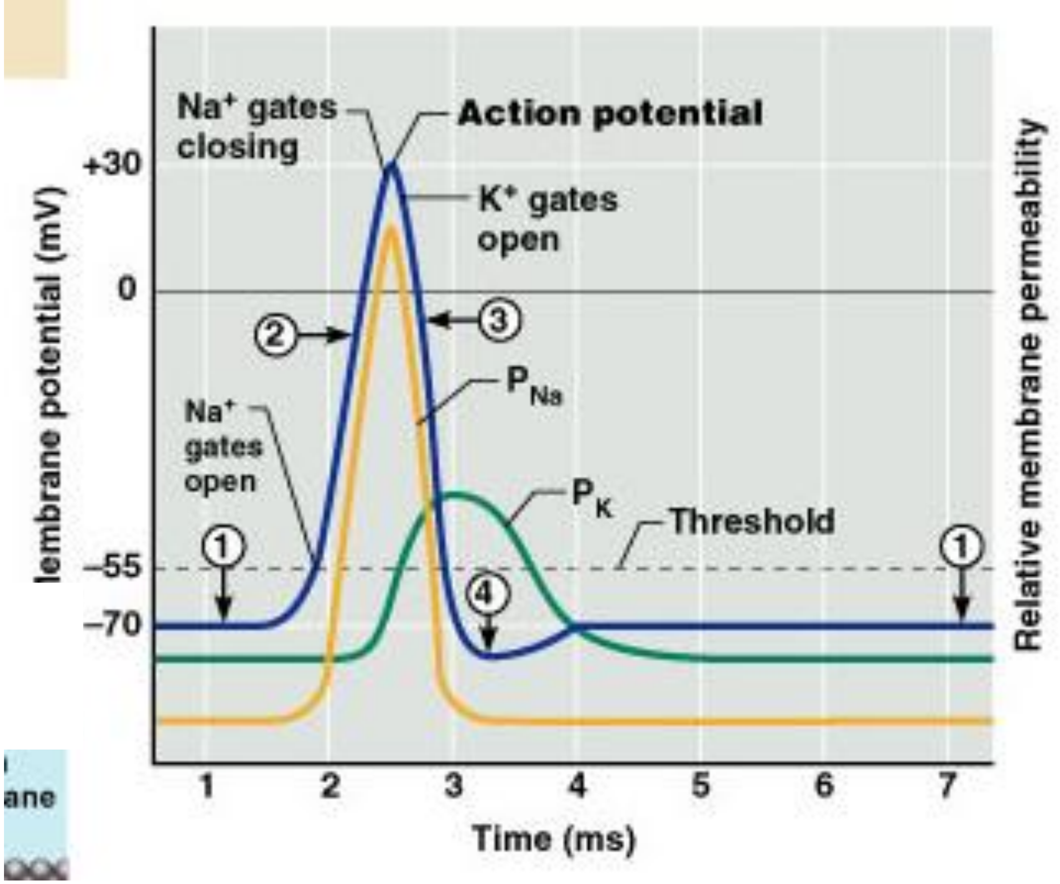
Figure 11.12.4

Membrane & Channel Changes during an Action Potential



Phases of the Action Potential

- 1 – resting state
- 2 – depolarization phase
- 3 – repolarization phase
- 4 – hyperpolarization



Saltatory Conduction

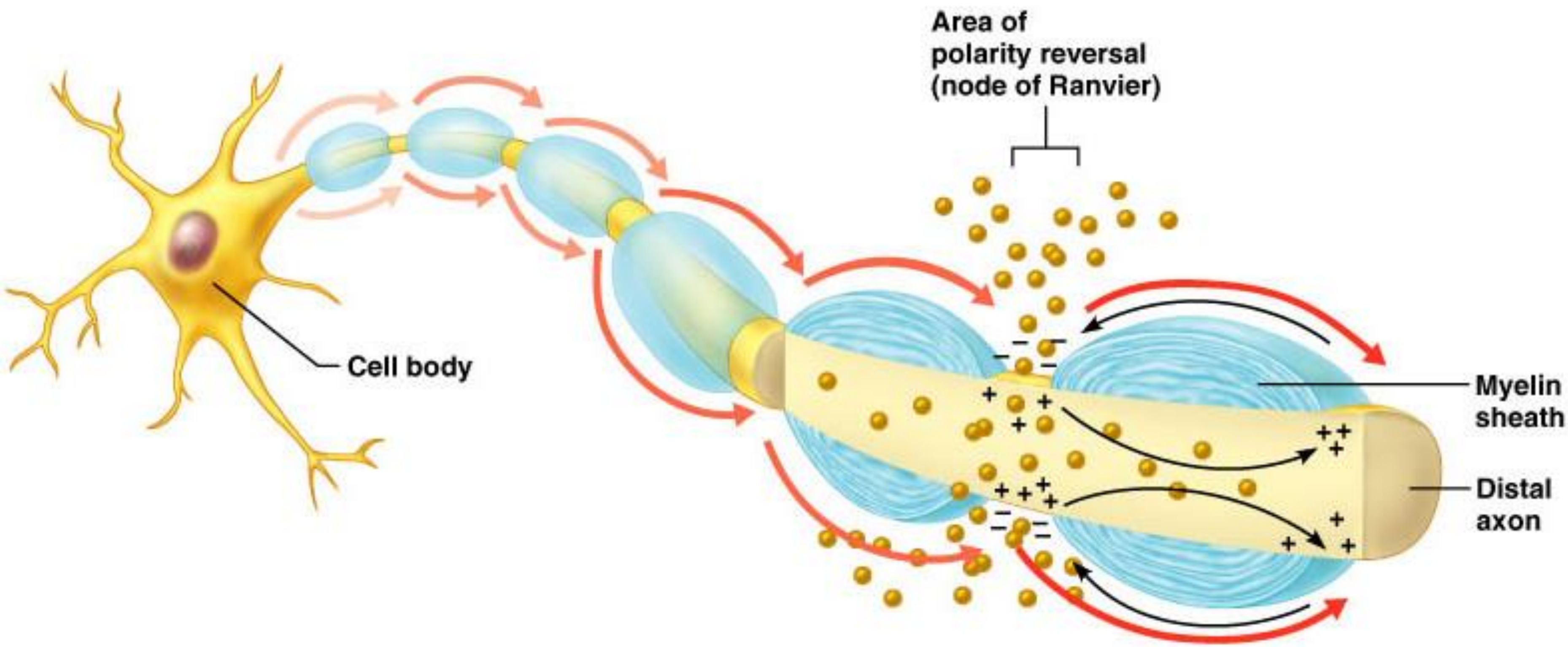


Figure 11.16

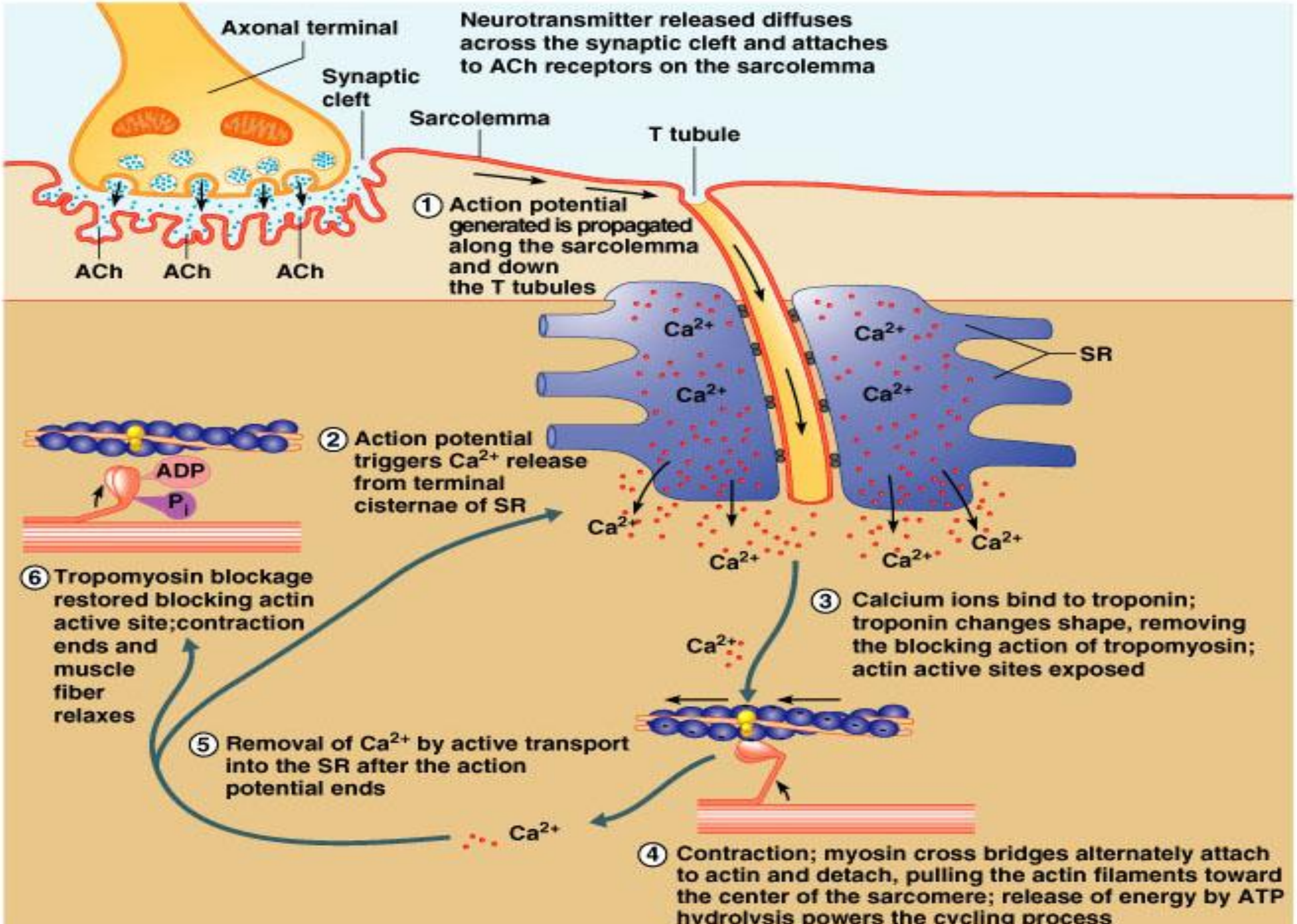
Excitation–Contraction Coupling

- Once generated, the action potential:
  - Is propagated along the sarcolemma
  - Travels down the T tubules
  - Triggers Ca^{2+} release from terminal cisternae
- Ca^{2+} binds to troponin and causes:
  - The blocking action of tropomyosin to cease
  - Actin active binding sites to be exposed

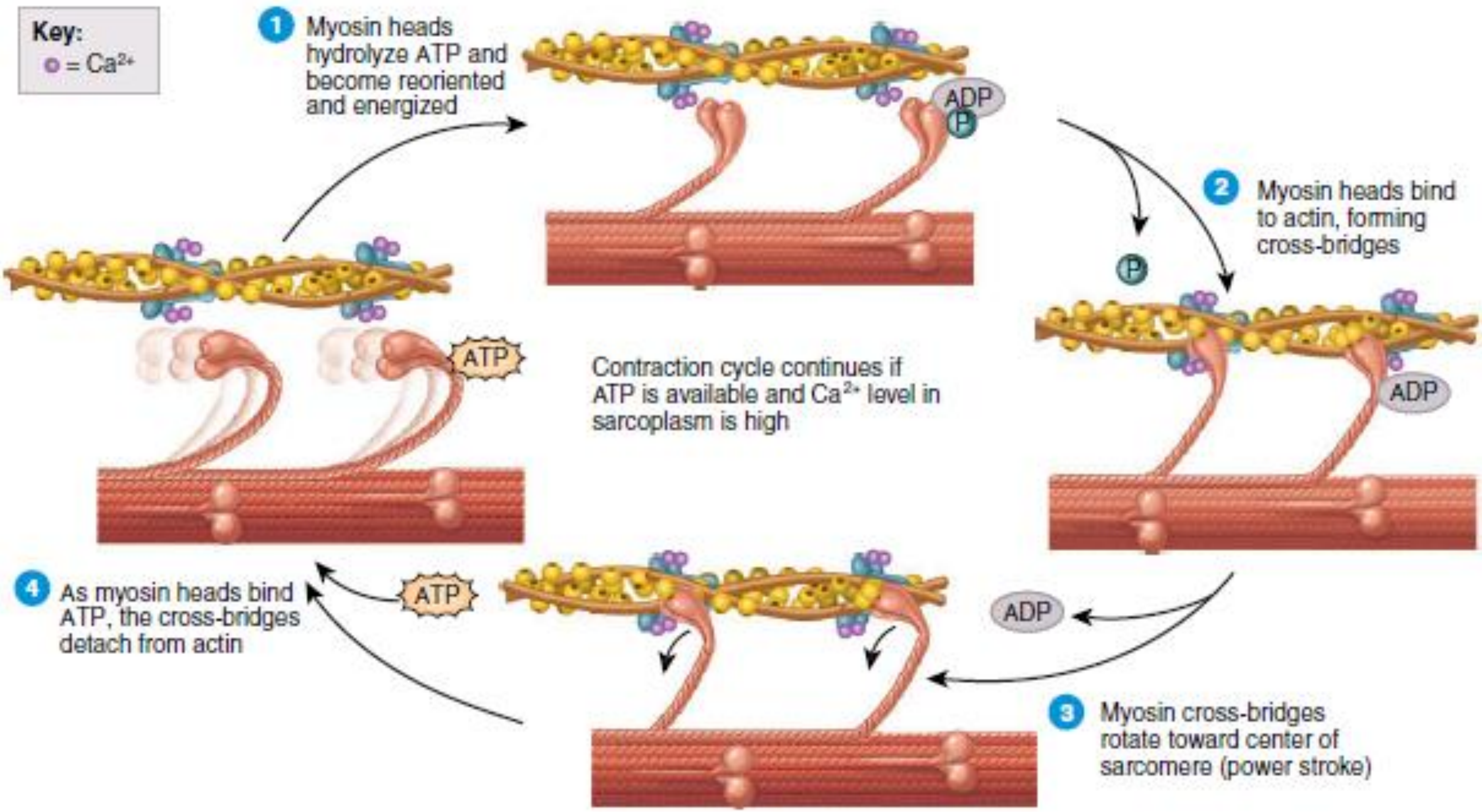
Excitation-Contraction Coupling

- Myosin cross bridges alternately attach and detach
- Thin filaments move toward the center of the sarcomere
- Hydrolysis of ATP powers this cycling process
- Ca^{2+} is removed into the SR, tropomyosin blockage is restored, and the muscle fiber relaxes

Excitation–Contraction Coupling

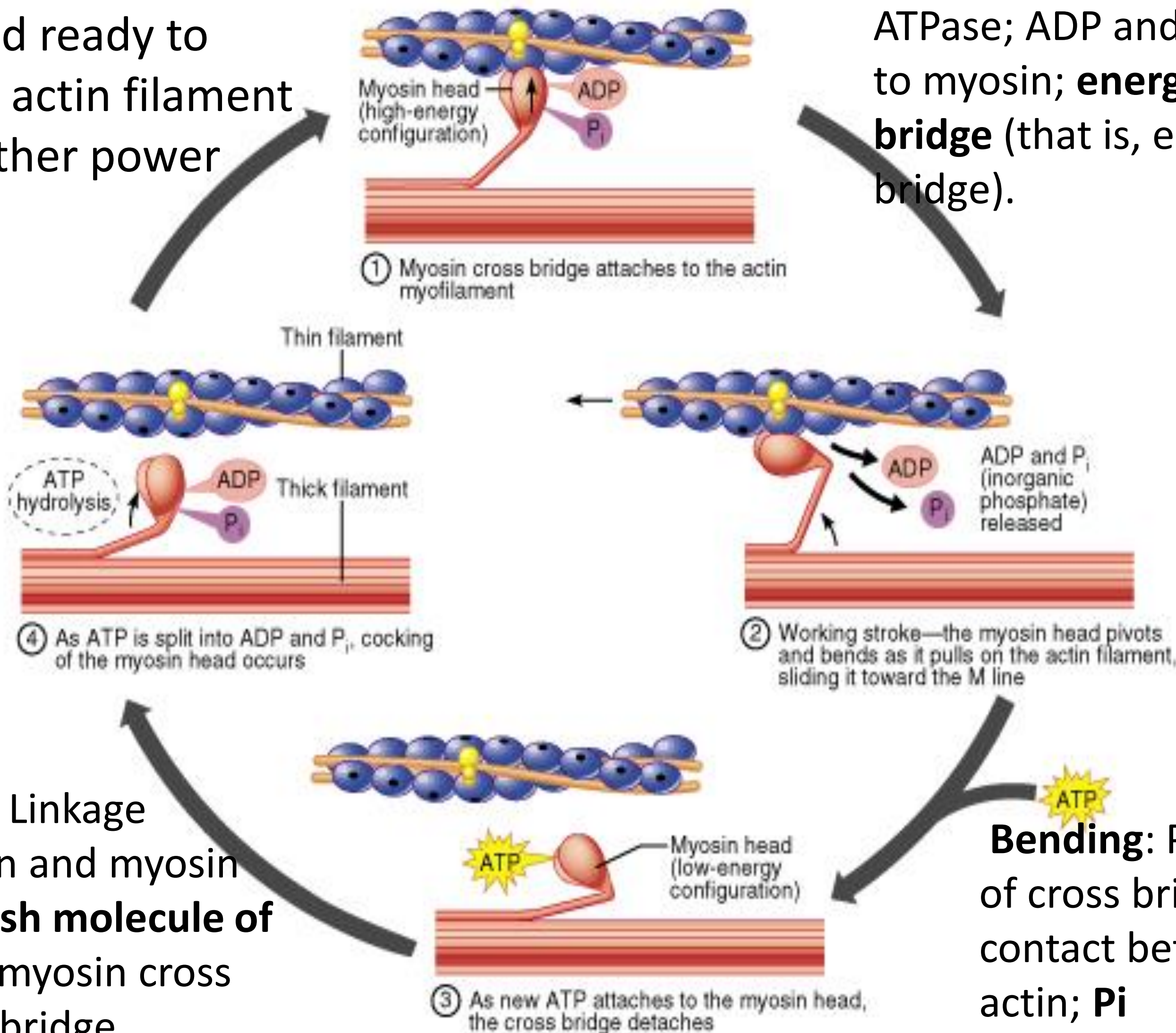


Contraction cycle



In step 4 the myosin head is cocked and ready to attach to an actin filament to start another power stroke.

Energized: ATP split by myosin ATPase; ADP and Pi remain attached to myosin; **energy stored in cross bridge** (that is, energy "cocks" cross bridge).



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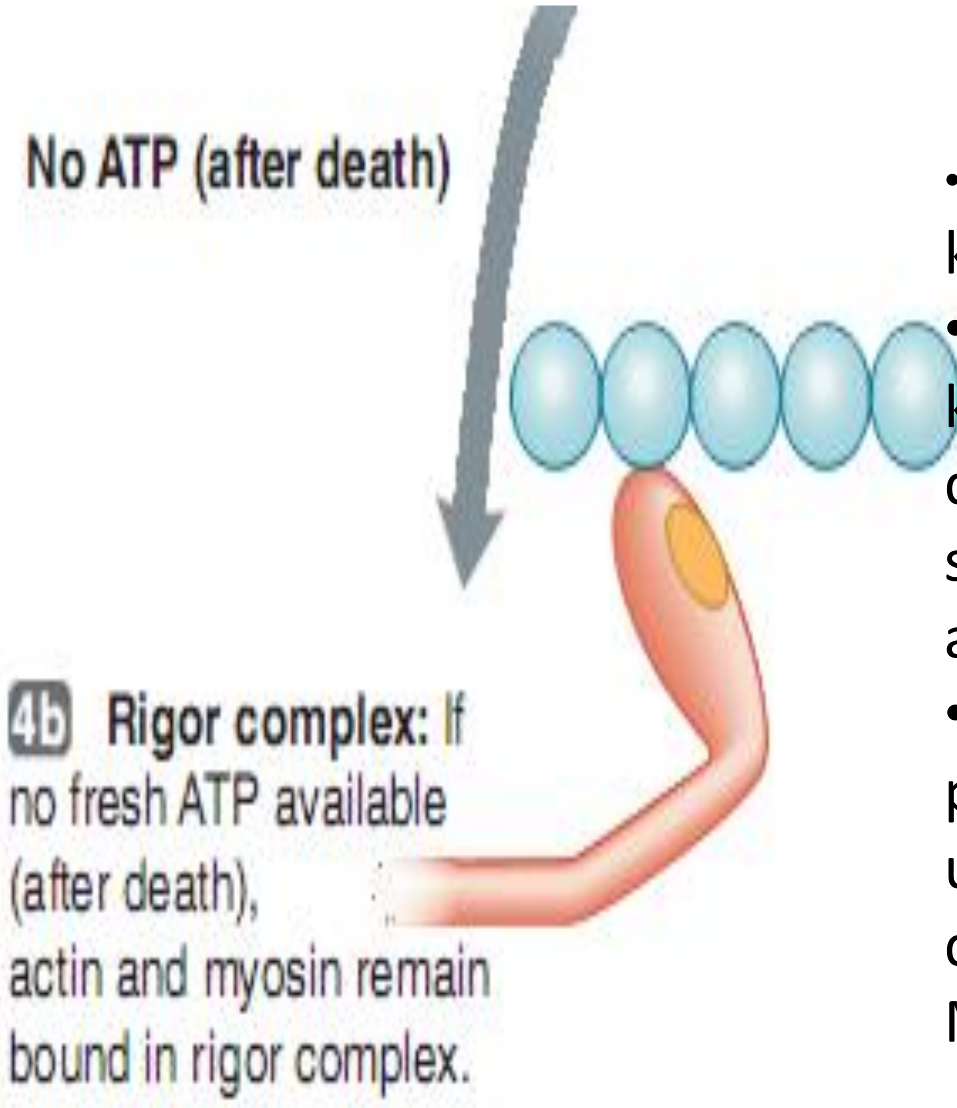
Detachment: Linkage between actin and myosin **broken as fresh molecule of ATP binds** to myosin cross bridge; cross bridge assumes original conformation; ATP hydrolyzed

Bending: Power stroke of cross bridge triggered on contact between myosin and actin; **Pi released during and ADP released after power stroke.**

Rigor mortis



- Dimulai 3 - 4 jam setelah kematian, lengkap dalam 12 jam.
- Karena Ca^{2+} sitosol yg banyak, kemungkinan karena bocornya Ca^{2+} dari saccus lateralis dan membran sel otot inaktif tidak dapat menjaga agar Ca^{2+} tetap diluar
- Sel yang mati → tidak dapat produksi ATP lagi yang diperlukan untuk melepas ikatan myosin dengan aktin → KAKU MAYAT/RIGOR MORTIS

Contraction of Skeletal Muscle Fibers

- Contraction – refers to **the activation of myosin's cross bridges** (force–generating sites)
- **Shortening** occurs when the tension generated by the cross bridge exceeds forces opposing shortening
- Contraction ends when cross bridges become inactive, the tension generated declines, and relaxation is induced

Contraction of Skeletal Muscle (Organ Level)

- Contraction of muscle fibers (cells) and muscles (organs) is similar
- The two types of muscle contractions are:
  - **Isometric contraction** – increasing muscle tension (muscle does not shorten during contraction)
  - **Isotonic contraction** – decreasing muscle length (muscle shortens during contraction)

Relaksasi

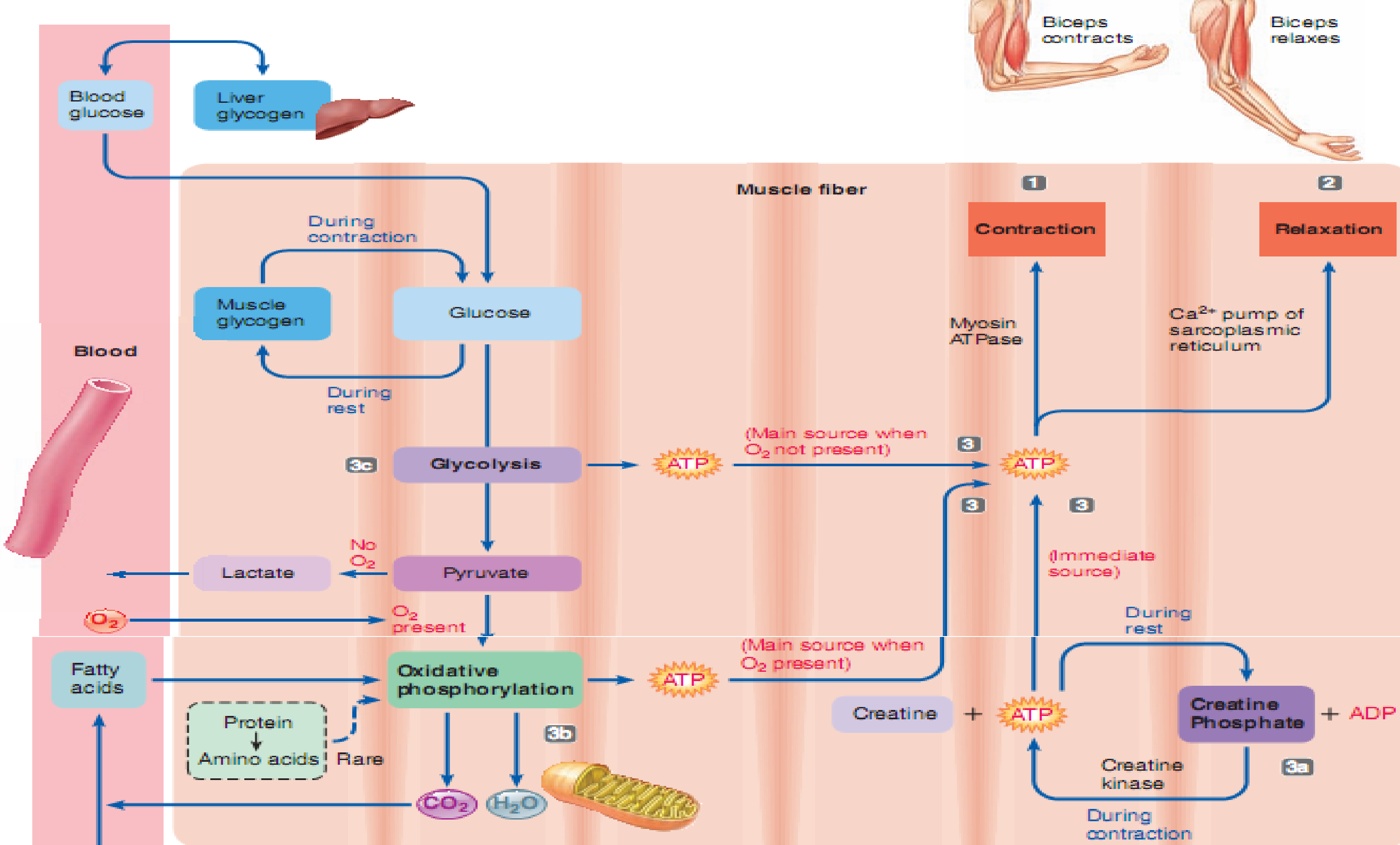
- Kontraksi dipicu oleh release Ca^{2+} dari saccus lateralis ke sitosol, Relaksasi terjadi ketika Ca^{2+} dikembalikan dari sitosol ke saccus lateralis ketika aktivitas listrik (Aksi potensial) berhenti.
- Retikulum sarkoplasma memiliki suatu carier/pembawa yang memerlukan energi, yaitu *Sarcoplasmic/endoplasmic reticulum Ca^{2+} ATPase* ***(SERCA) pump***, yang secara aktif mentransport Ca^{2+} dari sitosol dan mengkonsentrasikannya kembali ke saccus lateralis
- Ketika aksi potensial lokal tidak ada lagi dalam tubulus T (yang memicu release Ca^{2+}) → aktivitas SERCA pump mengembalikan Ca^{2+} yang di-*release* ke saccus lateralis.
- Hilangnya Ca^{2+} di sitosil → komplek **troponin-tropomyosin** bergeser kembali ke posisi **blocking**→ sehingga actin dan myosin tidak bisa berikatan lagi pada *cross bridges*. Filamen tipis lepas dari cross-bridge dan kembali secara pasif ke posisi istirahat.

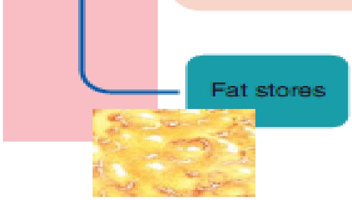
- Satu aksi potensial otot rangka berlangsung hanya 1 - 2 msec.
- Onset kontraksi terjadi setelah aksi potensial. Antara keseluruhan *excitation-contraction coupling* dengan *cross-bridge activity* memiliki jeda waktu.
- Jeda waktu antara stimulasi dengan onset kontraksi ini disebut ***latent period.***
- Waktu dari onset kontraksi sampai *peak tension* bervariasi dari 15 - 50 msec, tergantung jenis serabut otot.
- Respon kontraksi tidak berakhir sampai saccus lateralis mengambil semua Ca^{2+} yang direlease sebagai respon thd aksi potensial. Reuptake Ca^{2+} ini memerlukan waktu.
- Karena Ca^{2+} dipompa kembali ke saccus lateralis, cytosolic Ca^{2+} menjadi menurun.

Siklus kontraksi otot

- Fase laten
- Fase kontraksi
- Fase relaksasi

- Masa refrakter : fase dimana otot tidak menjawab rangsangan yang diberikan/datang, t.a masa refrakter absolut dan relatif
- Kontraksi tetani : terjadi bila masa refrakter relatif masih dapat menerima rangsang yang melampaui batas





1 During **muscle contraction**, ATP is split by myosin ATPase to power cross-bridge stroking. Also, a fresh ATP must bind to myosin to let the cross bridge detach from actin at the end of a power stroke before another cycle can begin.

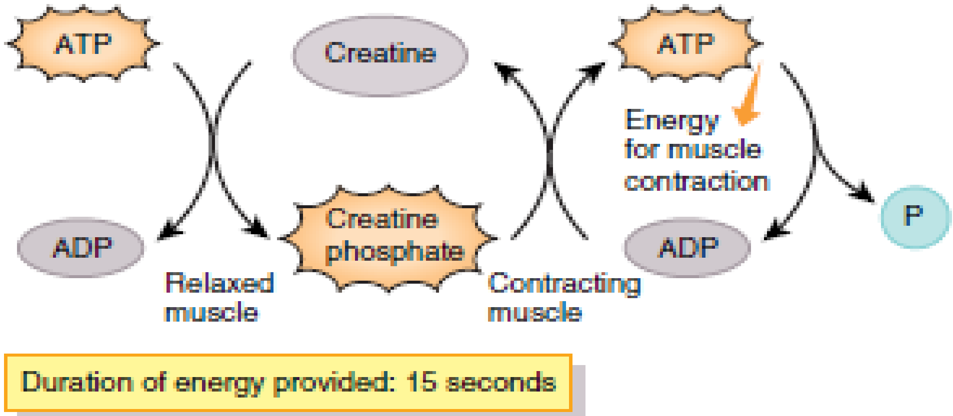
2 During **relaxation**, ATP is needed to run the Ca^{2+} pump that transports Ca^{2+} back into the lateral sacs of the sarcoplasmic reticulum. ATP is also used by the Na^+–K^+ pump to return Na^+ and K^+ moved during contraction-inducing action potentials.

3 The **metabolic pathways that supply the ATP** needed to accomplish contraction and relaxation are

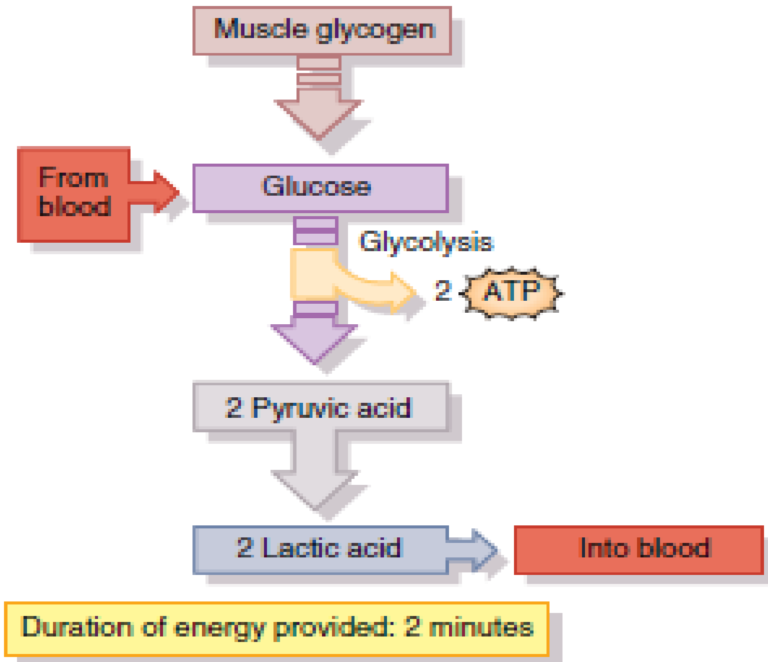
3a transfer of a high-energy phosphate from **creatine phosphate** to ADP (immediate source);

3b **oxidative phosphorylation** (the main source when O_2 is present), fueled by glucose derived from muscle glycogen stores or by glucose and fatty acids delivered by the blood; and

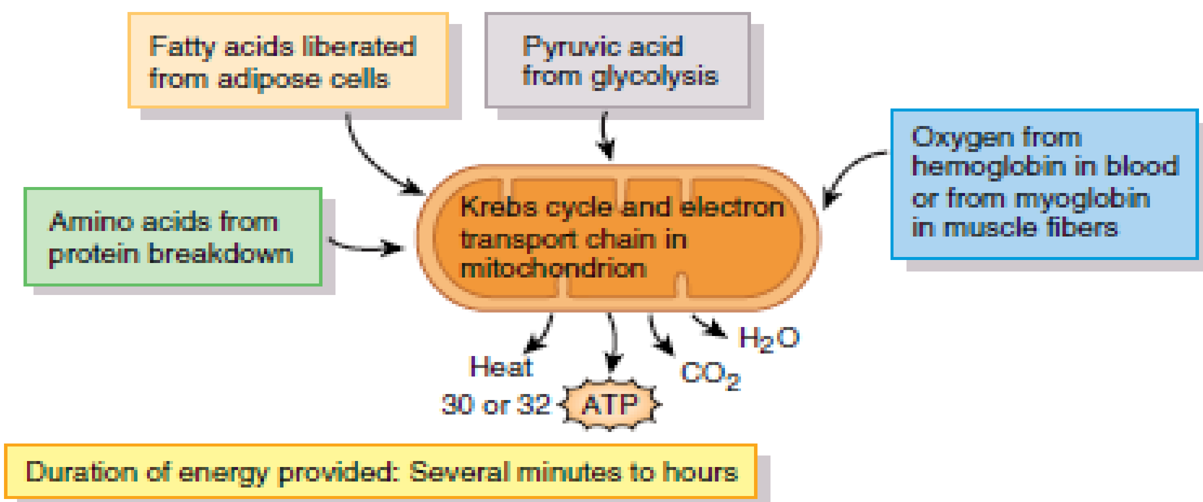
3c **glycolysis** (the main source when O_2 is not present). Pyruvate, the end product of glycolysis, is converted to lactate when lack of O_2 prevents the pyruvate from being further processed by the oxidative phosphorylation pathway.



(a) ATP from creatine phosphate



(b) ATP from anaerobic glycolysis



(c) ATP from aerobic respiration

Fatigue

- Central : fisiologis karena dehidrasi, osmolaritas ↑, pH rendah, Gula darah rendah
- Neuromuscular fatigue : motor neuron tidak mampu menghasilkan Neurotransmitter yang cukup
- Peripheral : (in or near muscle), otot tidak mampu menjawab rangsangan o.k akumulasi asam laktat, peningkatan fosfat inorganik (yang mengganggu hidrolisis ATP), kekurangan cadangan glikogen otot.

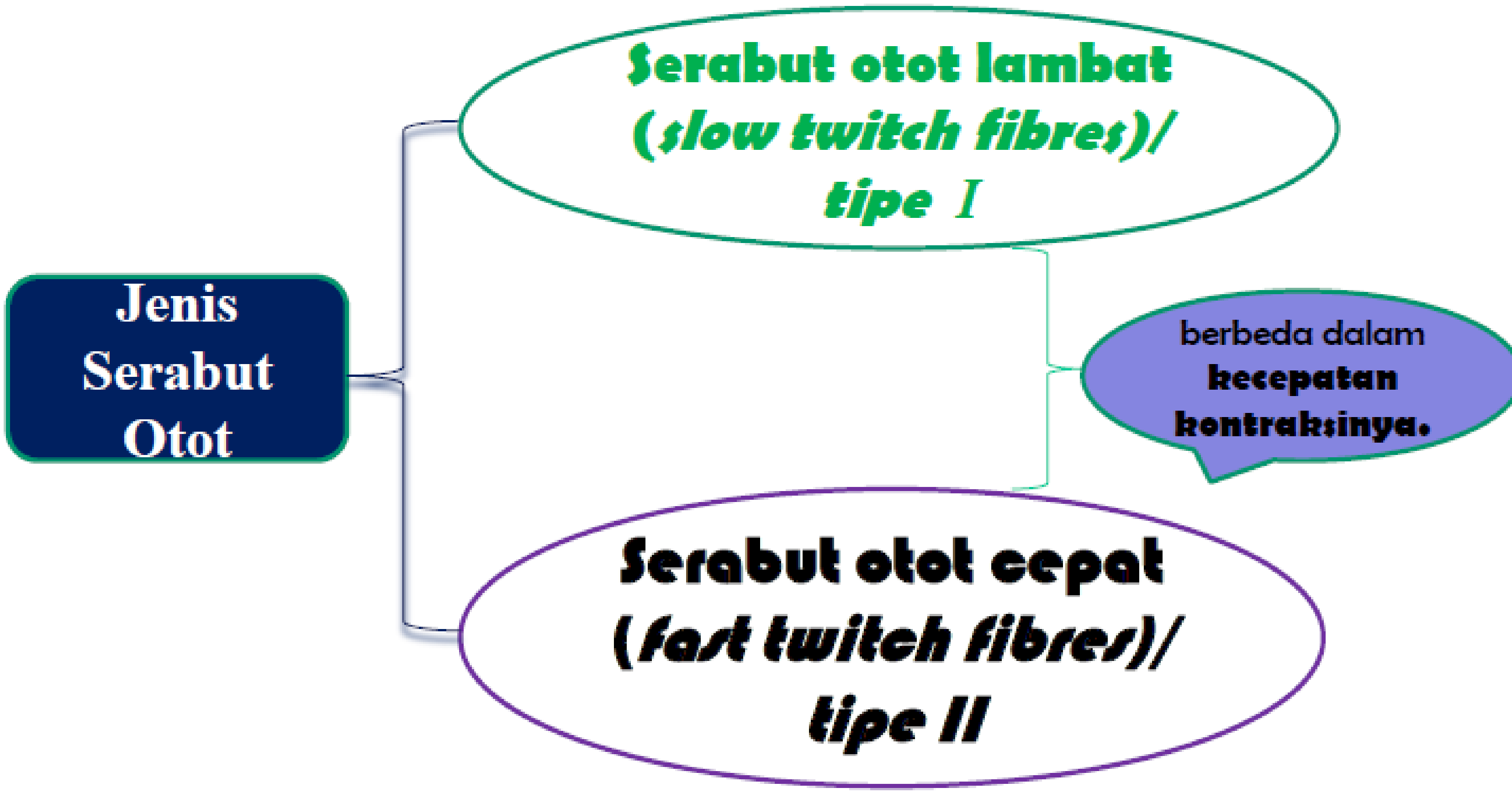
Jenis kontraksi otot

- Kekuatan kontraksi otot tgt : 1. Derajad penggiatan; 2. Panjang otot; 3. Derajad pemendekan; 4. Jumlah serat paralel
- Kontraksi tetani (tertahan) : terjadi peristiwa kontraksi yang berulang-ulang tanpa ada fase relaksasi, akibat rangsangan yang cepat dan berulang ulang.

Jenis kontraksi otot

- Kontraksi isometrik (statis) : panjang otot tetap/tdk terjadi pengurangan panjang otot/ujung ujung saling terfiksasi – otot hanya ditegangkan
- Kontraksi isotonik/konsentris (dinamis): terjadi pemendekan otot/panjang otot berubah

- Kecepatan kontraksi otot berkaitan dengan **jenis serabut otot,** yaitu



- **tipe I atau serabut otot merah atau serabut otot lambat** →lebih kuat untuk bekerja secara **aerobik.**
- **tipe II atau serabut otot putih atau serabut otot cepat** →lebih kuat untuk bekerja secara **anaerobik.**

Serabut tipe II inilah yang banyak dibutuhkan untuk lari cepat (*sprint*)

Variasi jumlah tipe otot tersebut dalam tiap individu ditentukan oleh:

- faktor genetik
- Aktivitas otot

• otot-otot yang aktivitasnya mempertahankan kontraksi intensitas rendah dalam waktu lama tanpa mengalami kelelahan, misalnya: **otot-otot punggung→ dominan otot tipe lambat.**

• otot-otot yang banyak melakukan gerakan yang kuat dan cepat, misalnya: otot lengan → **dominan otot tipe cepat.** (Sherwood, 2011)

SIFAT	OTOT LAMBAT	OTOT CEPAT
Kecepatan aktivitas ATPase miosin	Rendah	Tinggi
Kadar mioglobin	Tinggi	Rendah
Kecepatan kontraksi	Lambat	Cepat
Cadangan lemak	Tinggi	Rendah
Kandungan glikogen	Rendah	Tinggi
Kepadatan mitokondria	Tinggi	Rendah
Enzim oksidasi	Tinggi	Rendah
Jumlah kapiler darah	Tinggi	Rendah
Enzim untuk glikolisis anaerob	Rendah	Tinggi
Daya tahan terhadap kelelahan	Tinggi	Rendah
Warna serat	merah	Putih
	Slow Oxidative fiber	Fast Glikolitic fiber
Contoh OR :	Require endurance, such as long-distance running.	periods of intense activity, such as weight lifting or sprinting

Persentase serabut otot cepat dan lambat pada m.quadriceps pada atlet. (Guyton & Hall, 2007)

	Serabut Otot Cepat	Serabut Otot Lambat
Pelari Maraton	18 %	82 %
Perenang	26 %	74 %
Pria rata-rata	55 %	45 %
Atlet angkat berat	55 %	45 %
Pelari cepat	63 %	37 %
Pelompat	63 %	37 %

THANK YOU