October 06, 2025

Master Degree in Bionics Engineering

Course of Principles of Bionics and Biorobotics Engineering

Lesson title:

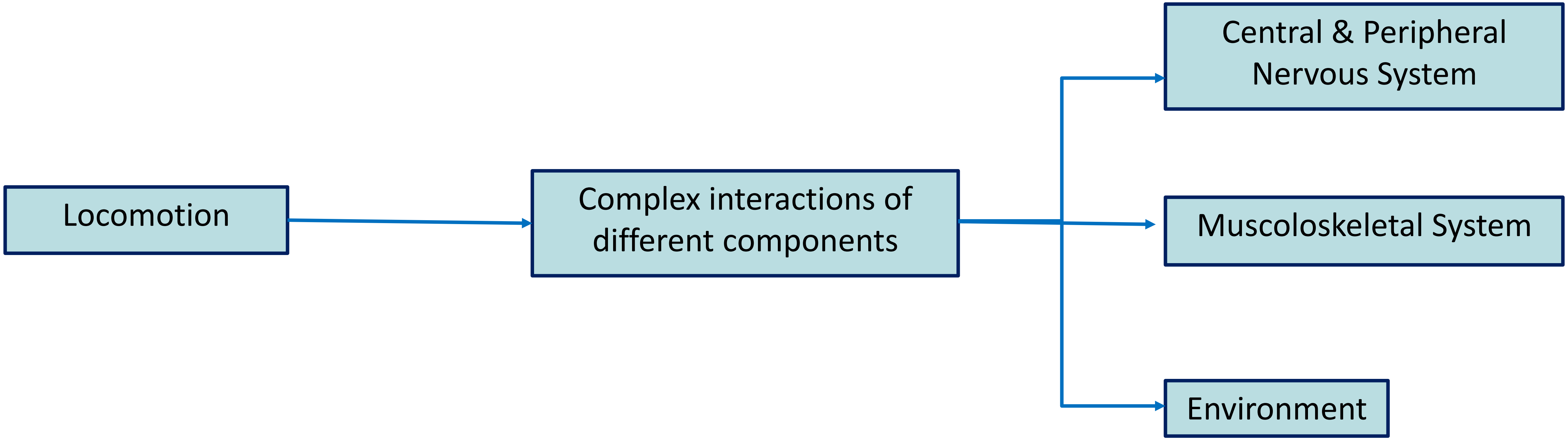
Locomotion and Movement

Prof. Donato Romano (donato.romano@santannapisa.it)

THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

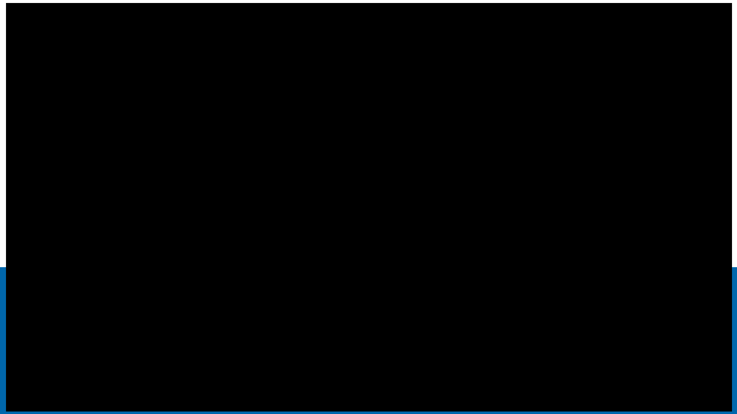
Biological Locomotion and Bioinspired Systems



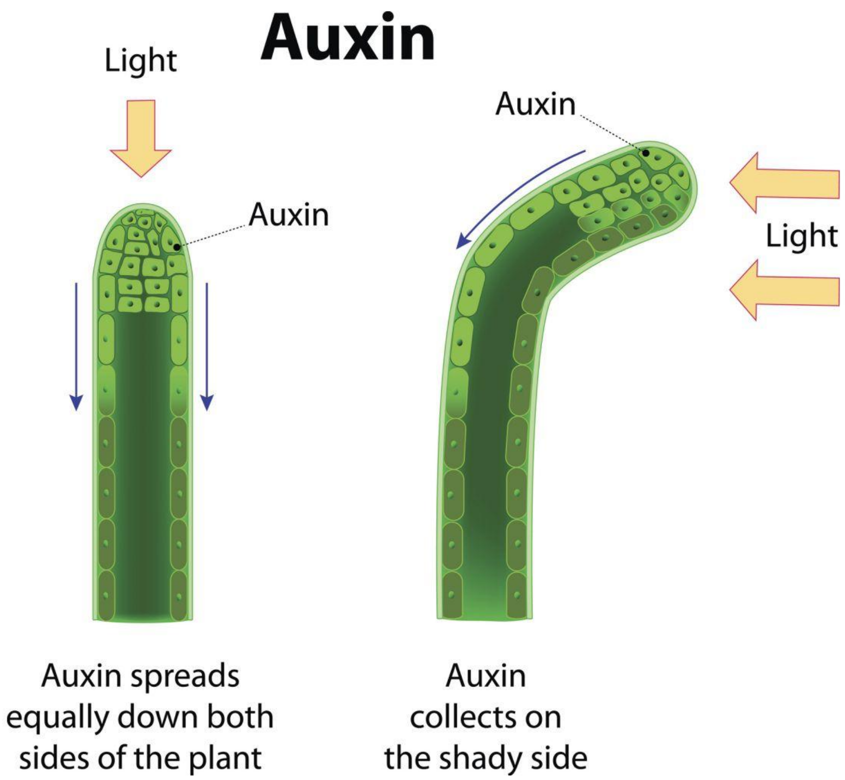
Movement or locomotion?

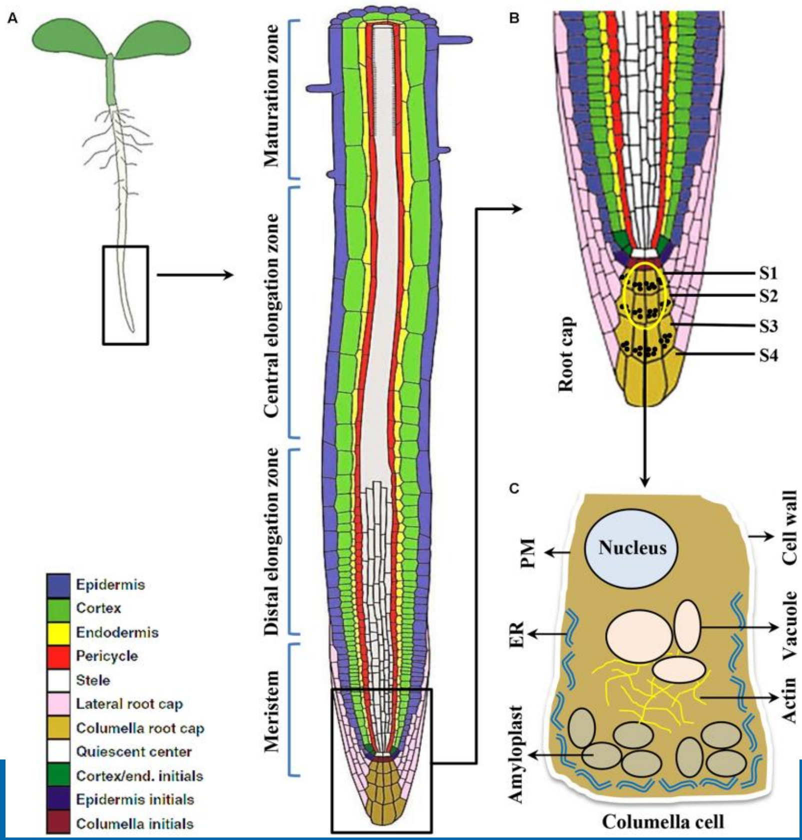
Movement: displacement of a body part or parts of an organism that does not produce a change in the position of the organisms.

Locomotion: the movement of a part of the body produce a change in the position and location of the organism.



Plant phototropism




A
B
C
Maturation zone
Central elongation zone
Distal elongation zone
Meristem
Root cap
S1
S2
S3
S4
Nucleus
PM
Cell wall
ER
Vacuole
Actin
Amyloplast
Columella cell
Epidermis
Cortex
Endodermis
Pericycle
Stele
Lateral root cap
Columella root cap
Quiescent center
Cortex/end. initials
Epidermis initials
Columella initials

Biological Locomotion and Bioinspired Systems

Why to locomote?

Locomotion is essential for survival. It is used to find:

- food
- mates
- suitable microhabitats
- to escape from predators

Natural selection has shaped different locomotion strategies adopting different mechanisms and structures, and that are differently energy demanding (i.e migratory animals, travelling for long distances evolved locomotion mechanisms that costs very little energy per unit distance. Animal species that move very fast to escape predators or to predate, have energetically costly locomotion strategies.

Locomotion

Active

Passive

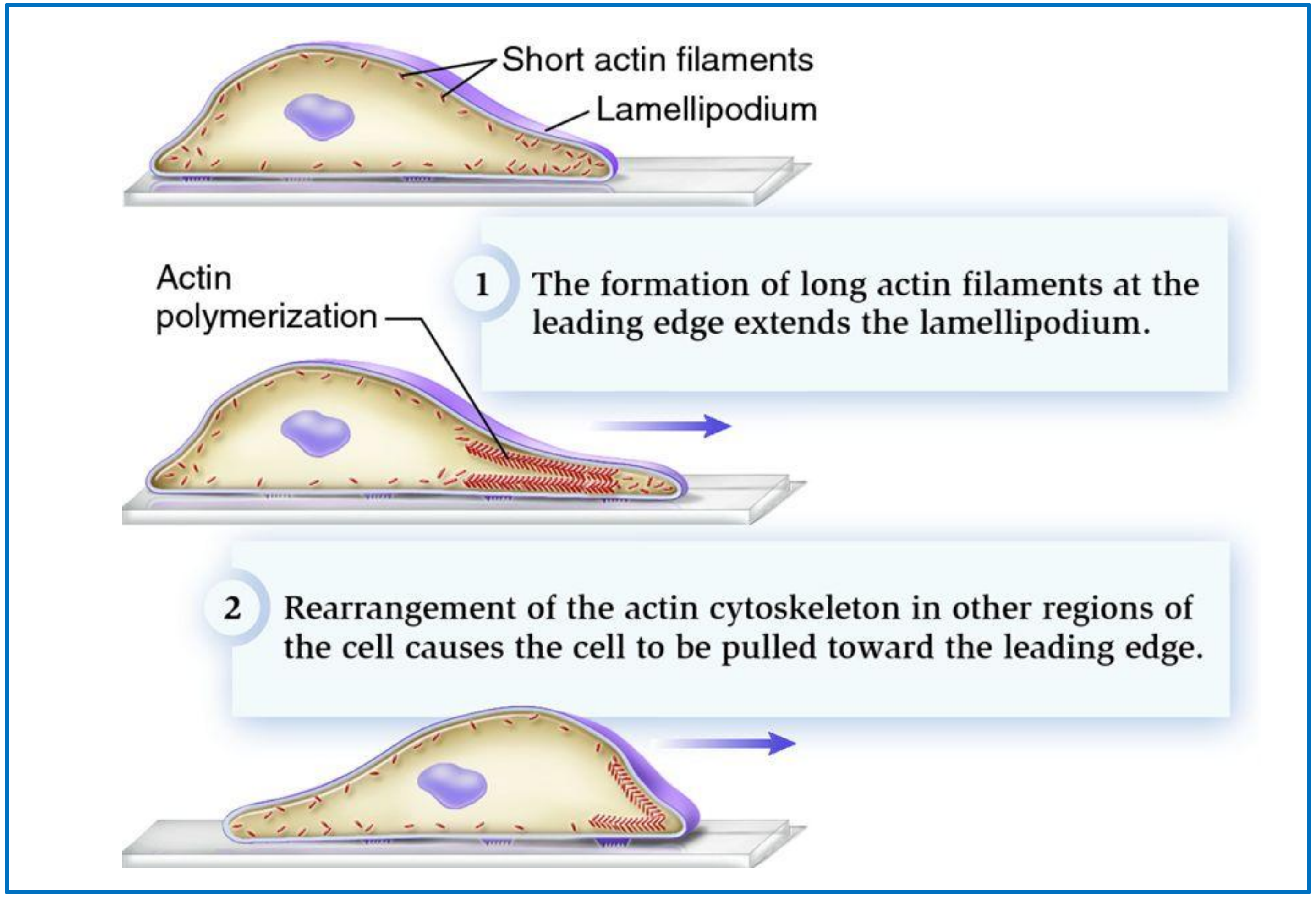
Type of locomotion depending on the environment

Ballooning: spiders can fly by using their silk filaments as paragliders

Rolling: The wheel spider and some other arthropods are able to roll along the surface at a high-speed using wind to propel themself

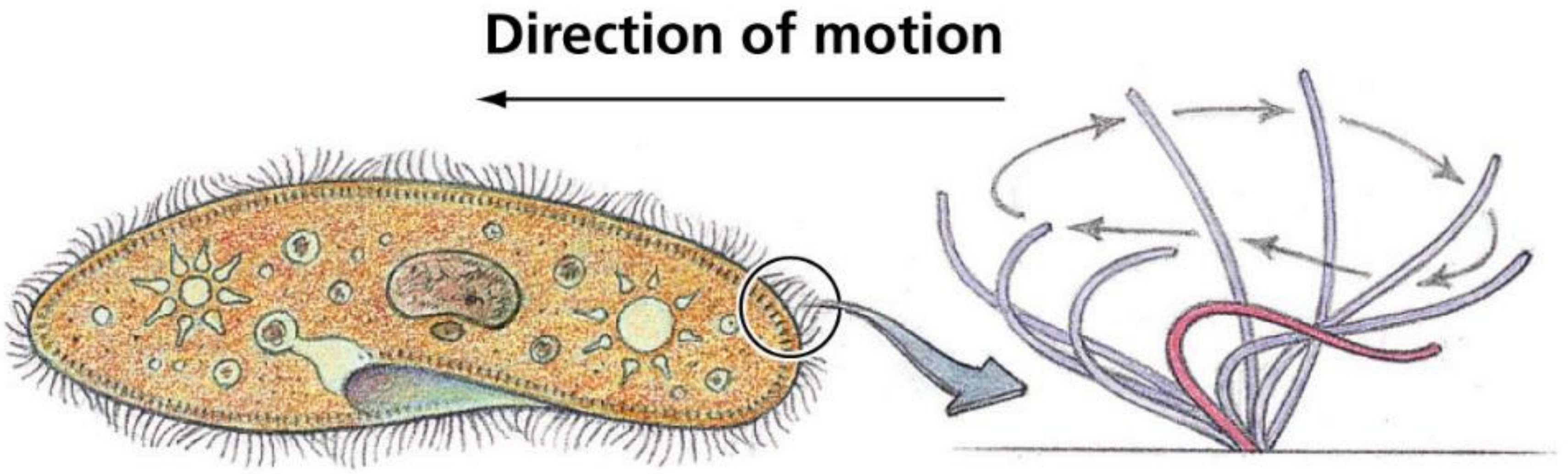
Phoresy: a non-permanent, commensalistic interaction in which one organism (a phoront or phoretic) attaches itself to another (the host) solely for the purpose of travel.

Amoeboid locomotion: appendages (pseudopodia) which moves with pressure by the cell's protoplasm.



Animals have evolved strategies to move through, or on, four types of environment: **terrestrial**, **fossorial**, **aquatic**, and **aerial**. In many cases animals can move through several types of medium (e.g. jump).

Ciliary locomotion: produced by hair-like extensions of the epithelium appendages called as cilia.



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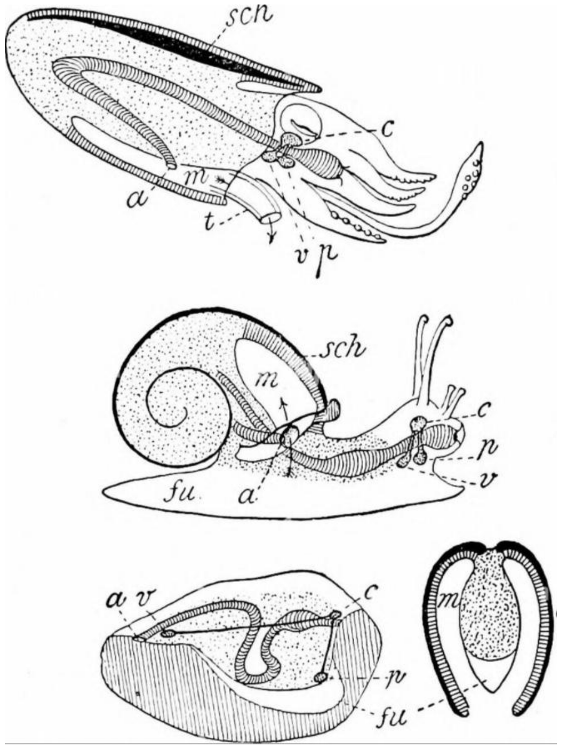
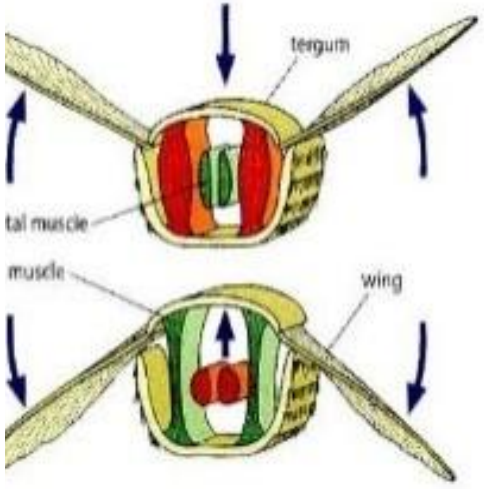
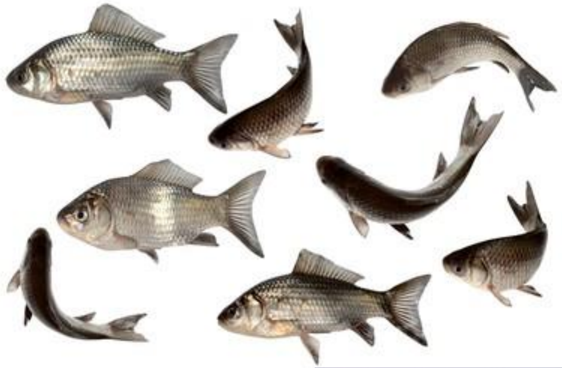
Muscular locomotion: produced by the musculoskeletal system achieving more complex behaviours thanks to the presence of muscles, and joints (not in all cases).







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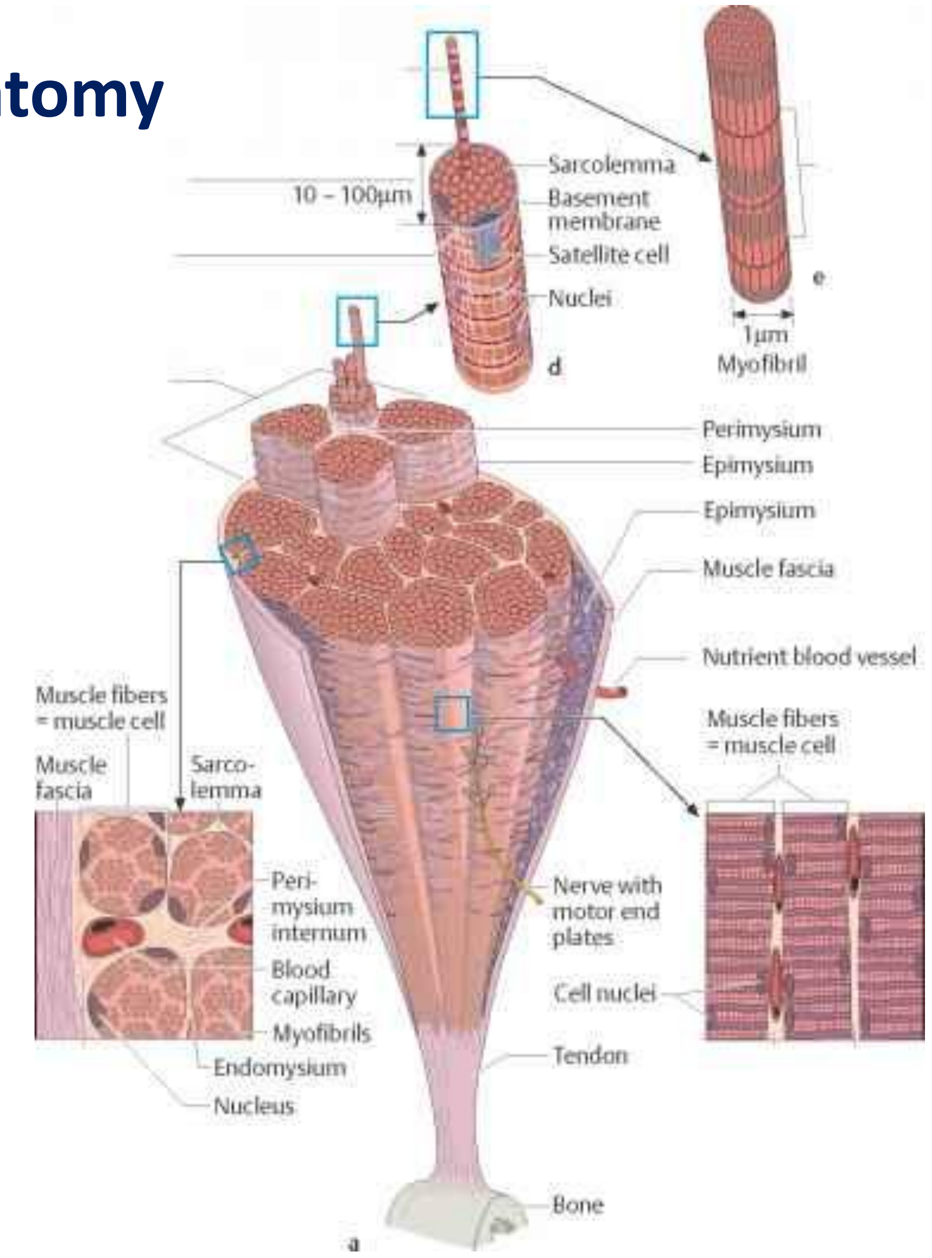
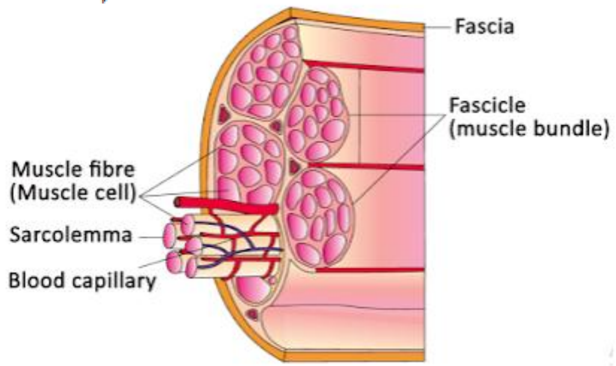
Structure of Muscle Anatomy

Myofibrils are the functional contractile unit of the muscle and are surrounded by sarcoplasm. Myofibrils make up the muscle fibre (muscle cell). Each individual **myofiber** or myotube is composed of hundreds of myofibrils and has a membrane (**sarcolemma**). The **endomysium**, is a wispy layer of areolar connective tissue that wrap each individual muscle fiber. Muscle fibers are grouped forming bundles (fascicles). These bundles are surrounded by **perimysium** (connective tissue that groups muscle fibers). Numerous fasciculi are surrounded by **epimysium**. These structures combine to form a muscle.



Structure of Muscles

Muscle fibres are lined by **plasma membrane (sarcolemma)** enclosing the **sarcoplasm.** Each muscle fibre contains **myofilaments (myofibrils).**



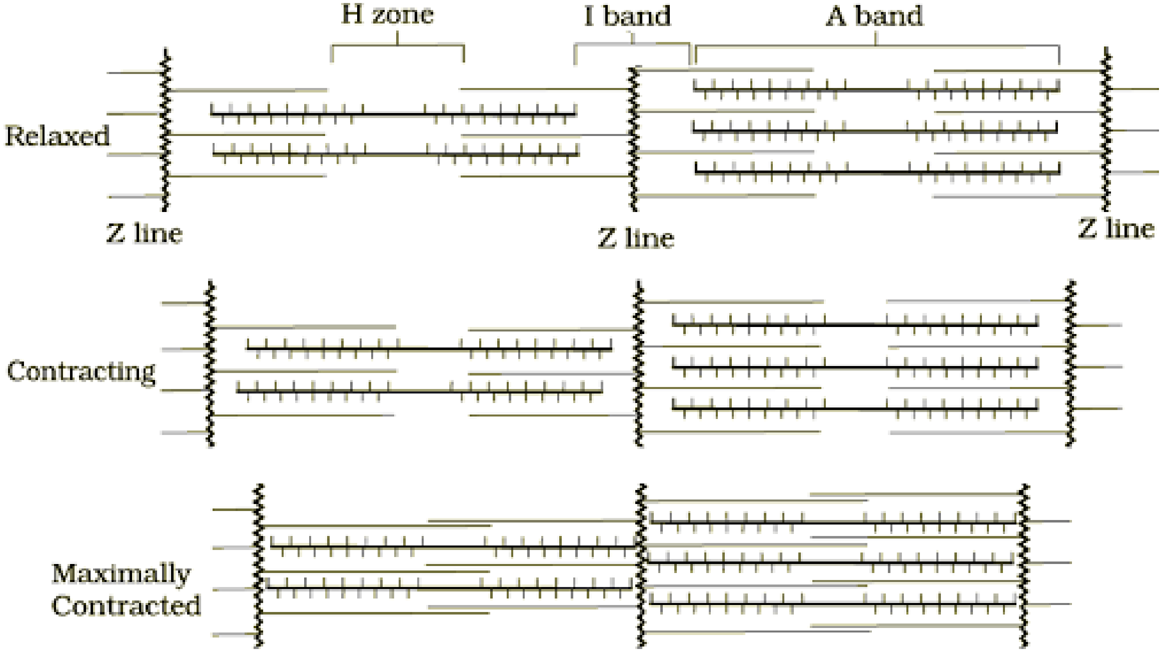
Each myofibril has alternate **dark (Anisotropic or A-band)** and **light striations (Isotropic or I-band).** This is due to the presence of 2 fibrous **contractile proteins**- thin **Actin filament** and thick **Myosin filament.**

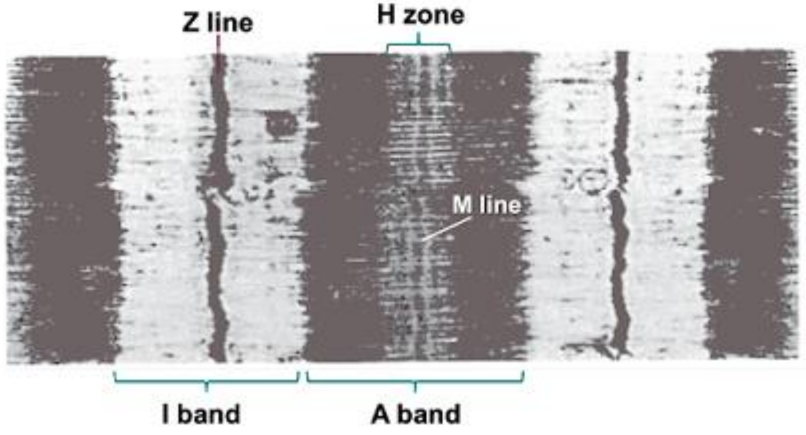
I-bands contain **actin.** A-bands contain actin and myosin. They are arranged parallel to each other.

A-band bears a lighter middle region **(H band)** formed of **only myosin.** A thin dark line **(M-line)** runs through the centre of H-zone.

I-band is bisected by a dense dark band called **Z-line**(alpha-actinin homodimers).

Region between two Z-lines is called **sarcomere**. They are the **functional units of muscle contraction.**

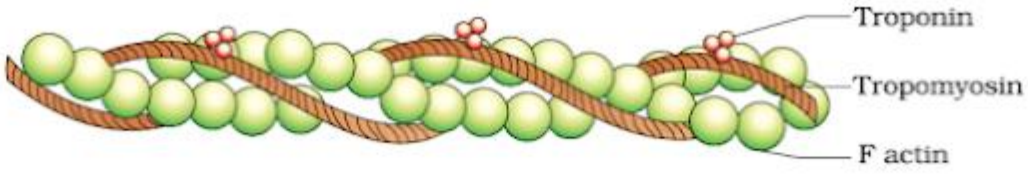




Mechanism of muscle contraction

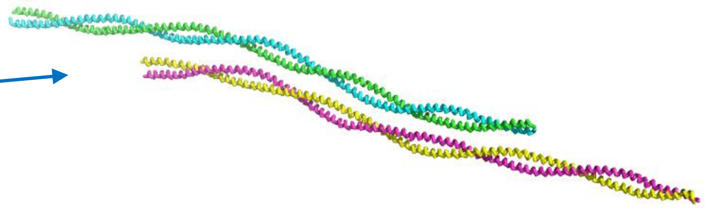
An actin filament is made of 2 **filamentous (F) actins** which form double helix.

F-actin is a polymer of monomeric **Globular (G) actins.**

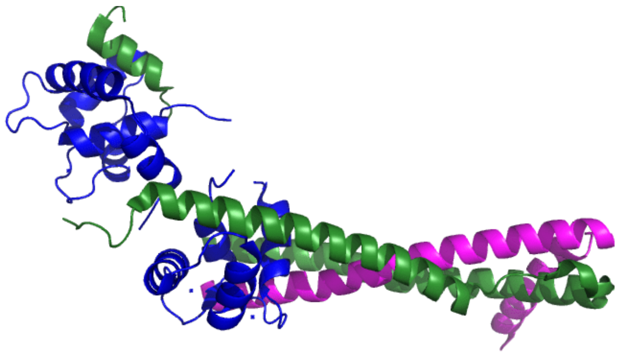


Actin contains 2 other proteins **(tropomyosin & troponin).**

Two filaments of tropomyosin run along the grooves of the F-actin double helix.

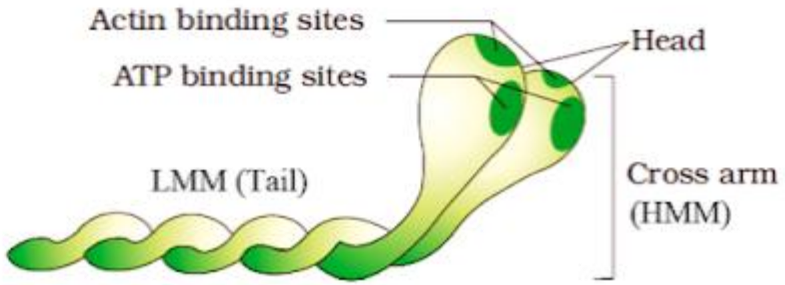


Troponin has **3 subunits**. It is seen at regular intervals on tropomyosin.



In the resting state, a subunit of troponin masks the binding sites for myosin on the actin filaments.

Each myosin filament is a polymer of many monomeric proteins called **Meromyosins.**



A meromyosin has 2 parts:

- **Heavy meromyosin or HMM or cross arm** (globular head + short arm): It projects outwards.
- **Light meromyosin or LMM (tail).**

The globular **head** is an active ***ATPase enzyme*** and has binding sites for ATP and active sites for actin.

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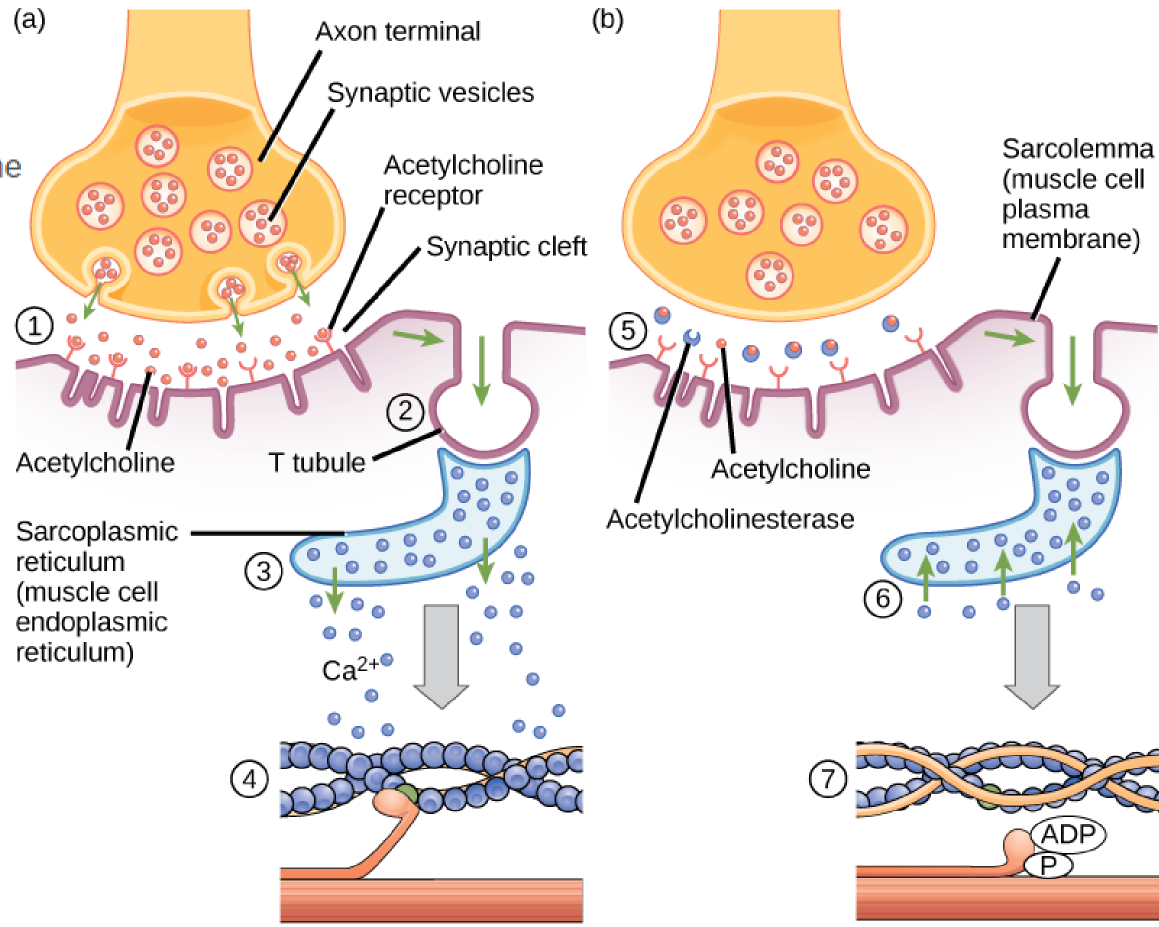
- An **impulse** from the CNS reaches the **neuromuscular junction (Motor-end plate)** via motor neuron.

Neuromuscular junction is the synapse between a motor neuron and the sarcolemma of the muscle fibre.
A motor neuron + muscle fibres = a motor unit.

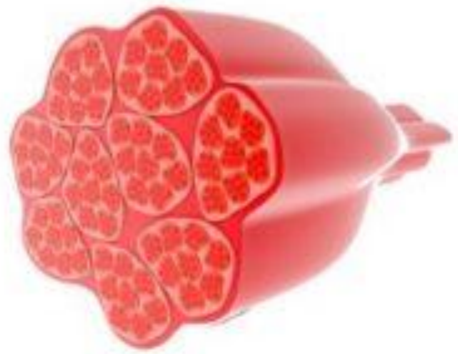
- Synaptic vesicles release a neurotransmitter **Acetylcholine.** It generates an **action potential** in the sarcolemma that spreads through the muscle fibre. It causes the release of **Ca2+** ions from **sarcoplasmic cisternae** into **sarcoplasm.**
- **Ca** binds with a subunit of **troponin** on actin filaments and unmask the active sites for myosin.
- Using energy from **ATP hydrolysis, myosin head** binds to active sites on the actin to form **cross bridge.** This pulls actin filaments on both sides towards the centre of **A-band.** Actin filaments partially overlap so that H-zone disappears.
- The **Z- line** attached to actins is also pulled inwards. It causes a **shortening (contraction) of sarcomere.**
- I-bands get shortened, whereas A-bands retain the length.
- Myosin releases **ADP** and **Pi** and goes back to its relaxed state. A new ATP binds and the cross-bridge is broken.
- The ATP is again hydrolyzed by the myosin head and the above processes are repeated causing further sliding.
- When Ca2+ ions are pumped back to sarcoplasmic cisternae, actin filaments are again masked. As a result, Z-lines return to their original position. It results in **relaxation.**



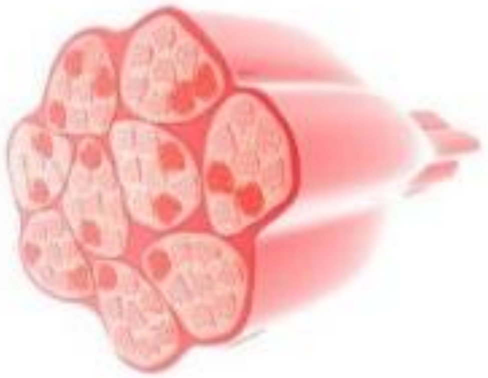
1. Acetylcholine released from the axon terminal binds to receptors on the sarcolemma.
2. An action potential is generated and travels down the T tubule.
3. Ca^{2+} is released from the sarcoplasmic reticulum in response to the change in voltage.
4. Ca^{2+} binds troponin; Cross-bridges form between actin and myosin.
5. Acetylcholinesterase removes acetylcholine from the synaptic cleft.
6. Ca^{2+} is transported back into the sarcoplasmic reticulum.
7. Tropomyosin binds active sites on actin causing the cross-bridge to detach.

Red and white muscles fibers

Red (Aerobic) muscles	White muscle
Red coloured due to myoglobin	White coloured due to lesser myoglobin
More mitochondria	Less mitochondria
Aerobic metabolism	Anaerobic metabolism
Slow & sustained contraction	Fast contraction for short period

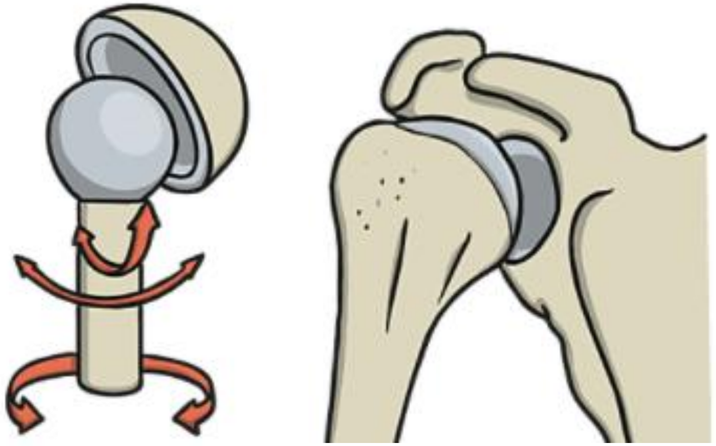


RED MUSCLE



WHITE MUSCLE

Joints



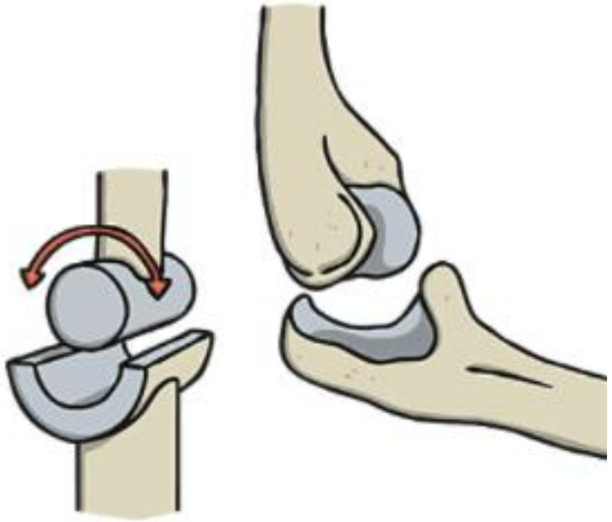
Joints are points of contact between bones, or between bones and cartilages. 3 types:

1. **Fibrous (immovable) joints:** E.g. sutures b/w skull bones.
2. **Cartilaginous joints (Slightly movable joints):** Bones are joined together with the help of cartilages. E.g. Joints between the adjacent vertebrae.
3. **Synovial (movable) joints:** They have a fluid filled synovial cavity between articulating surfaces of 2 bones.

ball and socket joint (also called enarthrosis, spheroidal joint) is a kind of joint that has one ball-shaped surface of a bone fitting into the cup-like depression of another bone. It allows the 360° movement.

Synovial Joints

Joint	Examples
Ball & socket	Shoulder joint & hip joints.
Hinge joint	Knee joint, elbow joint, phalanges joints
Pivot joint	Joints b/w atlas & axis.
Gliding joint	Joints b/w carpals
Saddle joint	Joints b/w carpal & metacarpal of thumb



Hinge joints allow for movement in a single translational plane only. This one degree of freedom is typically in the flexion / extension direction in the human body. Generally, it allows the 90° movement.

Joints

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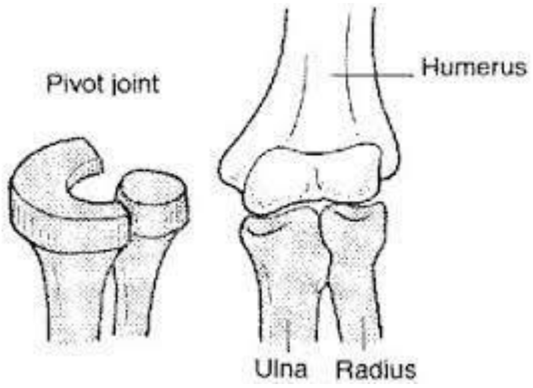
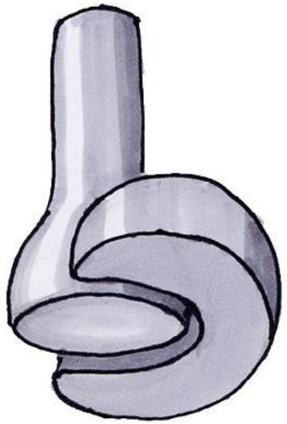
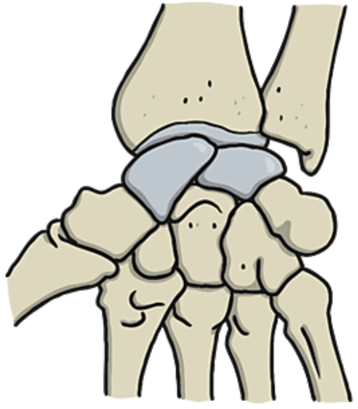


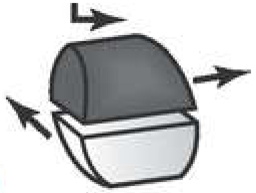


A **pivot joint** (trochoid joint, rotary joint or lateral ginglymus): its movement axis is parallel to the long axis of the proximal bone, which typically has a convex articular surface.

Synovial Joints

Joint	Examples
Ball & socket	Shoulder joint & hip joints.
Hinge joint	Knee joint, elbow joint, phalanges joints
Pivot joint	Joints b/w atlas & axis.
Gliding joint	Joints b/w carpals
Saddle joint	Joints b/w carpal & metacarpal of thumb





Gliding joint a synovial joint in which the opposed surfaces are flat or only slightly curved, so that the bones slide against each other in a simple and limited way. They can go up and down, left and right, and even diagonally. A gliding joint is also called a plane joint or planar joint. Examples: the intervertebral joints, and many of the small bones of the wrist and ankle.

Joints

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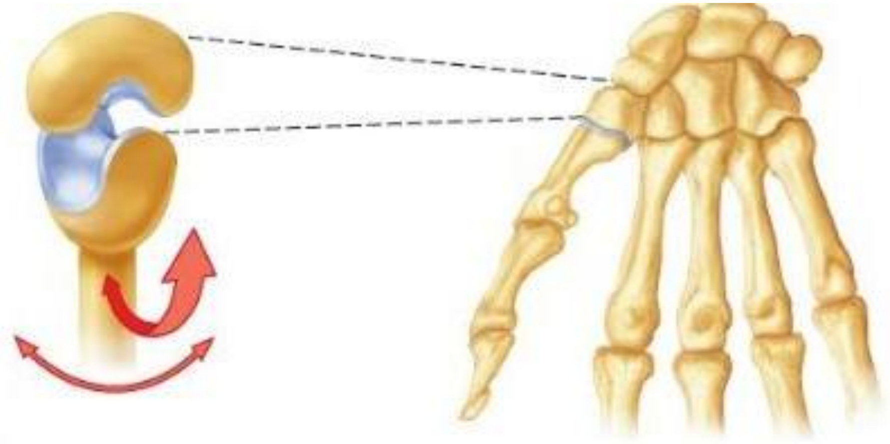


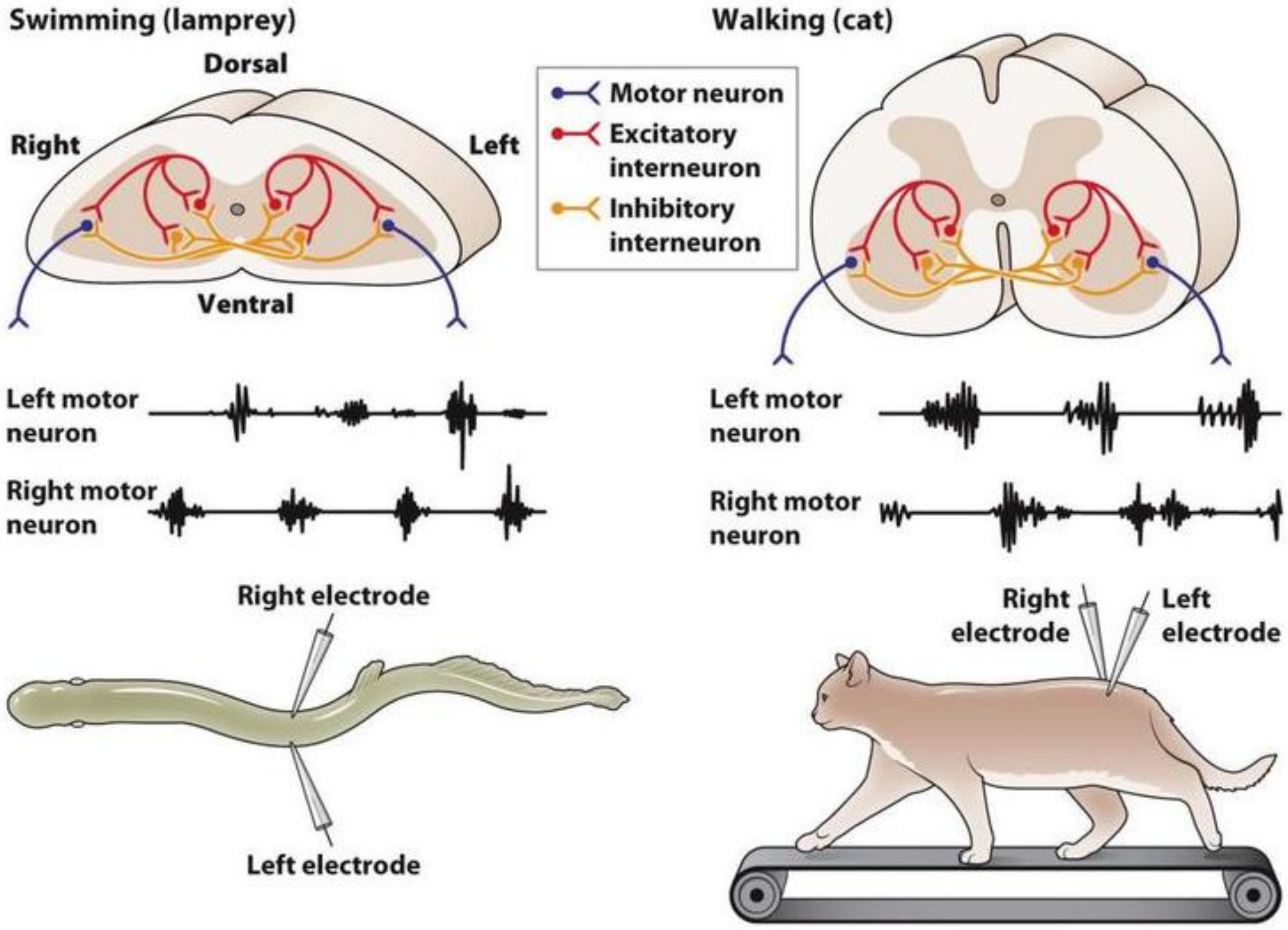
Saddle joint (carpometacarpal joint of thumb)

In a **saddle joint**, one bone surface is concave while another is convex. This creates significant stability. The movements of saddle joints include flexion, extension, adduction, abduction, and circumduction. However, axial rotation is not allowed. Saddle joints are biaxial, allowing movement in the sagittal and frontal planes.

How locomotion is controlled

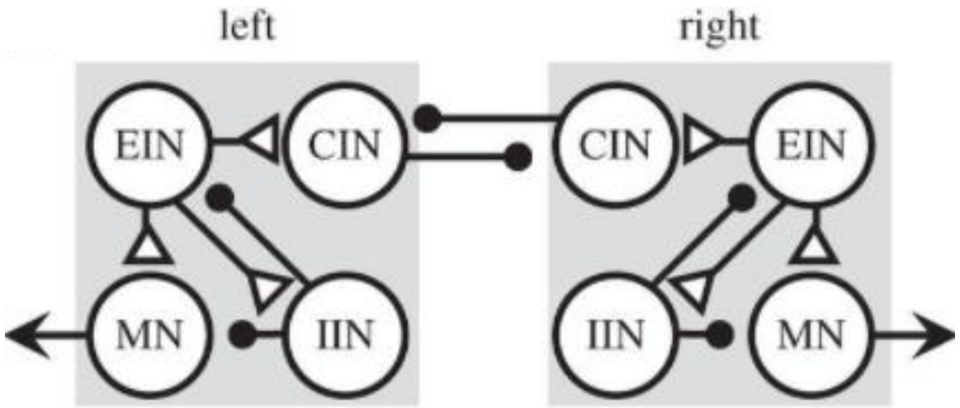
Two neural circuits (interacting each other):

- Central pattern generators (CPGs) producing rhythmic motor commands (even in the absence of feedback).
- Reflex circuits driven by sensory feedback.



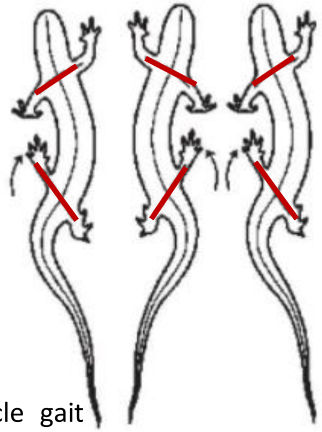
How locomotion is controlled

Central pattern generators (CPGs) produce the patterns of neural activity that underlie rhythmic motor behaviours such as walking, swimming and feeding, and more.
CPG preparations can continue to produce rhythmic neural activity even when isolated from the animal.
The basic organization of CPGs is the **half-centre oscillator**, in which two mutually inhibitory 'halves' alternate in activity.
These two neurons do not have rhythmogenic ability individually, but produce rhythmic outputs when reciprocally coupled.
Addition of limbs or fins requires more complex patterning than simple left–right alternation.



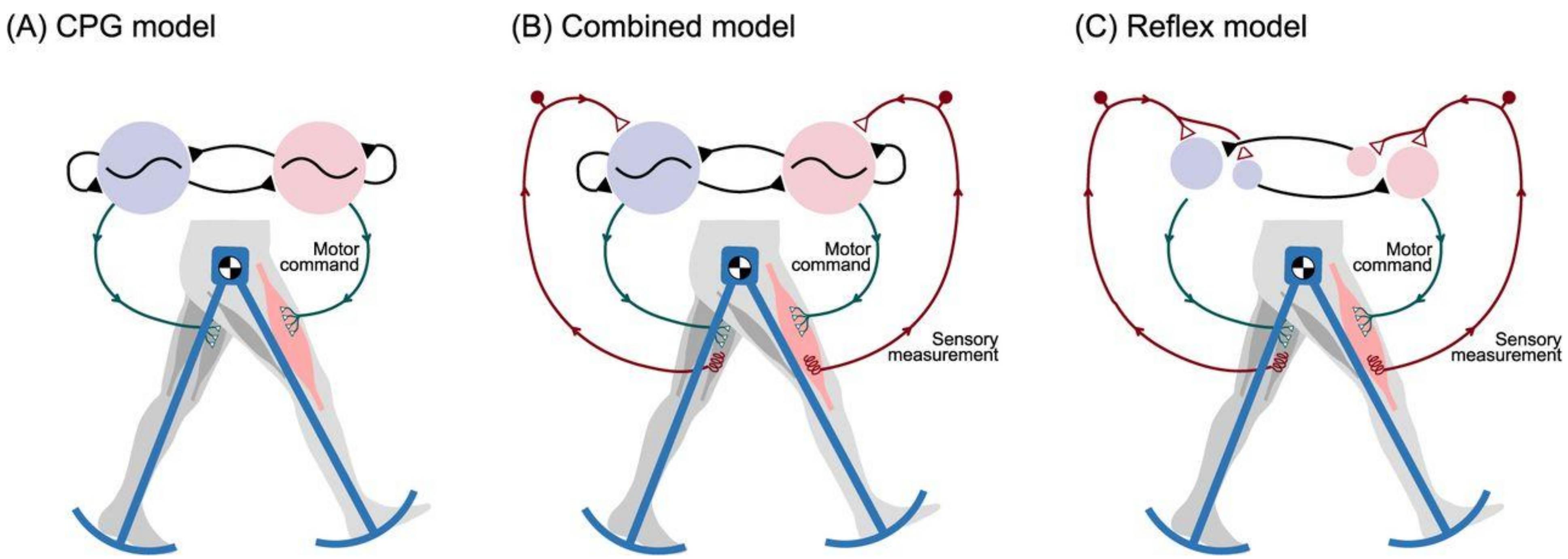
The left and right sides are mutually inhibitory through commissural interneurons (CIN) contributing to the coordination of muscle activity on both sides of the body.
Excitatory and inhibitory interneurons (EIN and IIN) participate in motor pattern generation. EIN synapses on motor neurons (MN) that cause muscle contraction.
Each neuron in the diagram represents large pools of heterogeneous neurons.
Triangles are excitatory synapses and circles are inhibitory.

Lamprey: the left and right sides of the body alternately flex.



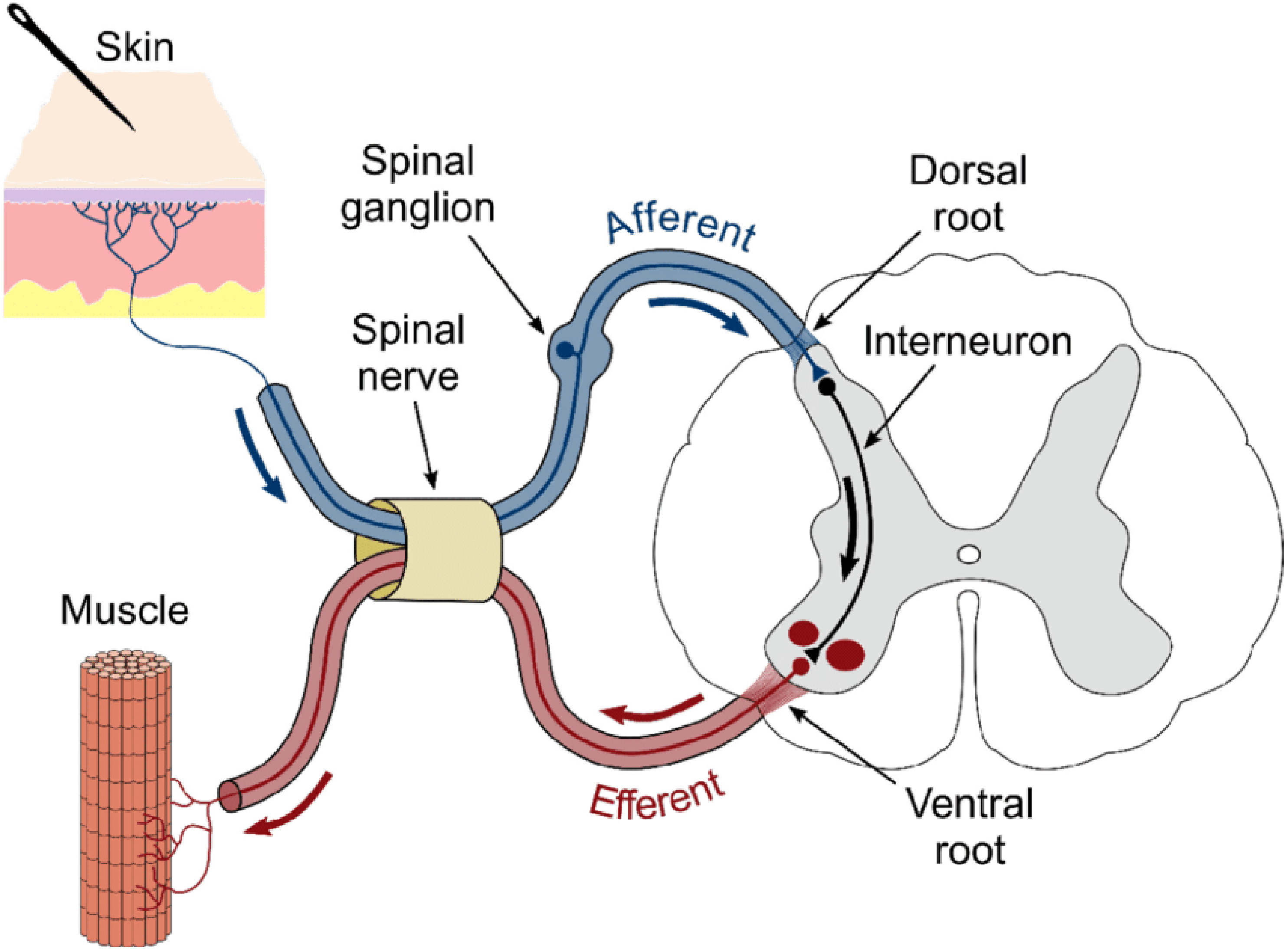
Salamander: an alternating axial muscle gait with left and right sides in alternation is used.

How locomotion is controlled



Three ways to control bipedal walking (and in general, locomotion). (A) The central pattern generator (CPG) comprises neural oscillators that can produce rhythmic motor commands. (B) The CPG can also incorporate sensory feedback, so that the periphery can influence the motor rhythm. (C) Sensory feedback can also control and stabilize locomotion through reflexes, without need for neural oscillators.
The extreme of (A) CPG control without feedback is referred to here as pure feedforward control.
The opposite extreme (C) with no oscillators as pure feedback control. Animal locomotion is thought to incorporate (B) a combination of feedforward and feedback.

Reflex circuits

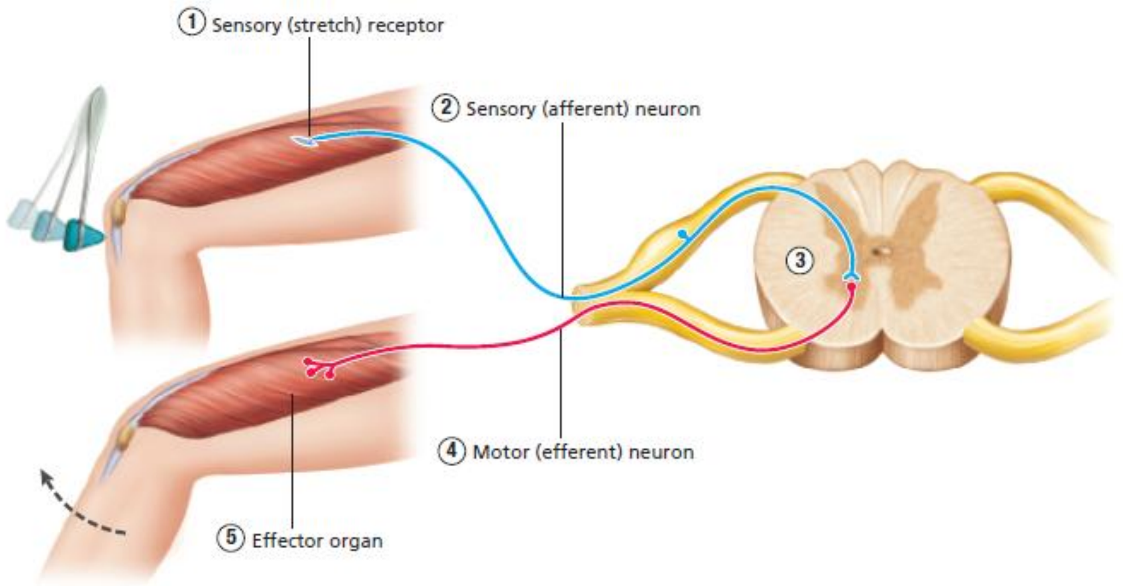


Reflex circuits are integrated within the central nervous system; nonetheless, it is also possible that the sensor neuron alone triggers a reflex.

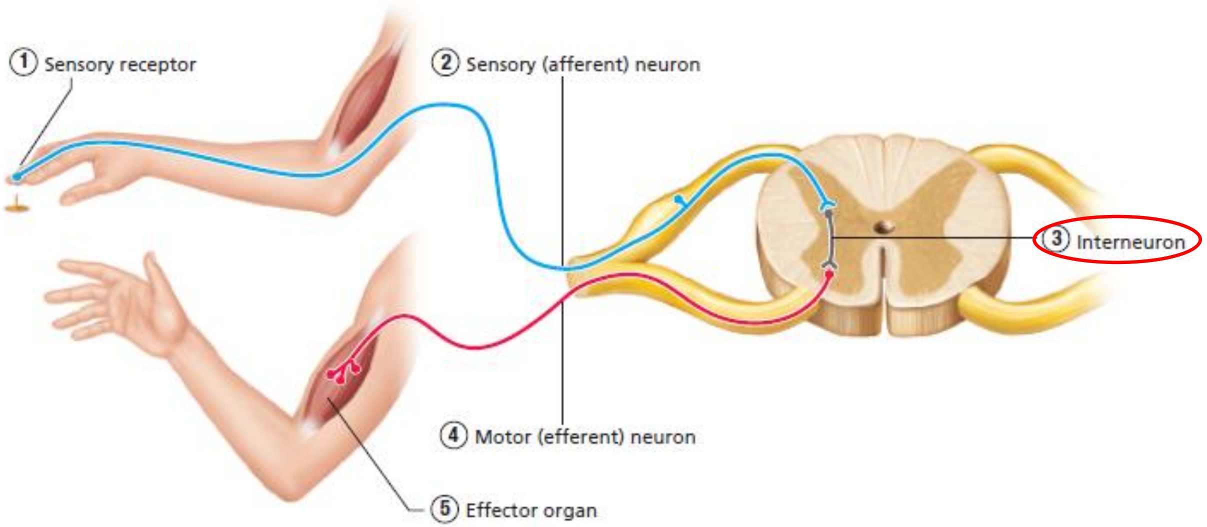
We have a **Monosynaptic** reflex when there are only two neurons (the sensory neuron and the motor neuron) with one synapse between them (analogous to a unipolar neuron at the individual cell level). Monosynaptic reflex arcs play an important role when very simple, rapid, responses are required.

Many reflex arcs are **Polysynapic** (there is more than one synapse and neuron providing input, analogous to multipolar neurons at the individual cell level). Having inputs from multiple sensory and integrating neurons allows for more nuanced responses to changing conditions. The neurons providing input to the motor neuron in the arc generally are **Interneurons** (e.g. neurons that reside and terminate inside the central nervous system). Their inputs may come either from sensory neurons or other interneurons and their outputs may go either to motor neurons or other interneurons.

Within the traditional polysynaptic class there is the **disynaptic reflex** (there is only one interneuron between the sensory and motor neurons creating two synapses).



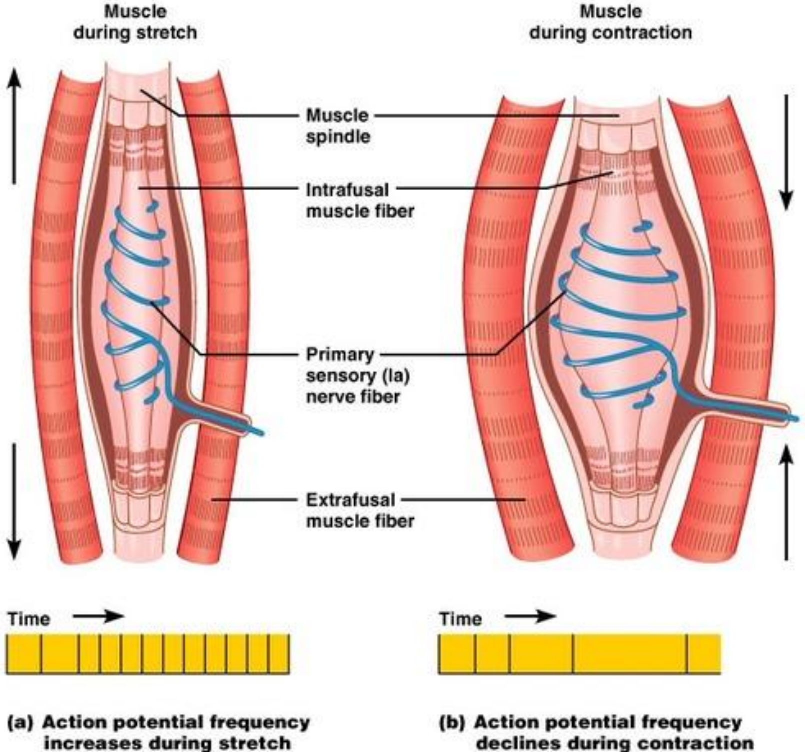
(a) Monosynaptic stretch reflex

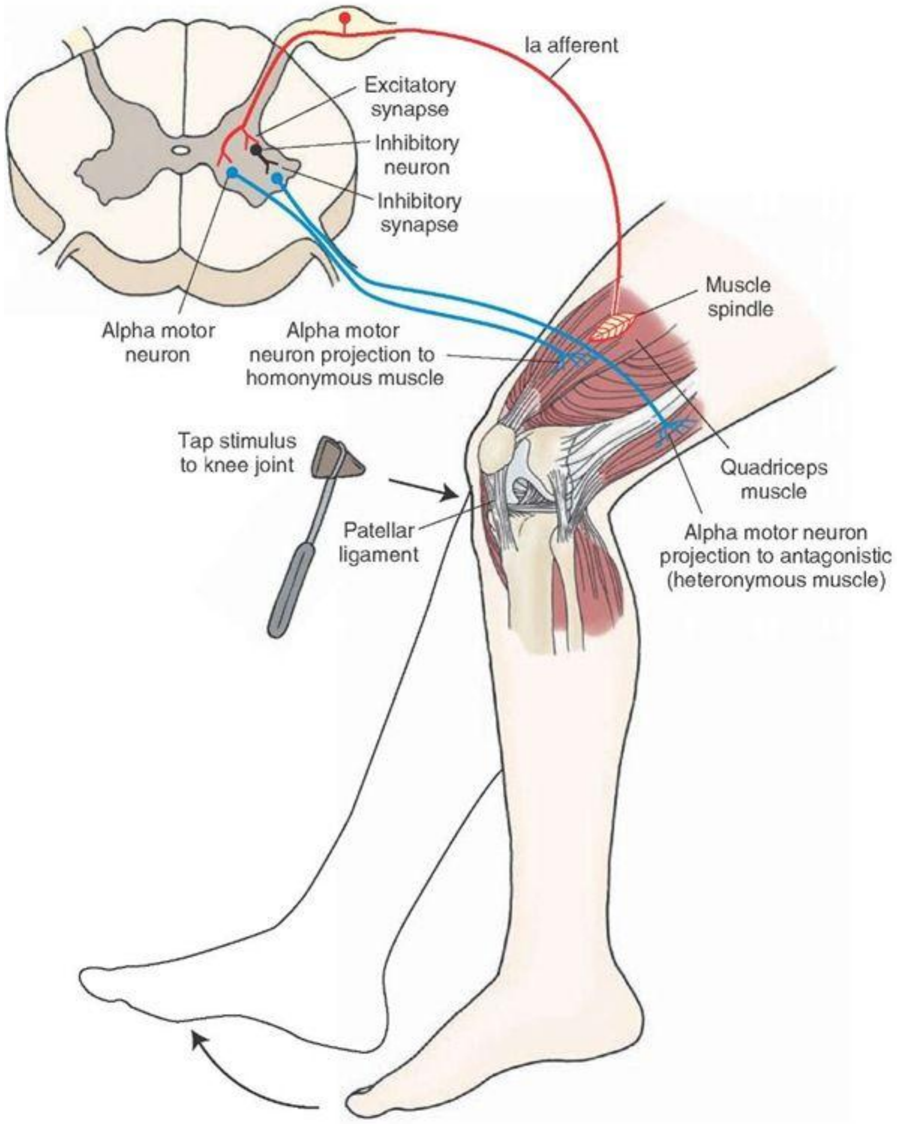


(b) Polysynaptic withdrawal reflex

Motor Reflex Patterns

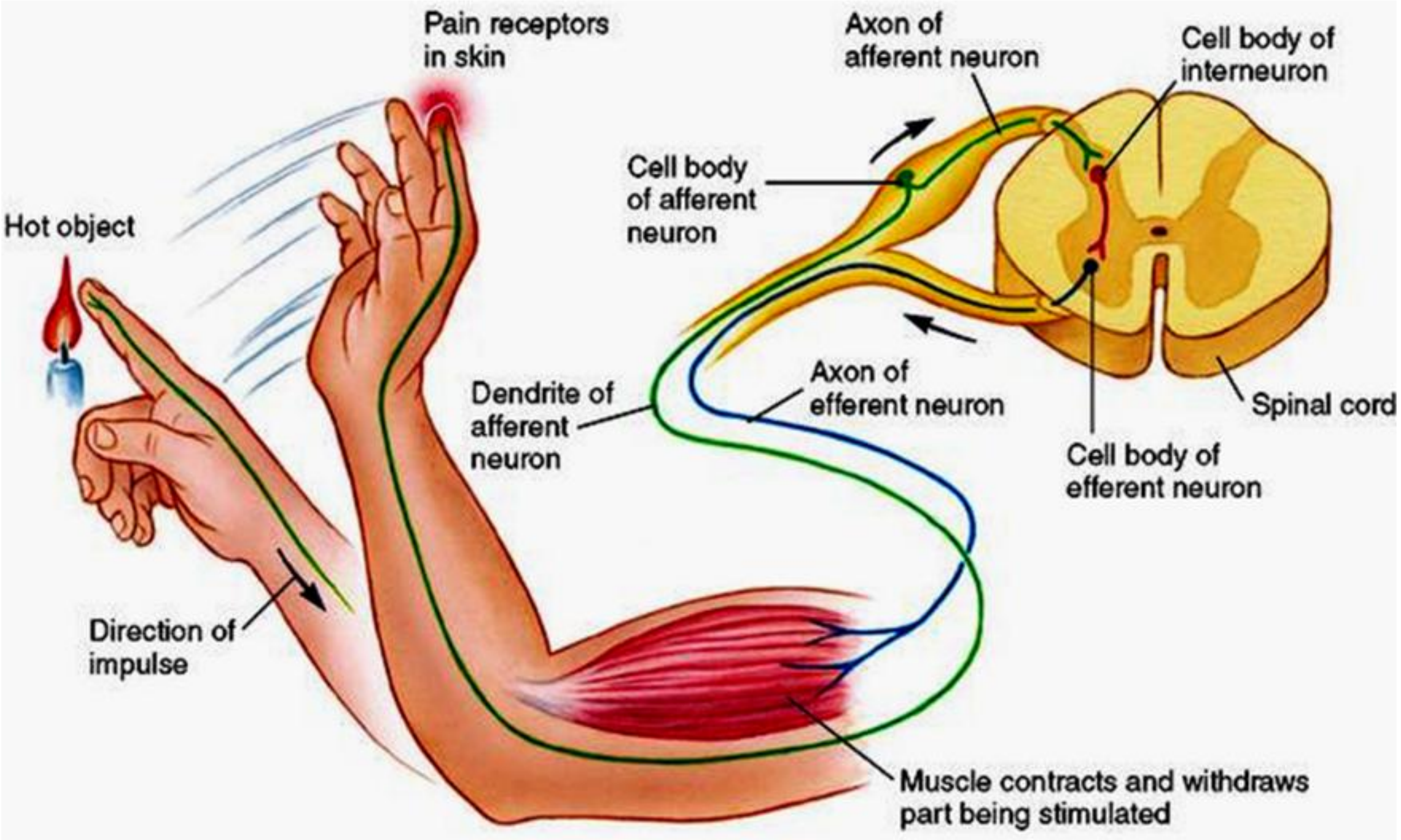
Stretch Reflex: In this reflex, when a skeletal muscle is stretched, a muscle spindle receptor is activated. The axon from this receptor structure will cause direct contraction of the muscle (a monosynaptic reflex). A collateral of the muscle spindle fiber will also inhibit the motor neuron of the antagonist muscles (a bisynaptic reflex). The reflex helps to maintain muscles at a constant length.





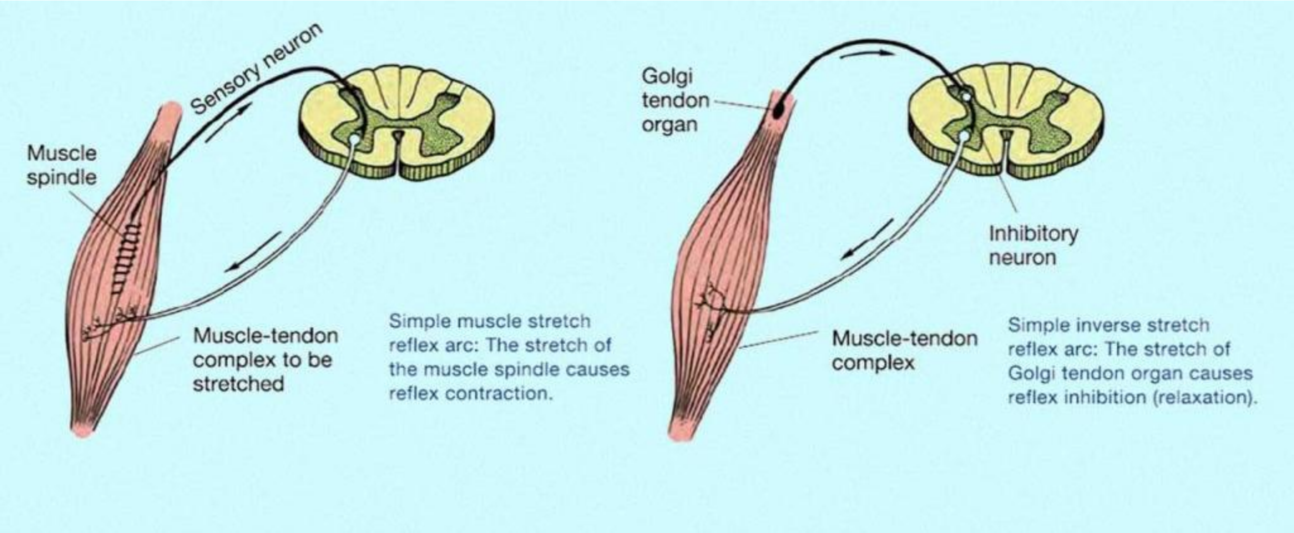
Motor Reflex Patterns

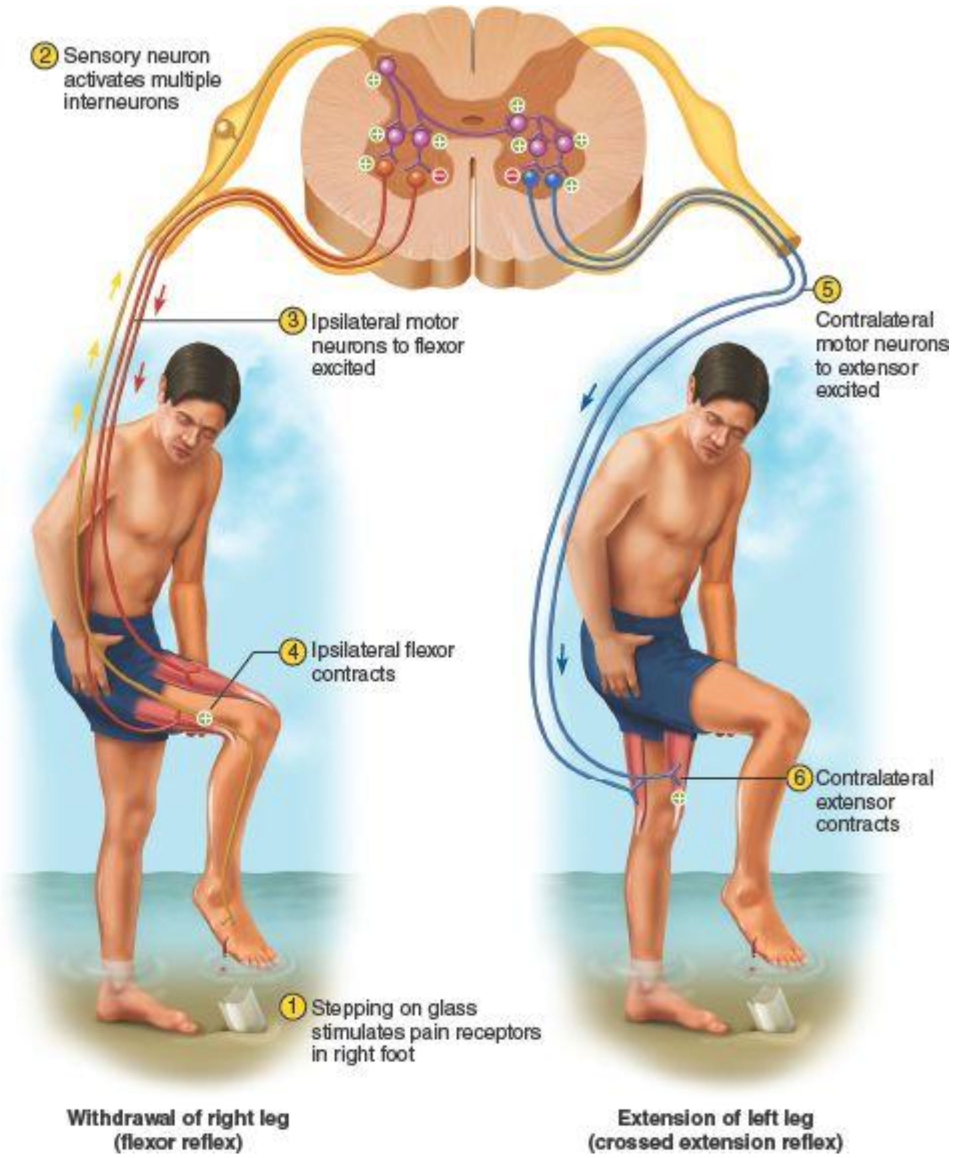
Withdrawal Reflex: As you withdraw your hand from a hot stove or other painful stimulus, you do not want to slow that reflex down. As the biceps brachii contracts, the antagonistic triceps brachii needs to relax.



Motor Reflex Patterns

Crossed-Extensor Reflex: is a withdrawal reflex. The flexors in the withdrawing limb contract and the extensors relax, while in the other limb, the opposite occurs. An example of this is when a person steps on a sharp object. The leg that is stepping on the sharp object flexes to pull away, while the other leg extends to support the weight of the whole body. To produce this reflex, branches of the afferent nerve fibers cross from the stimulated side of the body to the opposite side of the spinal cord.





Motor Reflex Patterns

Corneal Reflex: or the eye blink reflex is a specialized reflex to protect the surface of the eye. When the cornea is stimulated by a tactile stimulus, or even by bright light in a related reflex, blinking is initiated. This is an autonomic cranial, as opposed to spinal, reflex as the integration takes place in the brain via the cranial nerves.