BIE 3134 BIOMECHANICS

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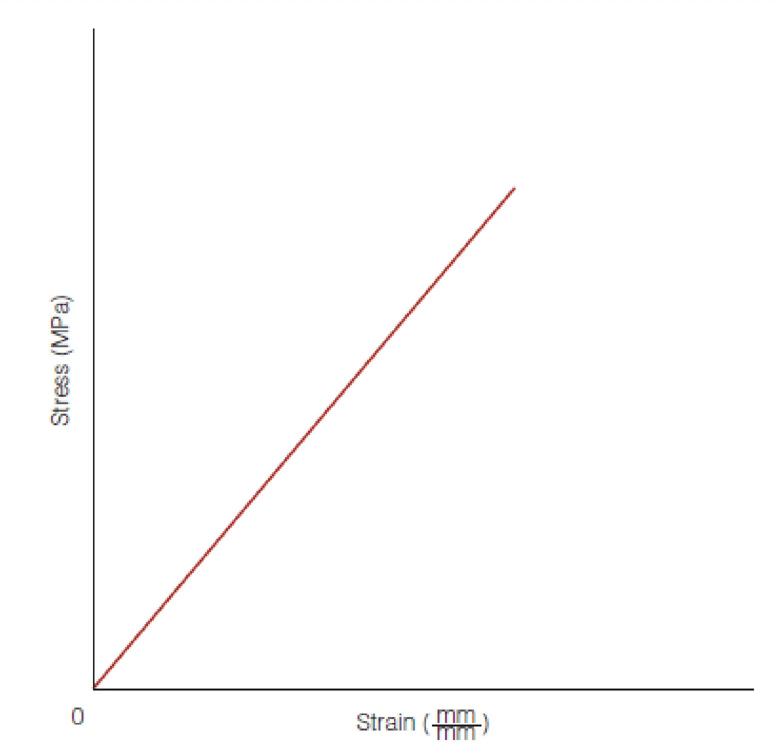
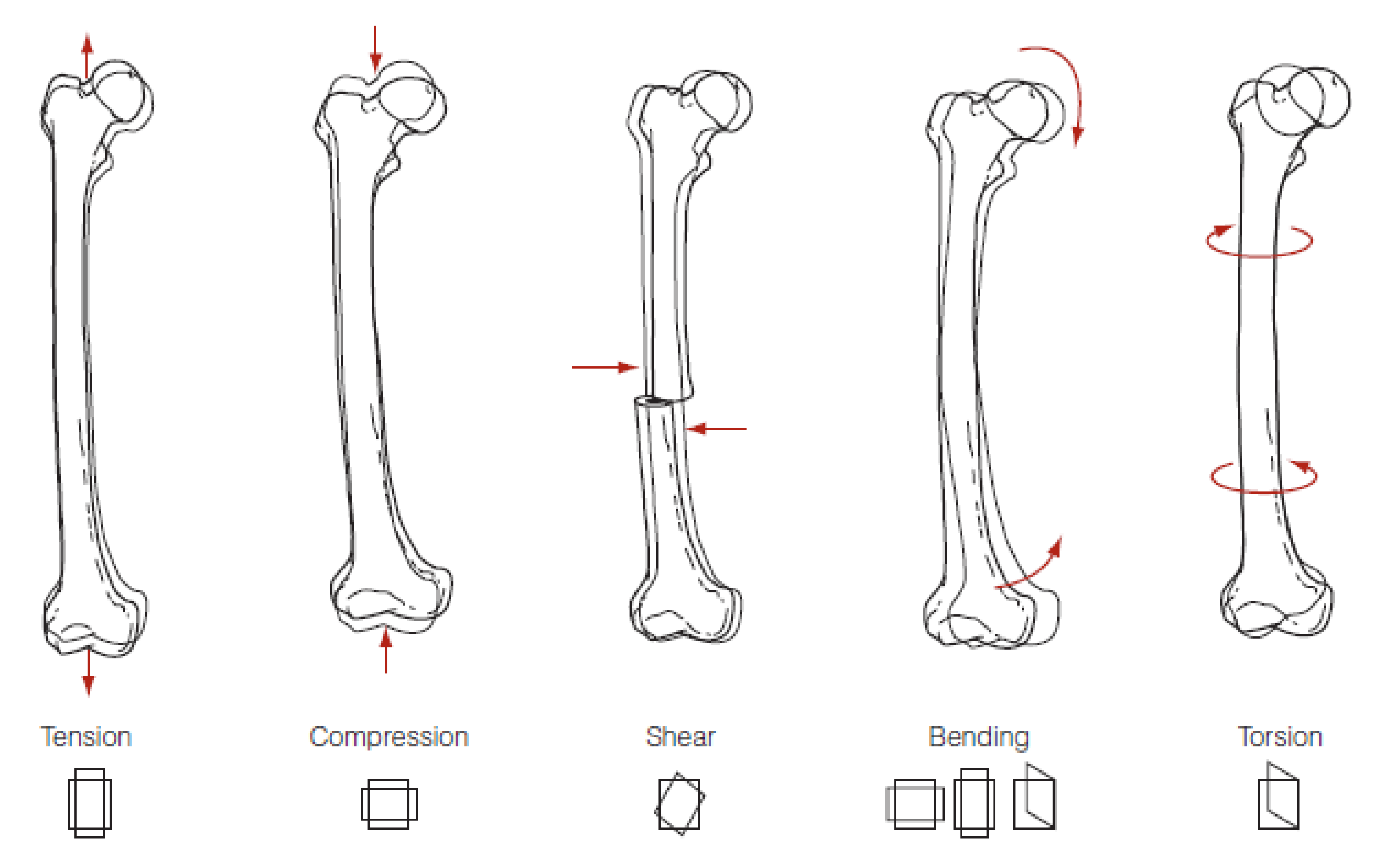
Elasticity


Stress (MPa)
0
Strain (mm/mm)


Tension
Compression
Shear
Bending
Torsion

Elasticity

- **Elastic modulus :** An expression of the relationship of stress and strain for a given material and type of deformation.
- **Tension stress :** Occurs when two forces are applied to a system in opposite directions away from each other.
- **Compression stress :** The result of two forces being applied to the system in opposite directions toward each other.
- **Shear stress :** Occurs from application of two parallel forces that tend to simultaneously displace one part of a system in a direction opposite another part of the system.

Elasticity

- **Bending :** Occurs when two off-axis forces are applied such that tension stress is caused on one side of the system and compression stress occurs on the other side.
- **Torsion :** Caused by two forces being applied in such a way that part of the system is rotated around its longitudinal axis in a direction opposite rotation of another part of the system

Elasticity

- **Young's modulus :** Term for the elastic modulus specifi cally referring to a condition of tension stress.
- **Elastic region :** The linear portion of any given stress/strain curve; a material will return to its original shape if the tensile stress is removed within this range.
- **Yield point :** The point at which an applied stress can lead to permanent deformation.
- **Plastic region :** The nonlinear response of the material after the yield point; some degree of deformation will persist after removal of the stress.

Elasticity

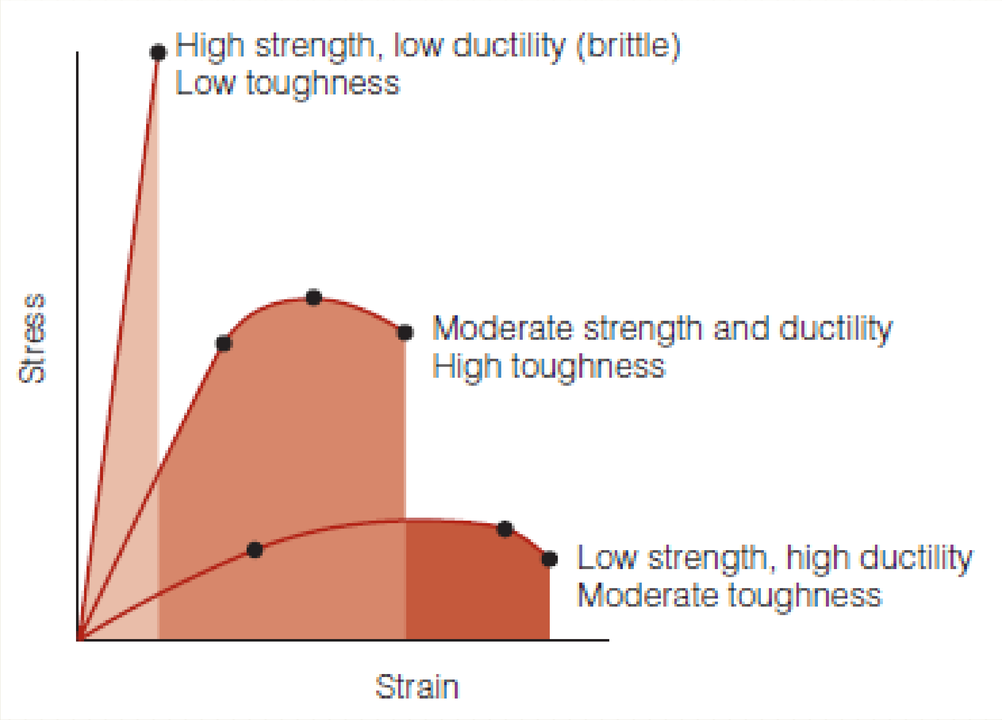
- **Strength :** The maximum stress or strain that a material can withstand without permanent deformation.
- **Ductility :** The force per unit area required to deform a material and is
- represented by the steepness (slope) of the stress/strain curve.
- **Toughness :** The total energy required to cause material failure.
- **Yield strength :** Stress at the yield point of a material.
- **Ultimate strength :** The maximal stress that a material can withstand before failing.
- **Failure strength :** The stress at which a material actually breaks or ruptures.

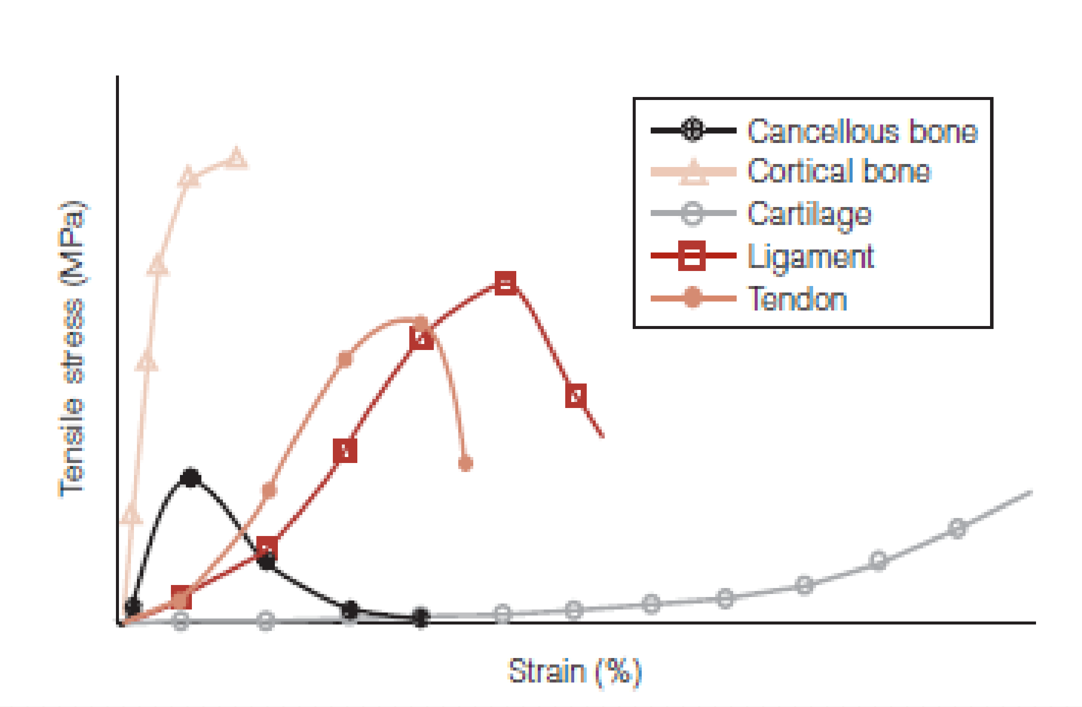
Elasticity

Young's modulus for various materials

Material	*Young's Modulus (Y) in GPa*	*Material*
Cartilage	0.0005–0.0008	
	0.01–0.1	Rubber
Ligament	0.3–0.4	
Tendon	0.8–1.2	
	2–4	Nylon
	11	Oak
Osteoporotic compact bone	12	
Normal compact bone	16	
Normal compact bone (6th decade)	17–20	
	30	Concrete
	72	Glass
	105–120	Titanium
	170	Stainless steel
	190–210	Wrought iron and steel
	400–410	Tungsten
	1,050–1,200	Diamond

Elasticity


High strength, low ductility (brittle)
Low toughness
Moderate strength and ductility
High toughness
Low strength, high ductility
Moderate toughness
Stress
Strain


Cancellous bone
Cortical bone
Cartilage
Ligament
Tendon
Tensile stress (MPa)
Strain (%)

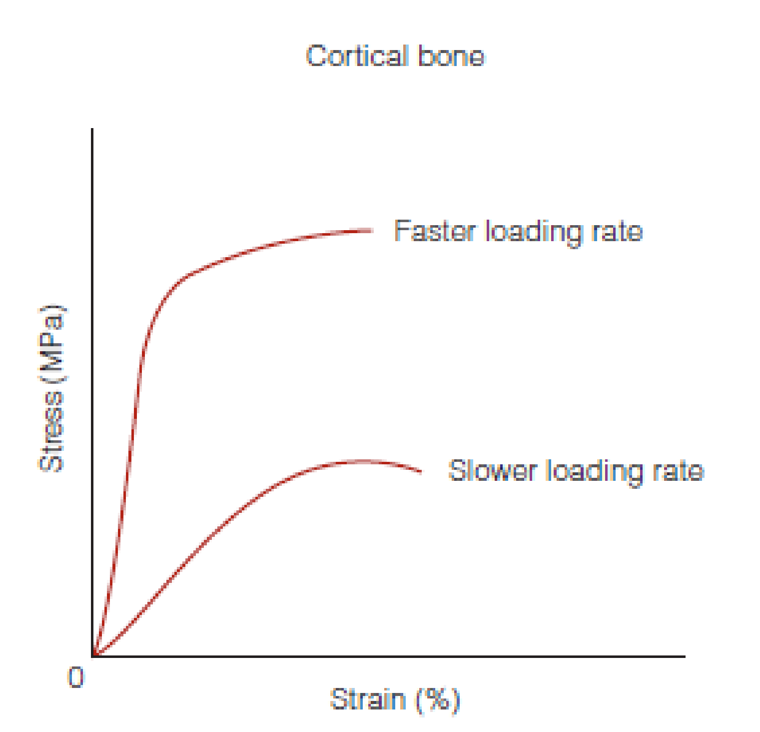
Elasticity

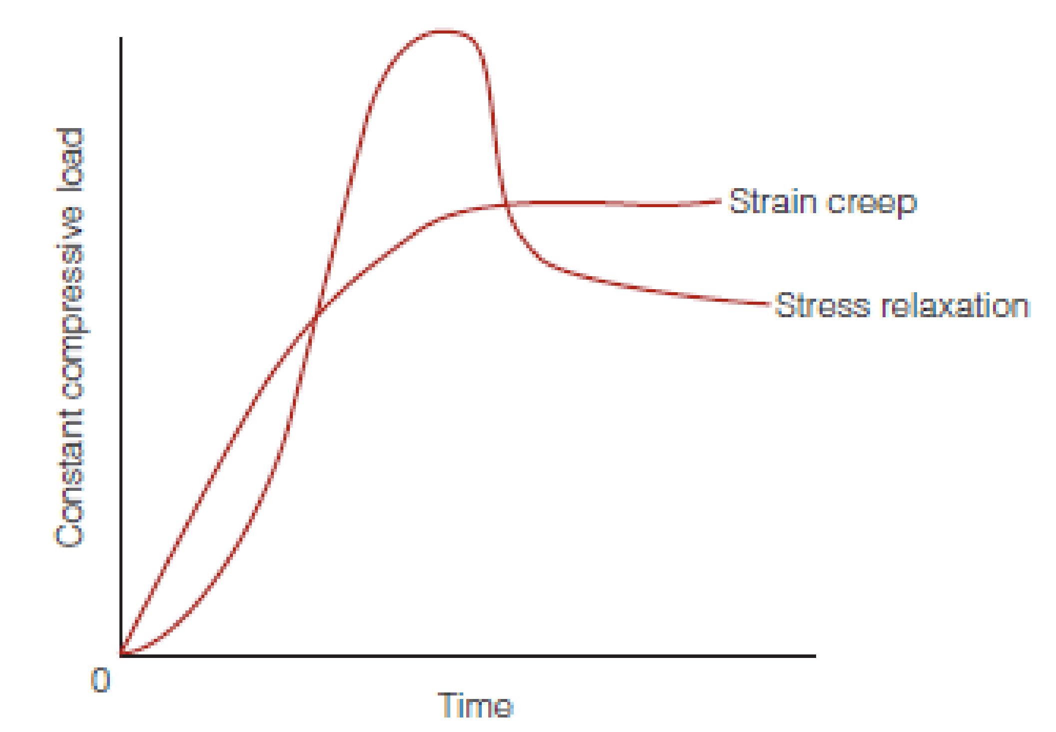
- **Ductile (or pliant) :** The quality of a material that fails at low stress but can withstand a large strain.
- **Brittle (or stiff) :** The quality of a material that can withstand high stress but fails with relatively low strain.
- **Coefficient of restitution (or coefficient of elasticity) :** A parameter observed after reformation that indicates the ability of an object to return to its original shape after deformation.

Visco-Elasticity

- **Viscoelastic :** The quality of a material whose deformation is affected by both the rate of loading and the length of time that it is subjected to a constant load.
- **Creep :** The term for the property of experiencing increasing strain (continued deformation) under a constant stress.
- **Stress relaxation :** The eventual decrease in stress that will occur as fluid is no longer exuded.

Visco-Elasticity





Fluid Forces

- **Buoyant fluid force :** The vertical, upward directed force acting upon an object that is submerged in a fluid.

- **Dynamic fluid force :** The equal and oppositely directed force of the fluid particles in reaction to the applied force of the system moving through the fl uid.

Fluids

- **Archimedes' principle :** A body submerged in a fluid will be buoyed up by a force that is equal in magnitude to the weight of the displaced water.
- **Drag force :** The parallel component of dynamic fluid force that acts in the opposite direction of system motion with respect to the fluid; tends to resist motion of the system through the fluid.
- **Lift force :** The perpendicular component of dynamic fluid force can act in any direction that is perpendicular to system motion with respect to the fluid; tends to change the direction of system motion through the fluid.

The Musculoskeletal System

- At the most basic level, motion of the human system is the result of muscles applying forces to bones through the process of tension development.

- The function of skeletal muscle is to apply forces to the bones. This function is intimately related to muscle structure.

Muscle Structure

- Muscle is composed of approximately ;

  75% water,

  20% protein

  5% inorganic salts

and other substances such as

enzymes,

the high-energy phosphates adenosine triphosphate (ATP)

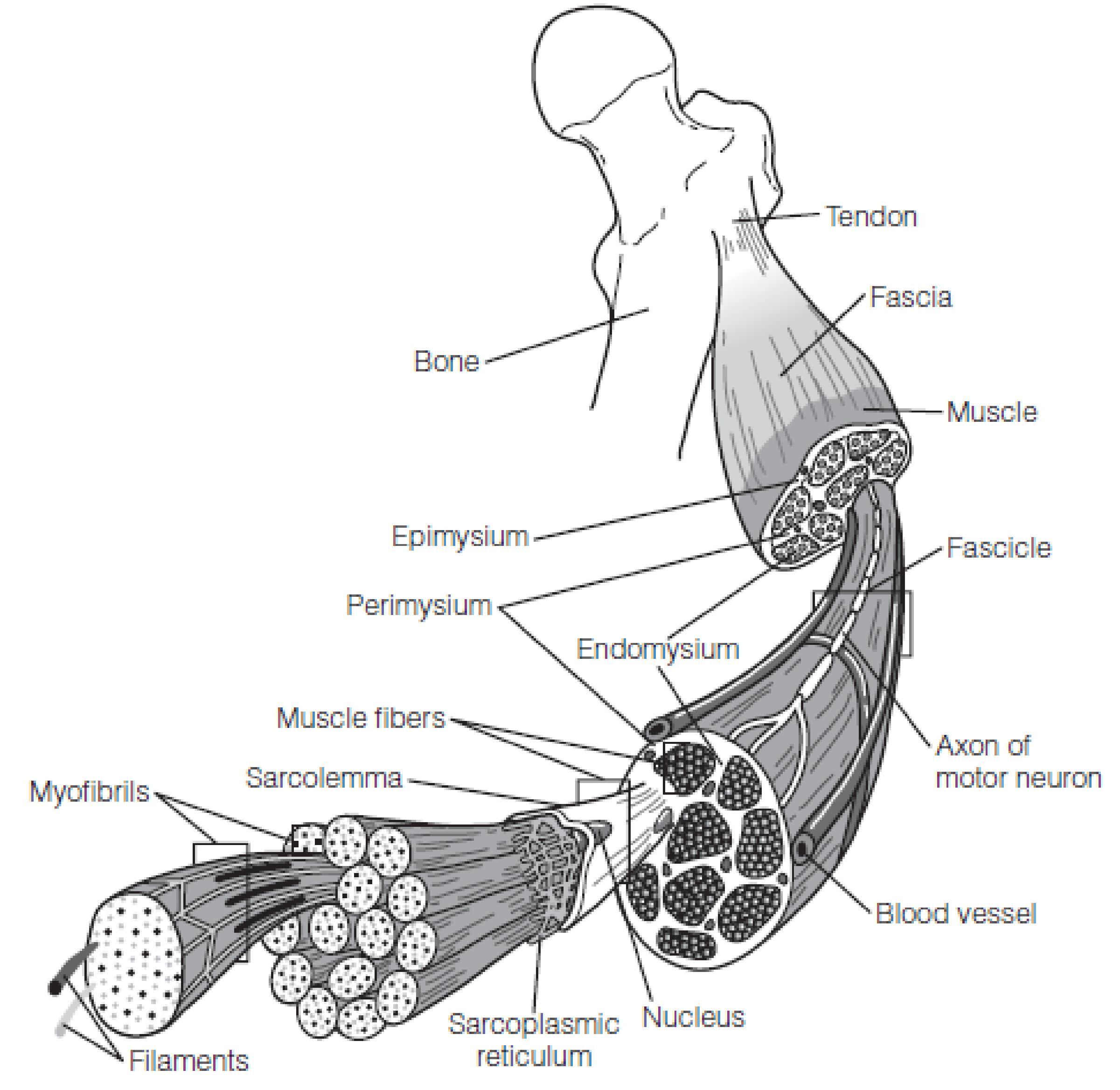
phosphocreatine (PCr),

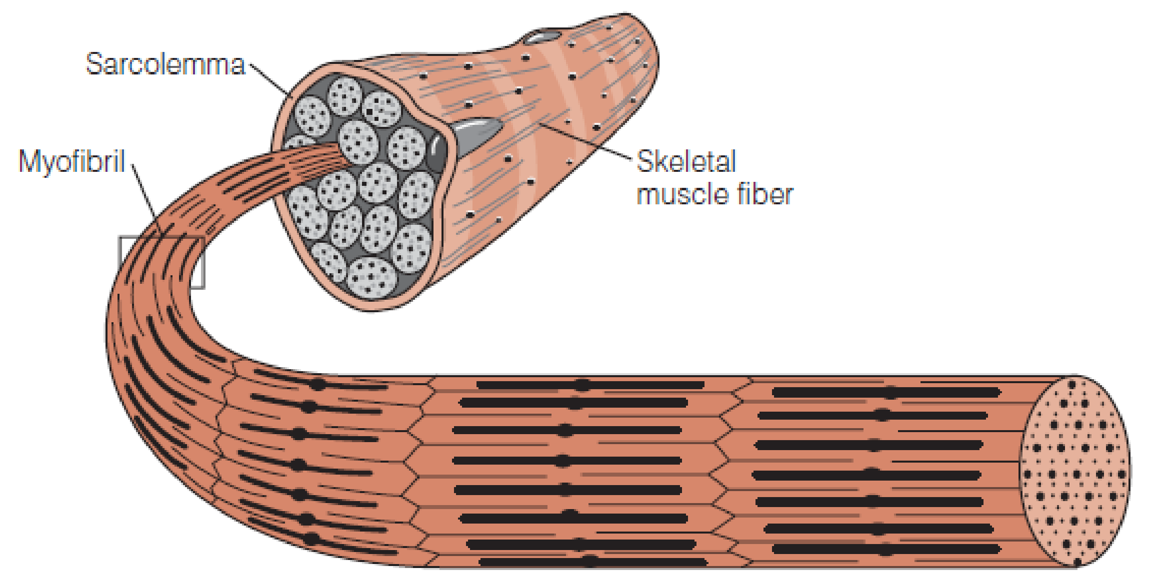
ions such as Na, K, and Cl,

minerals such as calcium,

particles of lipid and carbohydrate

Muscle Structure





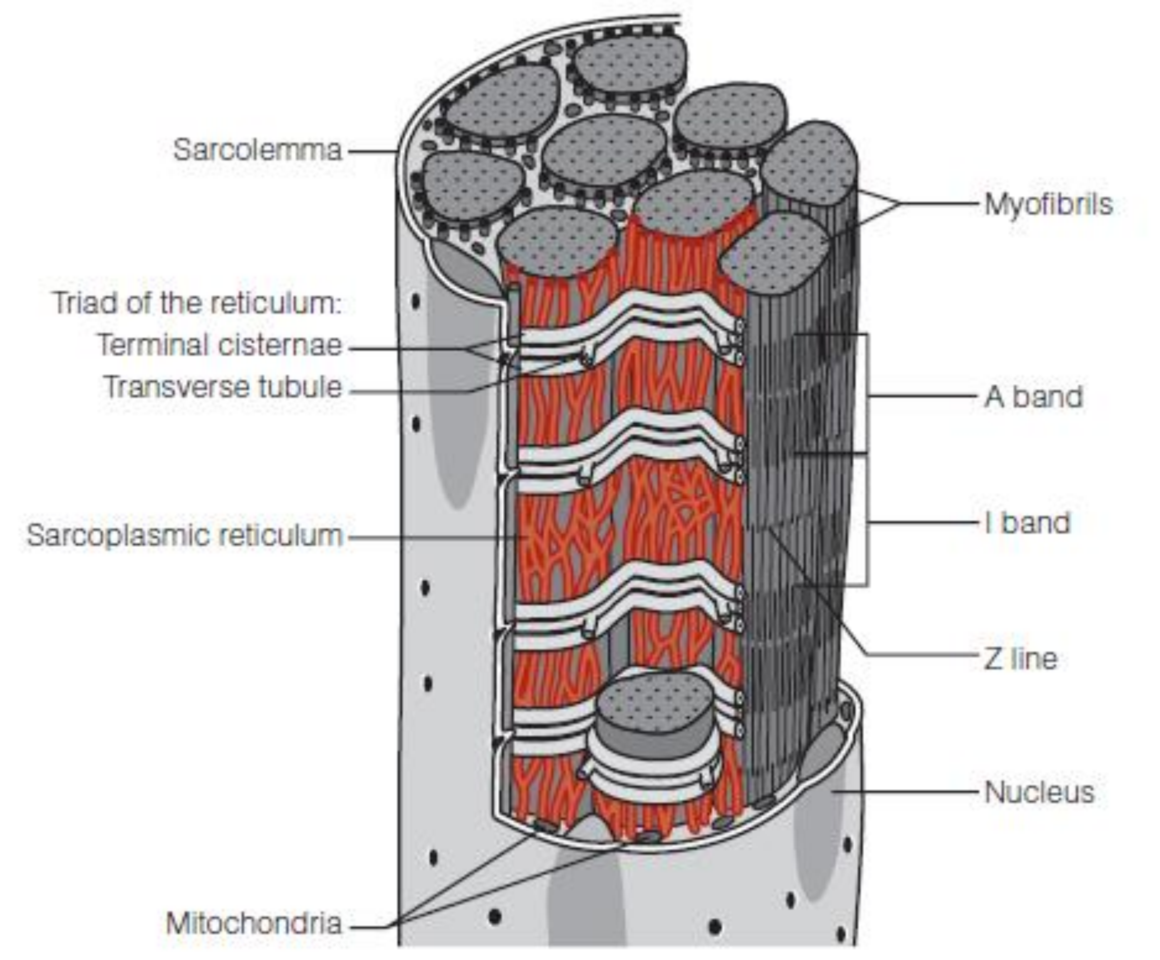
Muscle Struture

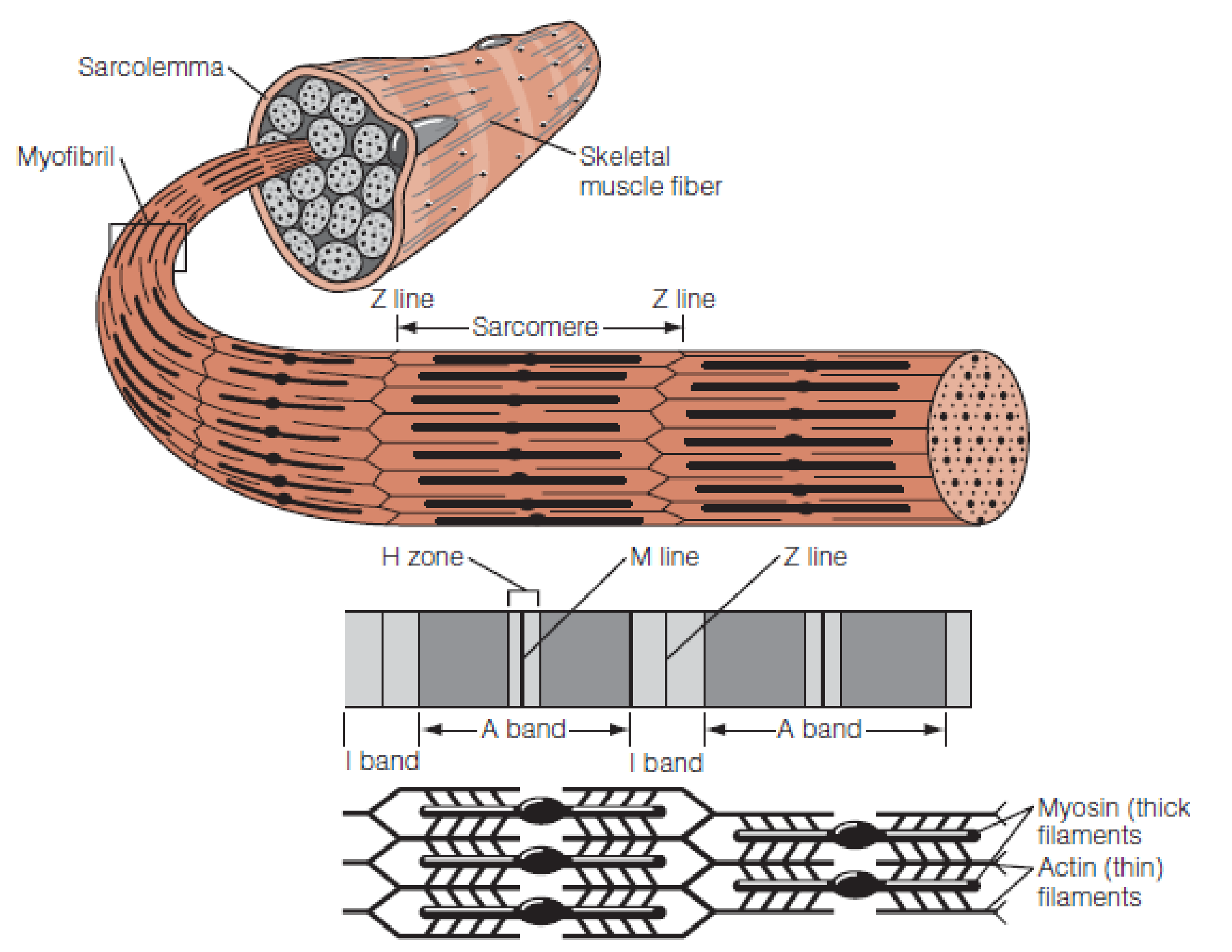
- **Muscle belly** The whole muscle between the tendons.
- **Fascia** The layer of connective tissue that holds the muscle belly in position and separates it from other muscles.
- **Epimysium** A deep layer of connective tissue that surrounds the entire muscle; sometimes called deep fascia.
- **Perimysium** The layer of connective tissue surrounding each fasciculus.
- **Fasciculus or fascicle** A bundle of the muscle fibers held together by perimysium.
- **Endomysium** The layer of connective tissue surrounding each muscle fiber.
- **Tendon** An extremely strong connective tissue formed by the convergence of epimysium, perimysium, and endomysium.
- **Periosteum** The outermost layer of the bone into which the tendons are inserted.

Muscle Structure

- Multiple layers of connective tissue running parallel to the muscle fibers contribute some ***elasticity*** to the whole muscle. The elasticity contributed by this noncontractile tissue within the muscle is referred to as a ***parallel elastic component***.
- The muscle fibers (cells) are multinucleated, elongated, cylindrical in shape, and have a striated appearance. Muscle fibers range in diameter from 10 to 100 μm (approximately the diameter of a human hair), and have lengths that vary from a few millimeters up to approximately 45 cm. The fibers usually extend from one end of the muscle belly to the other, so length varies accordingly. Muscle fibers, like other cells, have a cell membrane and contain cytoplasm.

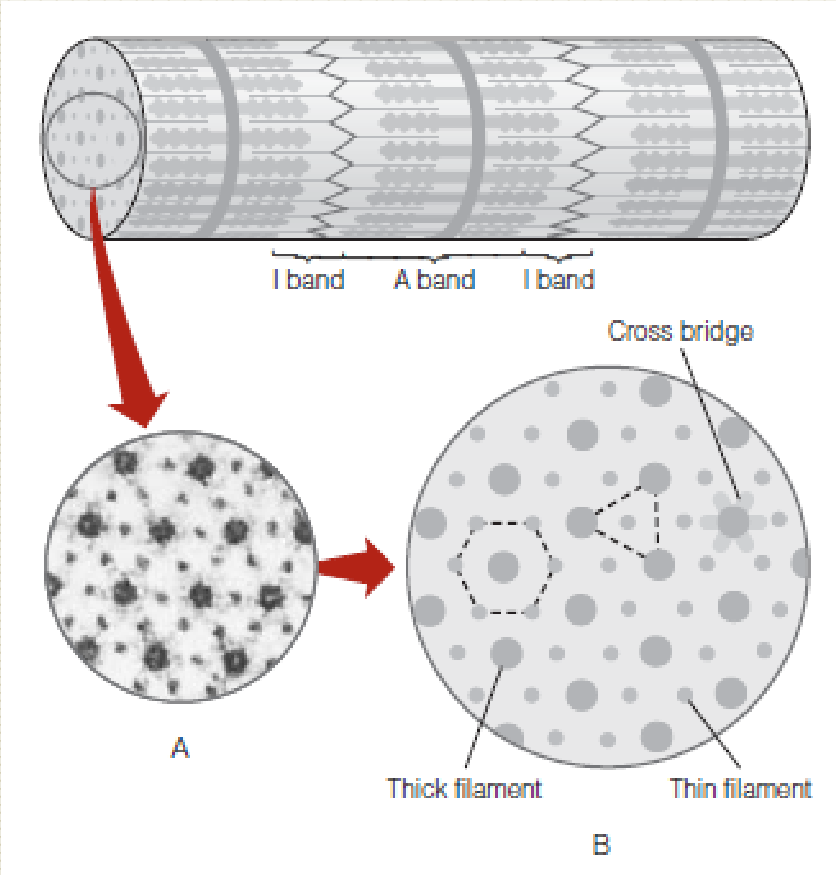
Muscle Structure





Muscle Structure

- The cross-sectional arrangement of myosin and actin filaments.



Muscle Structure

- **Sarcolemma** The cell membrane of a muscle fiber.
- **Sarcoplasm** The cytoplasm inside of a muscle fiber.
- **Myofibrils** A bundle of specialized threadlike structures making up the muscle fiber.
- **Sarcoplasmic reticulum** A system of channels that surround and run parallel to the myofibrils, and serve as a storage site for calcium.
- **Transverse tubules (T-tubules)** A continuation of the sarcolemma into the interior of the fiber; channels that run perpendicular to the myofibrils, connecting the sarcoplasmic reticulum to pores in the sarcolemma.

Muscle Structure

- **Terminal cisternae** Enlarged portions of the sarcoplasmic reticulum running perpendicular to the myofibrils.
- **Triad of the reticulum** One T-tubule passing between two terminal cisternae.
- **Sarcomeres** Segments of the myofibrils that are strung end to end and serve as the functional unit of the muscle (because it is the smallest unit that can perform the function of the whole muscle).
- **Z-disk** Structural protein connecting each sarcomere to the next.

Muscle Structure

- Each myofibril is approximately 1 μm in diameter and extends the entire length of the fiber.
- The number of myofibrils per muscle fiber depends on the diameter of the muscle fiber.
- A muscle fiber approximately 100 μm in diameter may contain up to 8,000 myofibrils.
- The sarcoplasmic reticulum and T-tubules play a major role in muscle contraction.
- Because the Z-disks are perpendicular to the muscle fiber, creating series of sarcomeres, the noncontractile elasticity contributed by the Z-disks is another component of the series-elastic component.

Muscle Structure

Although several different proteins are found within the sarcomere, two filamentous structures are most crucial to **muscle contraction**: thick filaments and thin filaments

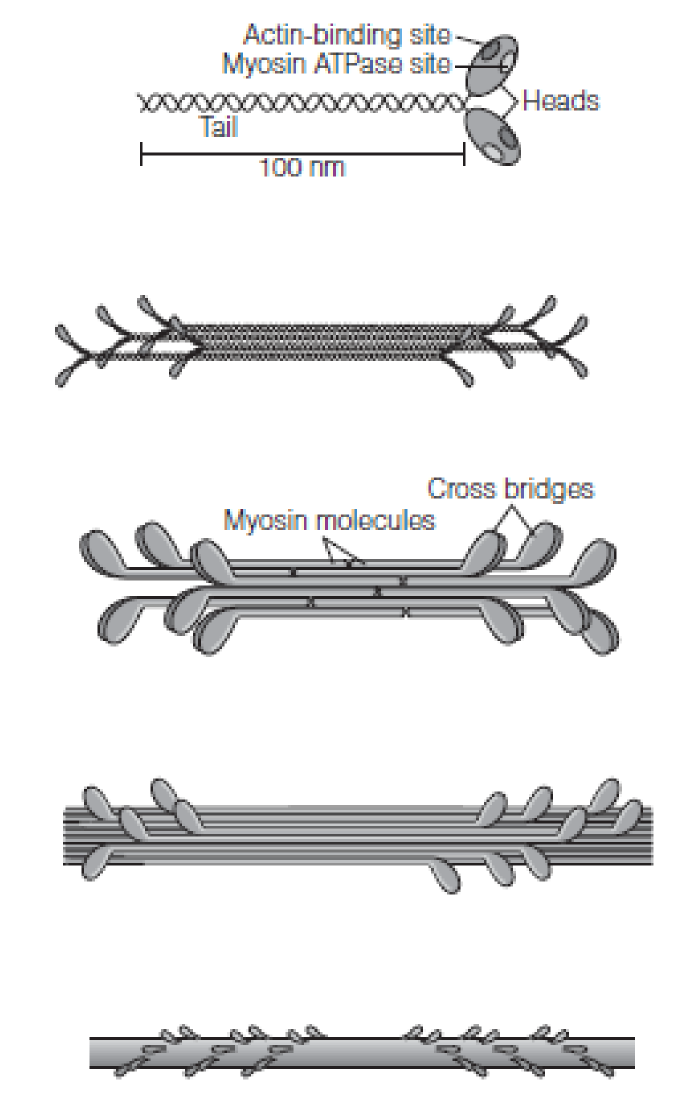
- **Thick filaments** Large polymers (assemblies) of the protein myosin (which have a diameter of approximately 15 nm and a length of approximately 1.5 μm)
- **Thin filaments** Polymers (assemblies) of the protein actin (with a diameter of approximately 7 nm and a length of approximately 1.0 μm).

Muscle Structure

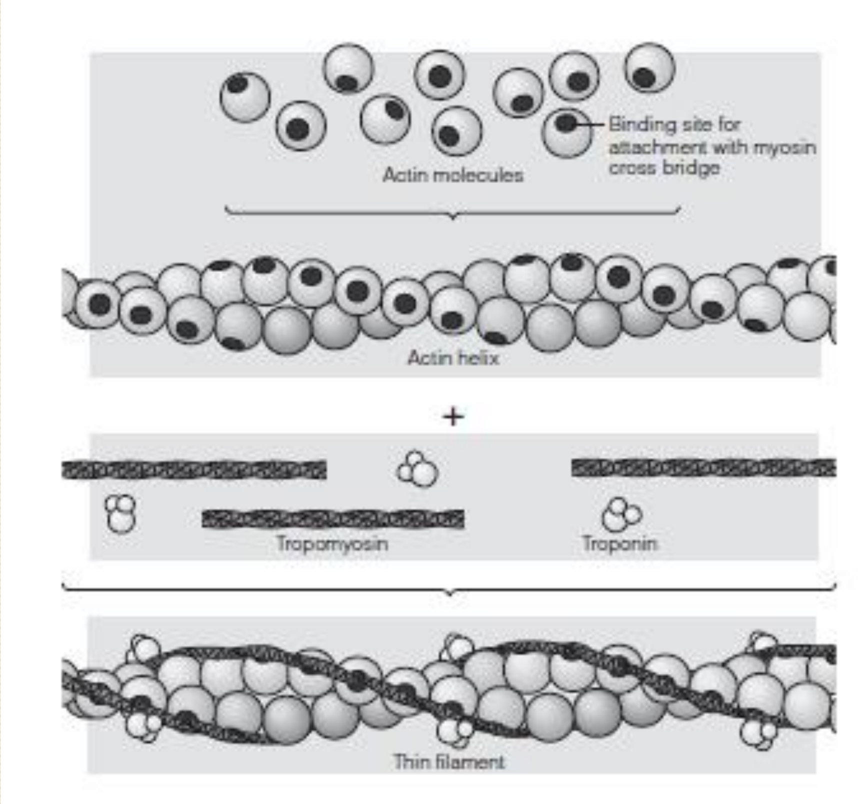
- **Myosin** A contractile protein that serves as the major structural component of the thick filaments in muscle fibers.
- **Actin** A contractile protein that serves as the major structural component of the thin filaments in muscle fibers.
- **Tropomyosin** A molecule made up of long thin threadlike proteins that spiral around the chains of actin molecules, blocking the myosin binding sites.
- **Troponin** A protein complex spaced at intervals along the thin filament that in the relaxed state, acts to maintain tropomyosin in a position to block the myosin binding sites of actin.

Muscle Structure

- The structure of a myosin molecule



The structure of an actin molecule

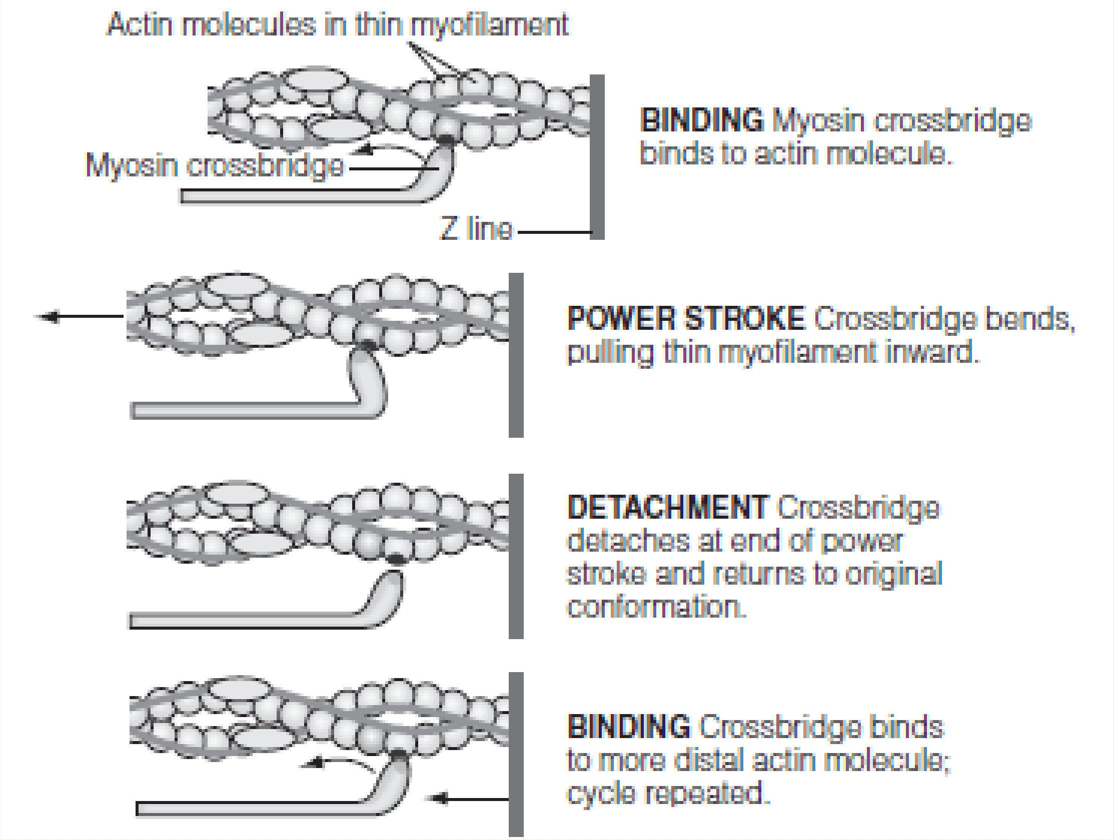


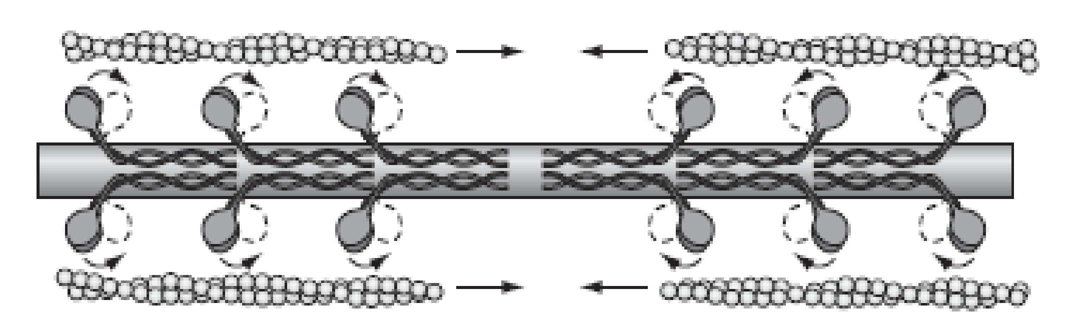
Muscle Contraction

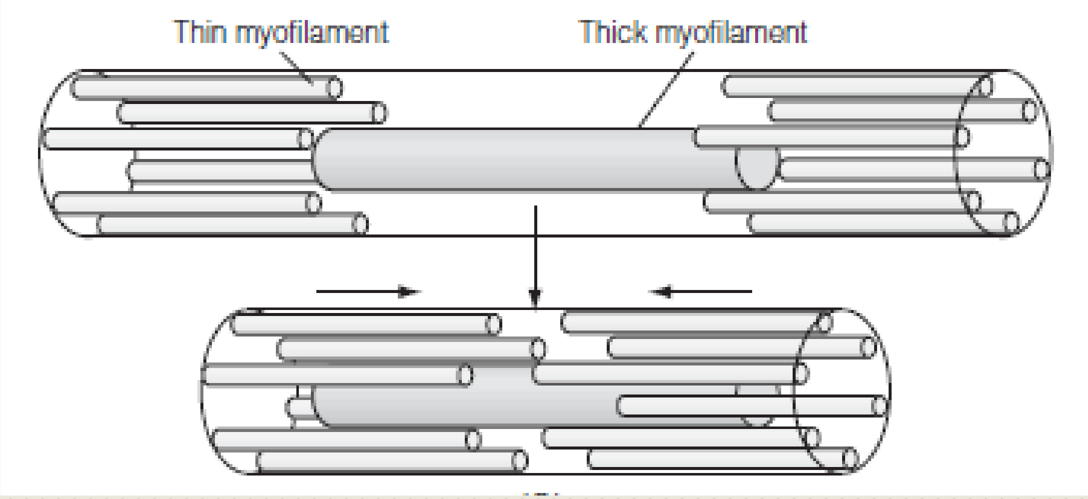
- Muscle contraction is controlled by the nervous system; therefore, we begin at the synapse, where the nervous system and muscular system meet. The neuromuscular junction is the site where muscle fiber is innervated. It is the site of interdigitation (physical interaction) of the motor neuron and the muscle fiber.
- *Troponin* is the protein complex that actually initiates the contraction process.

Muscle Contraction

- The crossbridge power stroke pulls the six surrounding thin filaments toward the center of the sarcomere simultaneously.







Muscle Contraction

- One power stroke pulls the thin filament only a very short distance, because the displacement is only the linear distance traveled by one myosin head.
- Therefore, full shortening of the muscle is achieved by repeated cycles of detachment, binding, and tilting. During these repeated cycles of crossbridge interaction, the thin filaments are sliding across the thick fi laments. This sliding of the thick and thin filaments relative to one another is often called the sliding filament theory(*) of muscle contraction.

(*)Sliding filament theory of muscle contraction : Theory of muscle force generation in which tension is generated by the interaction of myosin with actin leading to myofibrillar translation.

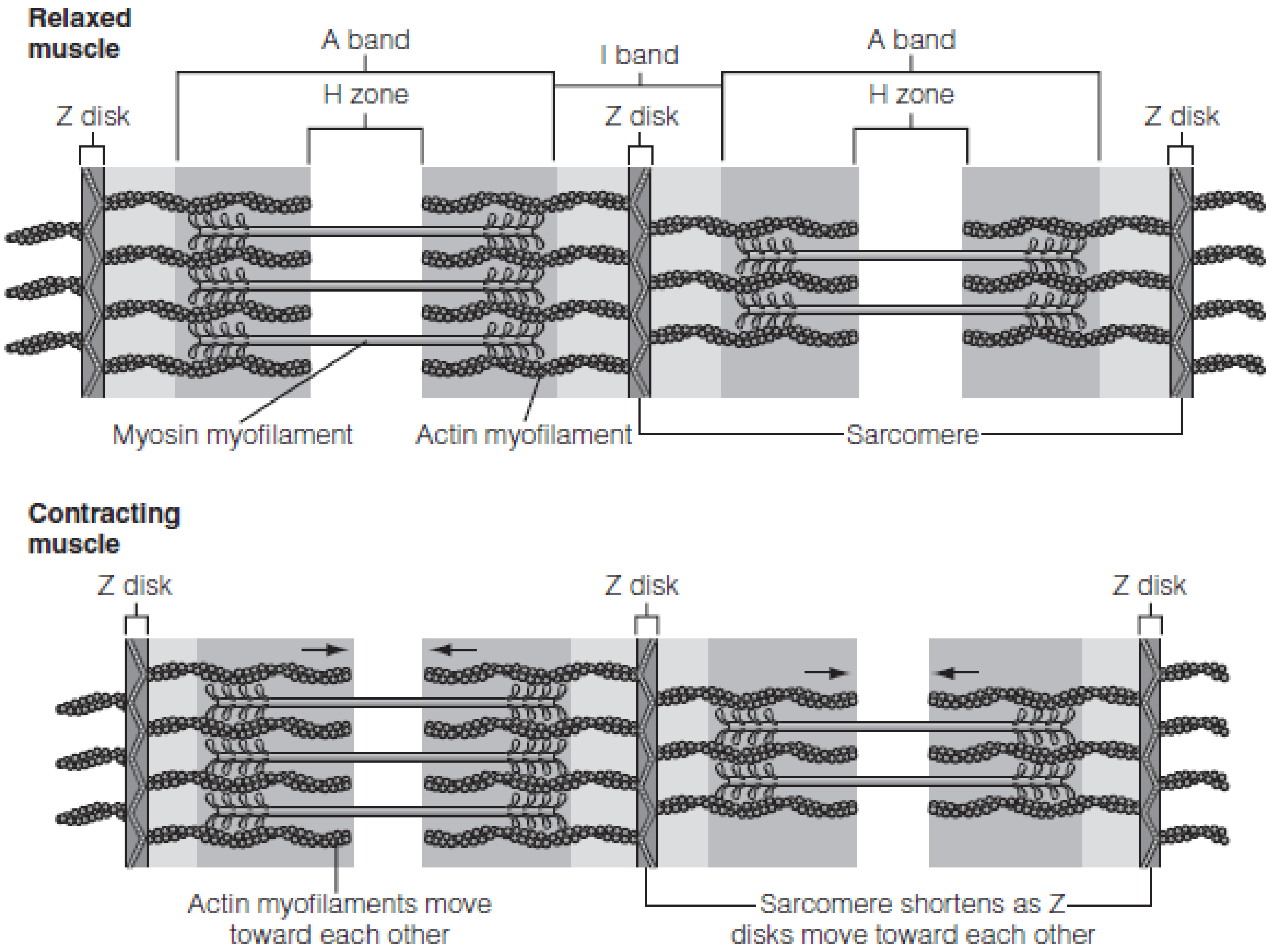
Muscle Contraction

- Because myofibrils are made up of sarcomeres, the myofibrils shorten. Muscle fibers are made up of myofibrils, so they shorten in turn. Muscle fibers make up fasciculi, and therefore the entire muscle shortens. The final result is that the entire muscle belly shortens. This shortening applies force to the tendons, and in turn, to the bones to which they are attached. So where does everything in the muscle go as it shortens? It is all forced toward the middle of the muscle; that’s why muscles bulge when they are contracted.

Muscle Contraction

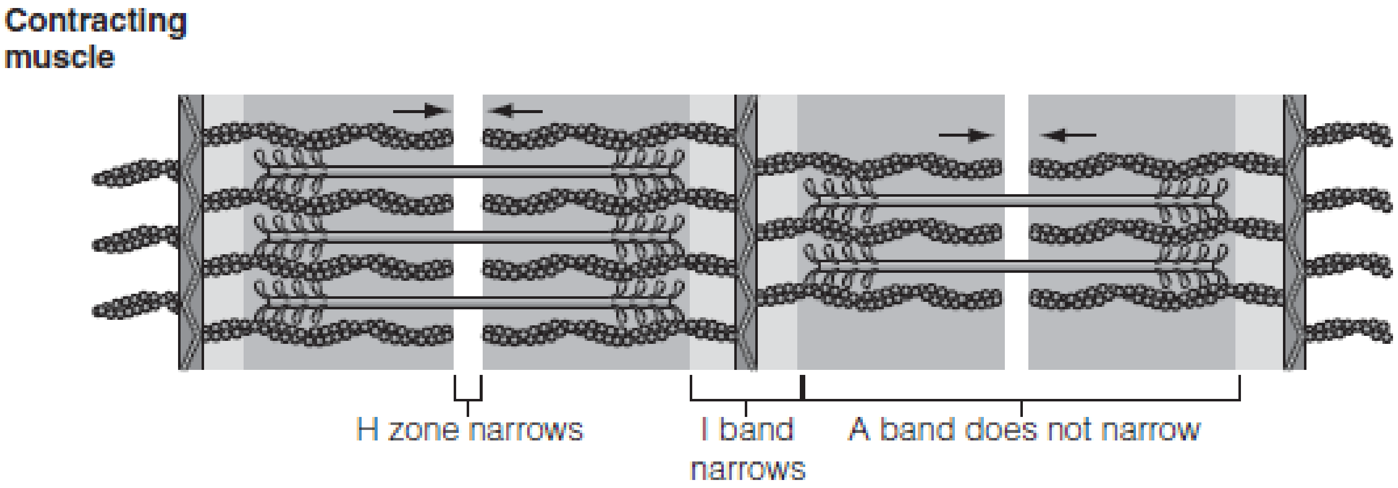
1. Actin and myosin myofilaments in a relaxed muscle (*right*) and a contracted muscle (*#4 below*) are the same length. Myofilaments do not change length during muscle contraction.

2. During contraction, actin myofilaments at each end of the sarcomere slide past the myosin myofilaments toward each other. As a result, the Z disks are brought closer together, and the sarcomere shortens.

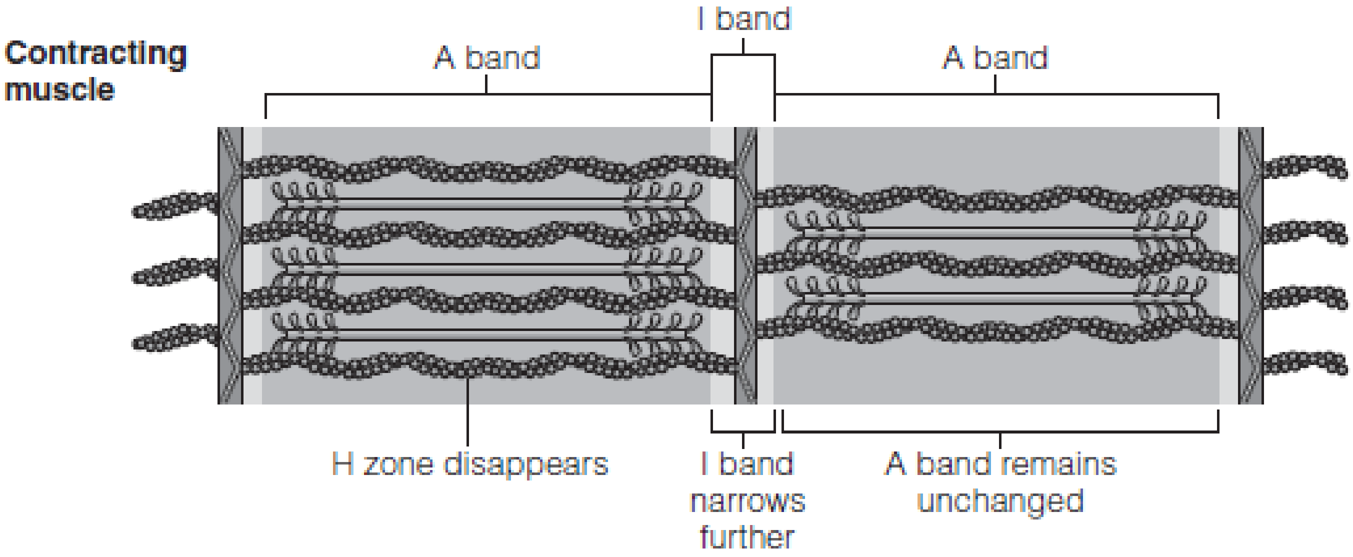


Muscle Contraction

3. As the actin myofilaments slide over the myosin myofilaments, the H zones and the I bands narrow. The A bands, which are equal to the length of the myosin myofilaments, do not narrow, because the length of the myosin myofilaments does not change.



4. In a fully contracted muscle, the ends of the actin myofilaments overlap and the H zone disappears.



Muscle Actions

- **Static muscle action** Tension is generated within the muscle, but the bone to which the muscle force is applied does not move.
- **Dynamic muscle action** Movement of the body segment occurs during generation of muscle tension.
- **Concentric muscle action** The muscle torque generated is greater than the load torque, and the muscle is therefore allowed to shorten.
- **Eccentric muscle action** The resultant muscle torque is less than the load torque and the muscle lengthens during generation of tension.

Factors Related To Contractile Force

The neuromuscular system can produce many different degrees of force. The contractile process that produces force, we can gain a deeper knowledge of the mechanisms by which this force is controlled. In general, two major factors affect whole muscle tension:

- (1) the number of fibers contracting
- (2) the tension developed by each individual fiber involved in the contraction.

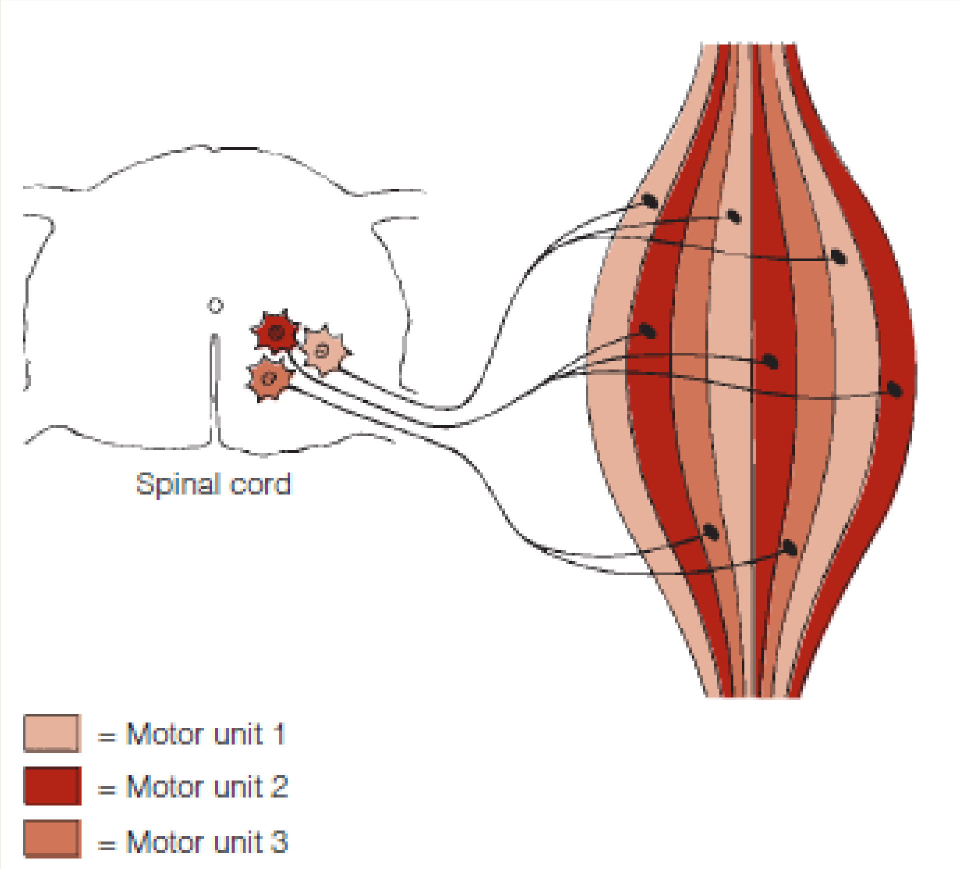
these two factors are associated with such varied degrees of force.

Motor Unit

- Number of muscle fibers that contract affects the tension generated by a whole muscle. Each whole muscle in the body is innervated by a different number of motor neurons. Each one of these motor neurons innervates a different number of muscle fibers. However, each muscle fiber is only innervated by one motor neuron. An individual motor neuron and the group of fibers that it innervates are collectively called **a motor unit**. When a given motor neuron is activated (recruited) by the nervous system, all of the fibers that it innervates are stimulated to act simultaneously. The muscle fibers of the motor unit are distributed throughout a whole muscle (i.e., they are not all lying parallel to each other in one area).

Motor Unit

- The importance of motor units in controlling muscle force should not be underemphasized. Because muscles have varying numbers of motor units as well as motor units of different sizes, many varying degrees of force can be achieved, depending on the situation.



Neural Stimulation Frequency

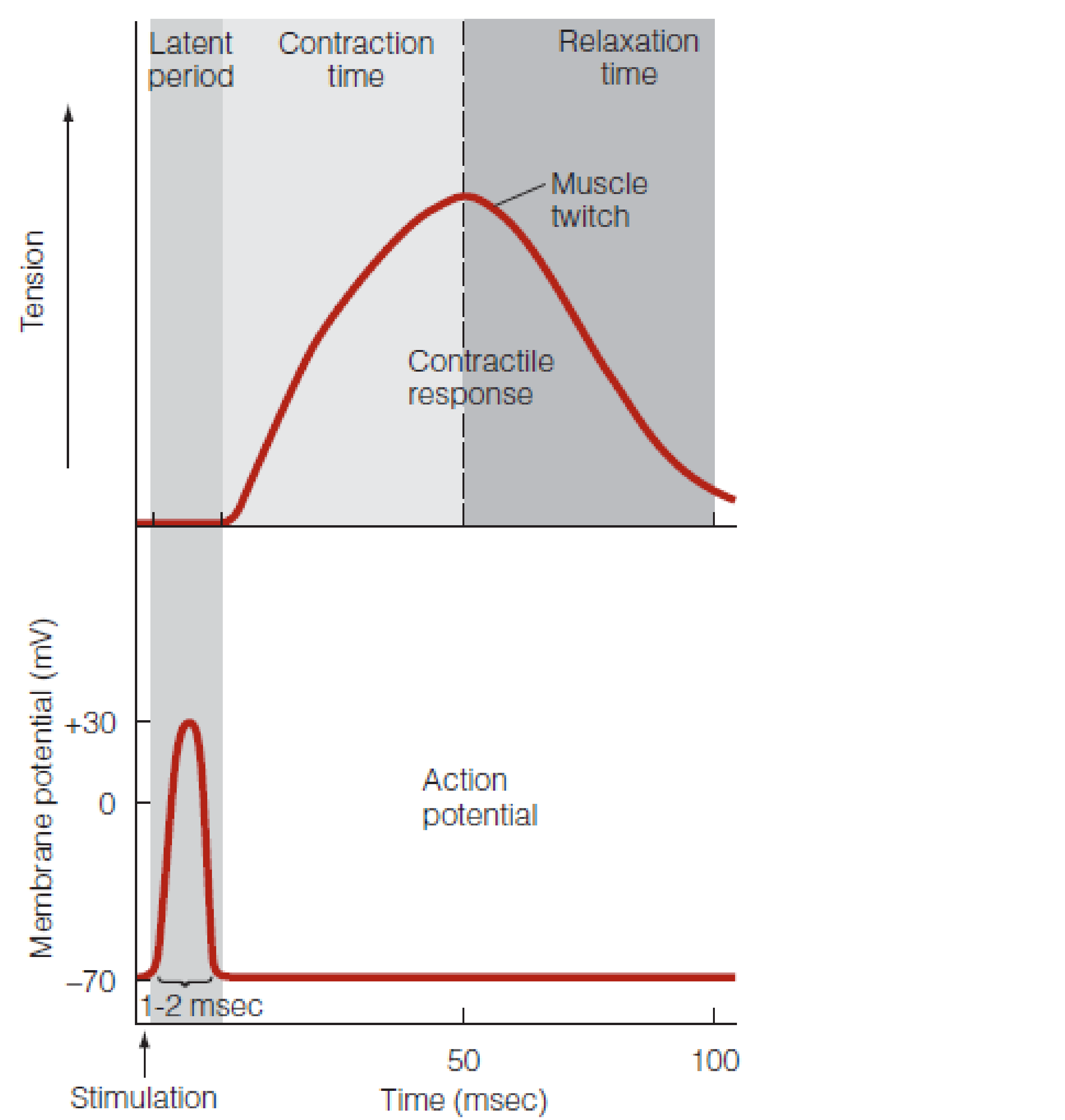
- Dividing the whole muscle into motor units provides a large number of possibilities for generating force. However, we can also control the tension developed by the fibers of a motor unit once it is recruited. In other words, they all contract simultaneously, but they do not necessarily contract maximally. The arrival of a single action potential in the muscle fiber produces a weak, very brief action of the fiber that is called a **twitch**. A muscle twitch is not very useful for most activities, because the contraction is weak. understanding a single muscle twitch can give you a better understanding of how muscle force is controlled by the frequency of neural stimulation. First, we must understand the time course of a single twitch. The single action potential that stimulates the muscle fi ber to twitch lasts approximately 1 to 2 msec.

Neural Stimulation Frequency

- **Twitch** A weak, very brief action of the fiber caused by the arrival of a single action potential.
- **Latent period** A period of a few milliseconds following the occurrence of the action potential, during which the fiber has not yet begun to generate tension.
- **Tension generation period** Period of time following the latent period during which the muscle fiber actually generates tension.
- **Relaxation period** Period following tension generation in which the muscle fiber returns to the resting state

Neural Stimulation Frequency

- Time course of a muscle twitch.

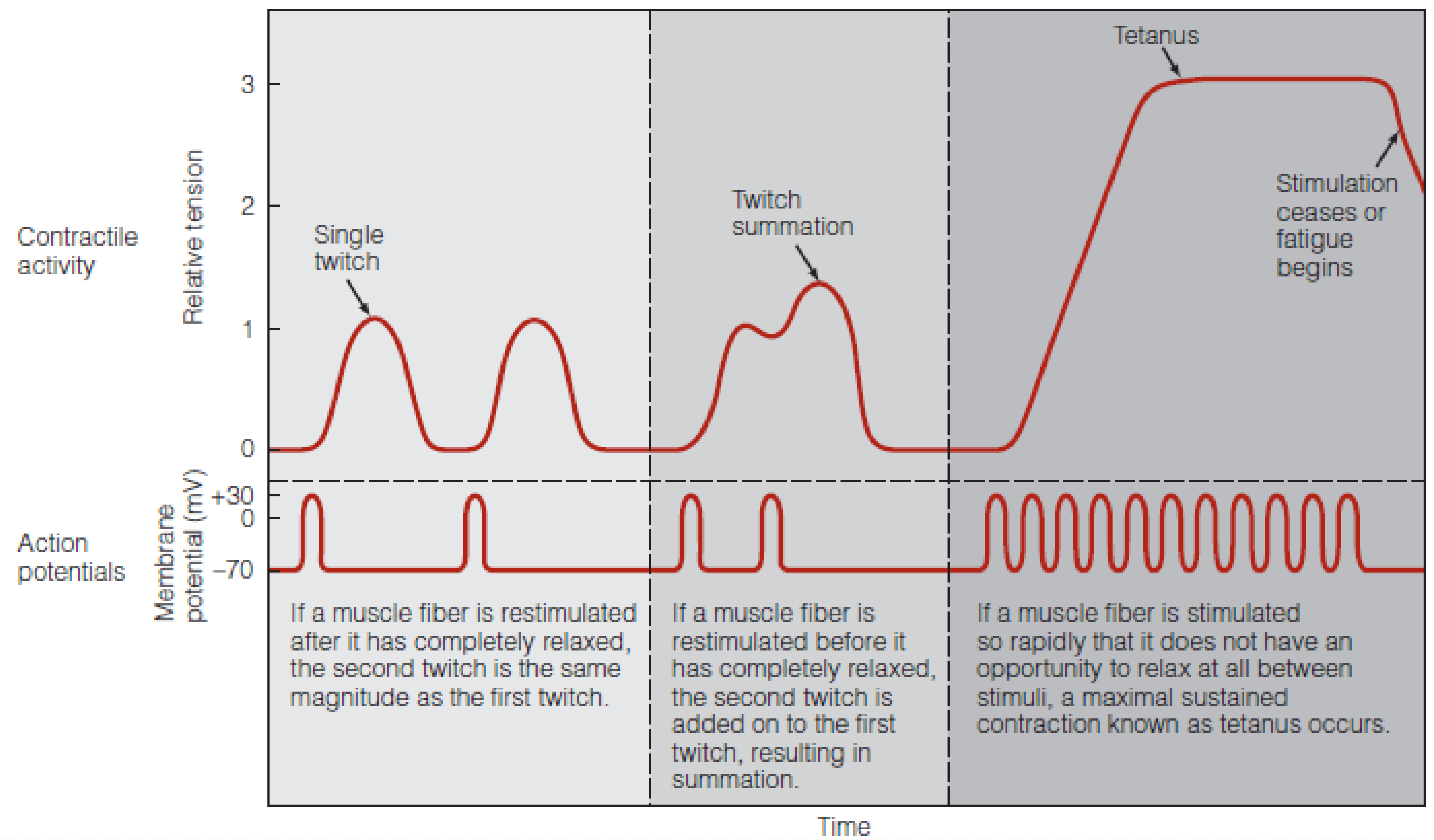


The duration of the action potential is not drawn to scale but is exaggerated.

Neural Stimulation Frequency

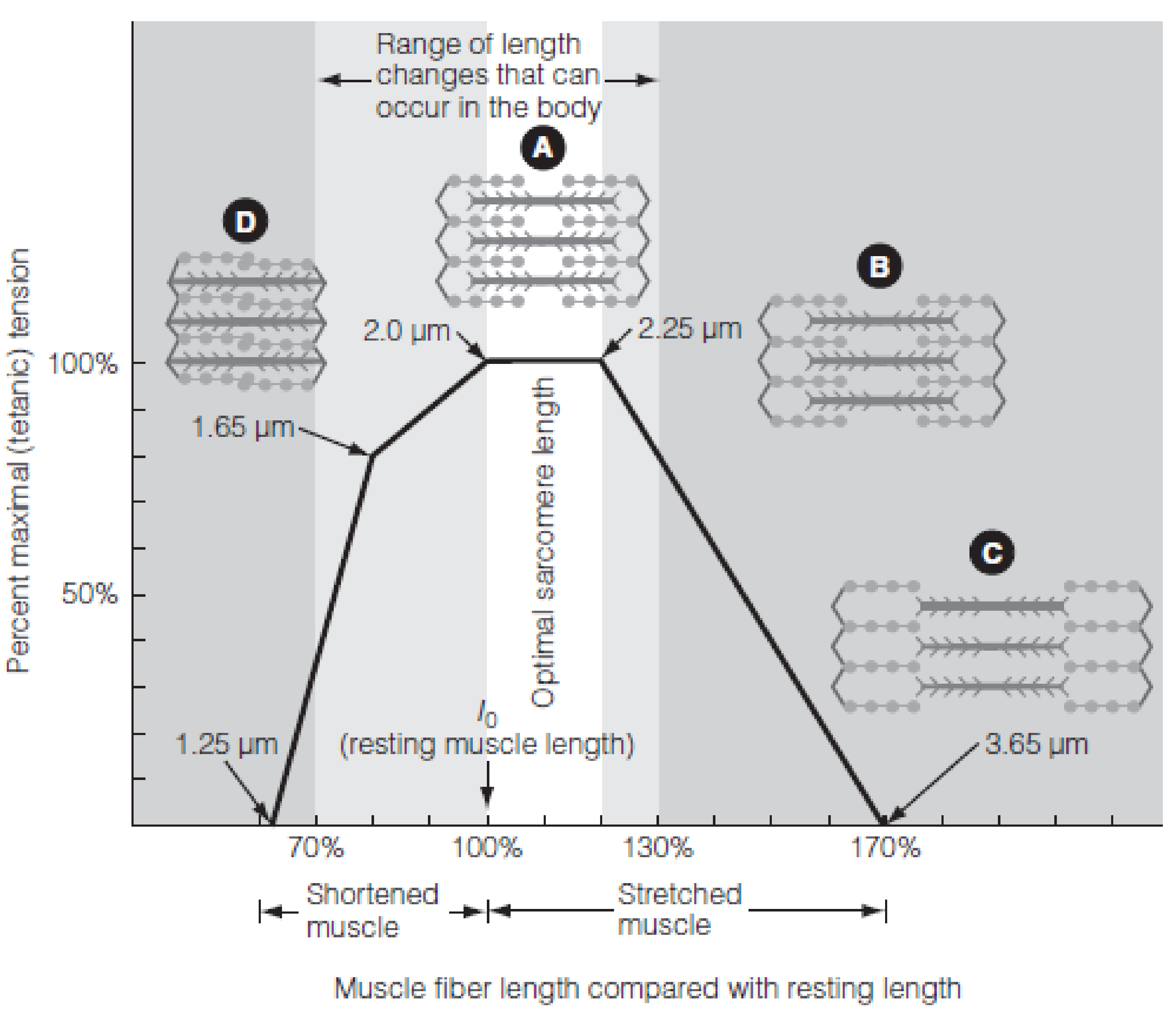
- **Twitch summation** The force of a second twitch is summed with the force remaining from the first twitch.
- **Tetanus** The point at which the maximum number of crossbridges are participating in the muscle action and the muscle fiber reaches peak tension development.

Summation versus tetanus



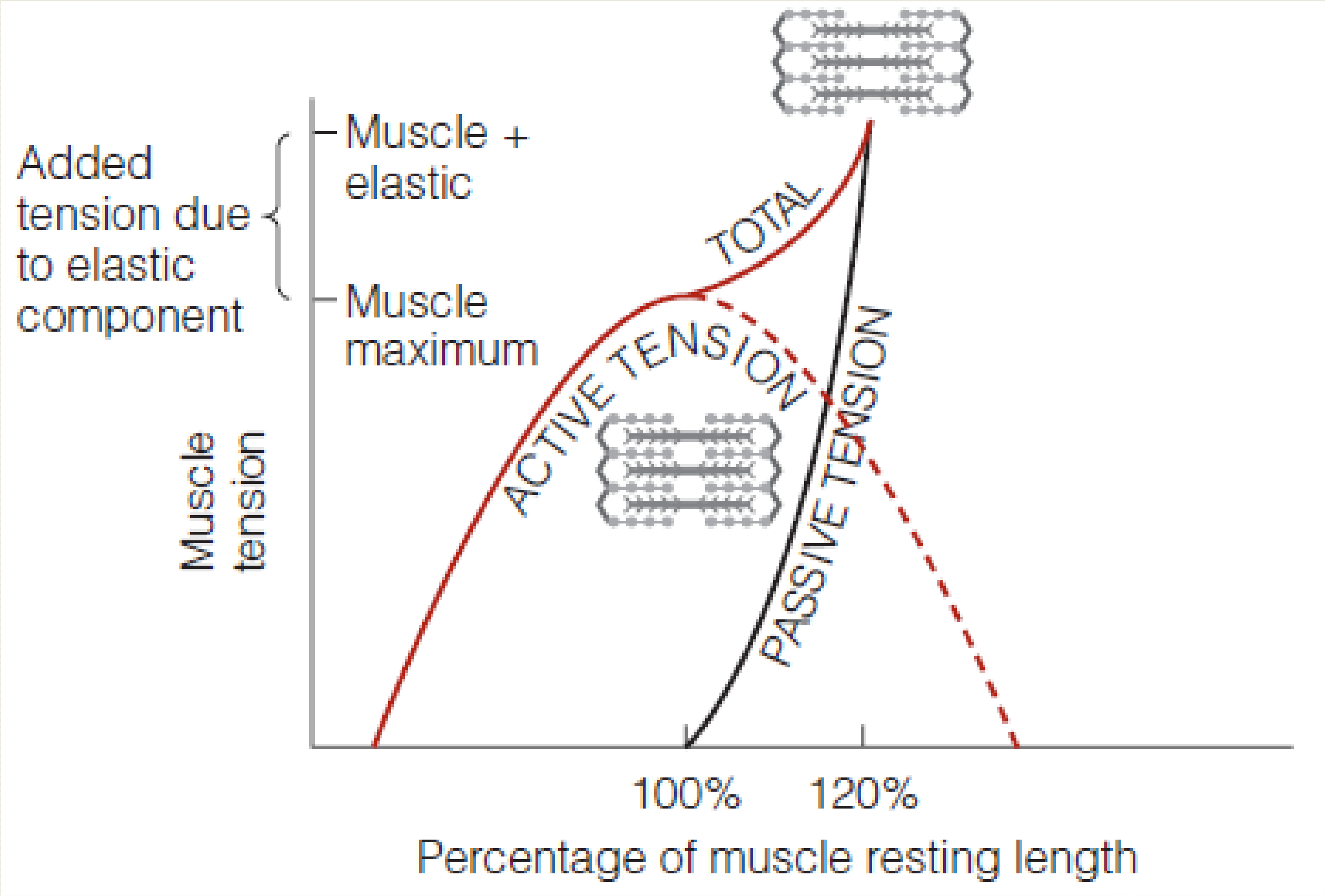
The length-tension relationship

Relationship between muscle fiber length prior to stimulation and subsequent tetanic tension development.



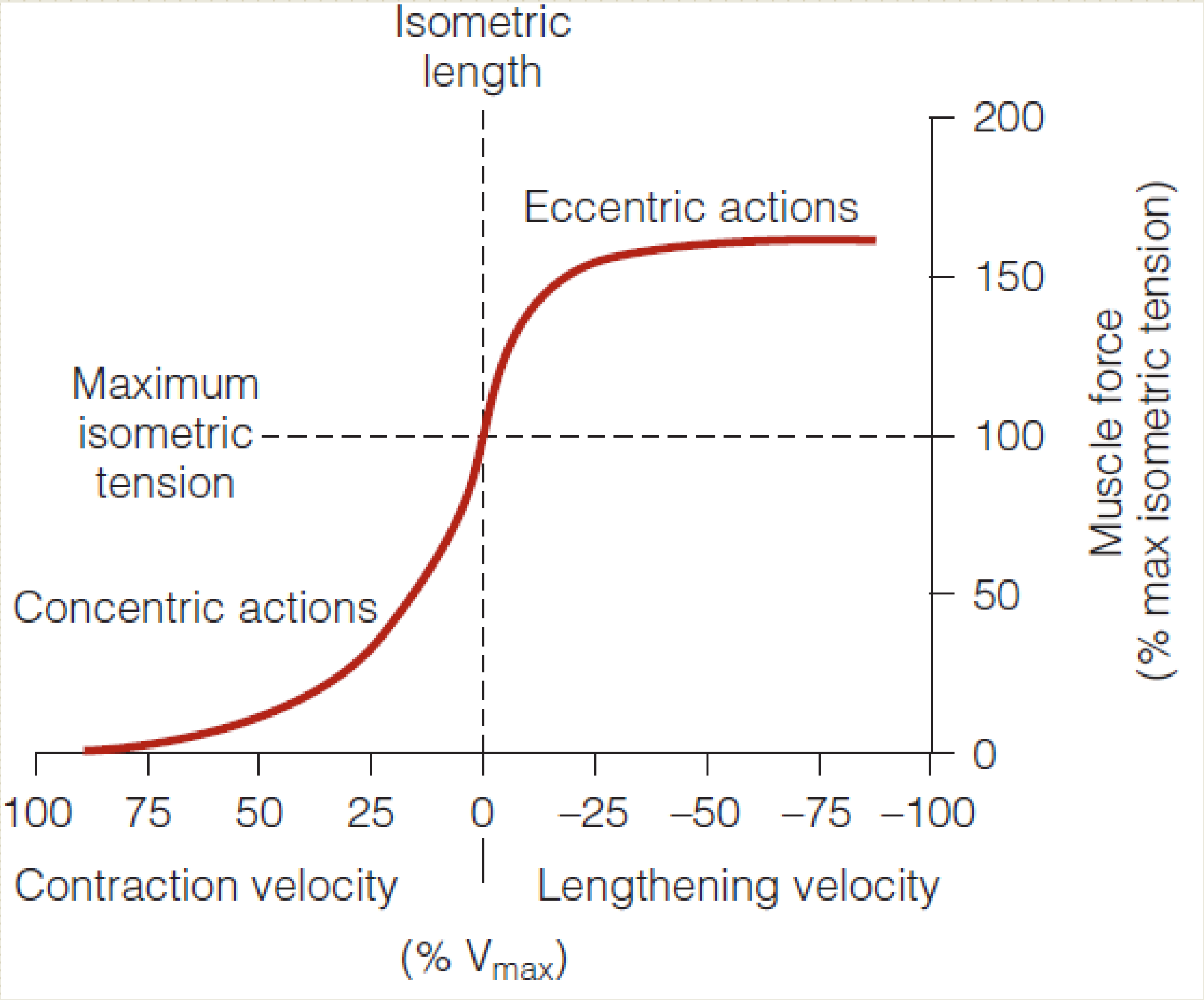
The contribution of the elastic component

- The contribution of the elastic component to muscle force.

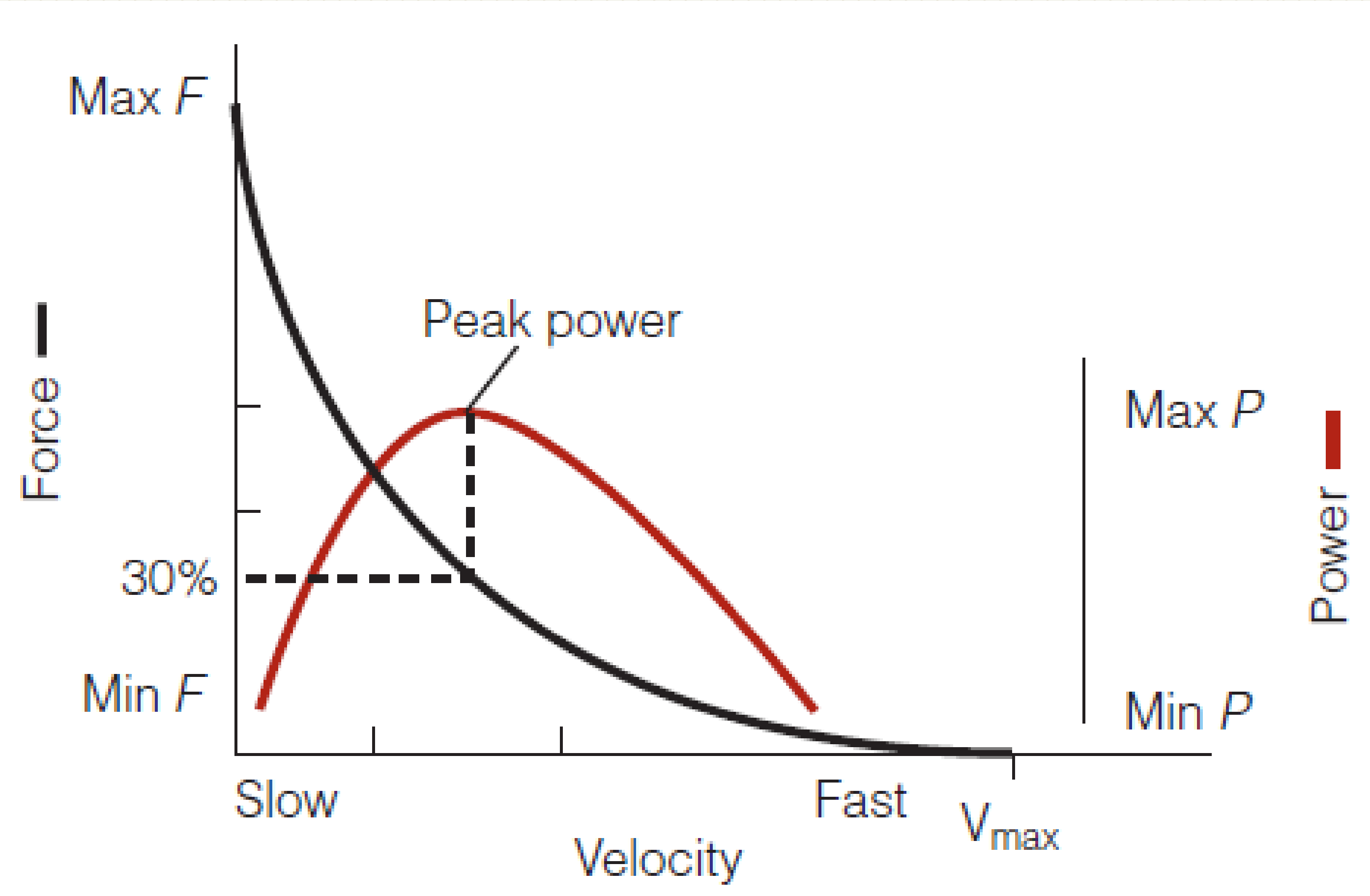


Force-velocity relationship

- **Force-velocity relationship** The greater the load against which a muscle must contract, the lower the velocity of that contraction.



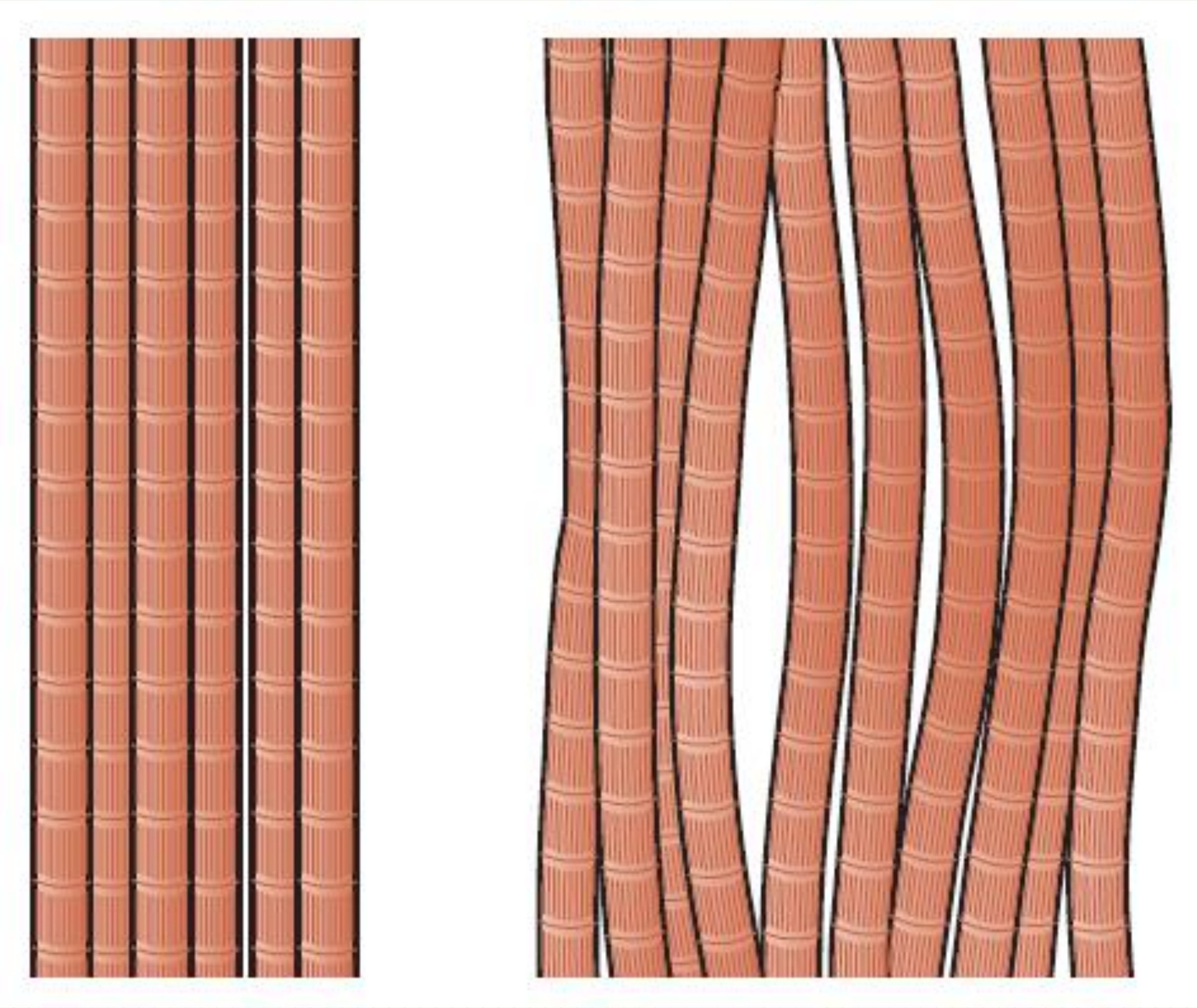
The force, velocity, power relationship



Stretch-shorten cycle

- **Stretch-shorten cycle** The phenomenon of enhanced force by generating eccentric tension immediately prior to the concentric action

Theoretically “slack” fibers



Biomechanics of Muscle Location-Origin-Insertion

Because of its specific location, each individual muscle is capable of carrying out a different movement function. In general, a muscle has two points of attachment: a proximal attachment (sometimes called an **origin**) that tends to be on a relatively immoveable location, and a distal attachment on a relatively more moveable segment (or i**nsertion**).

- **Origin** The point of muscle attachment that tends to be on a relatively immoveable or proximal location.
- **Insertion** The point of muscle attachment that tends to be on a relatively more moveable segment (or distal location).

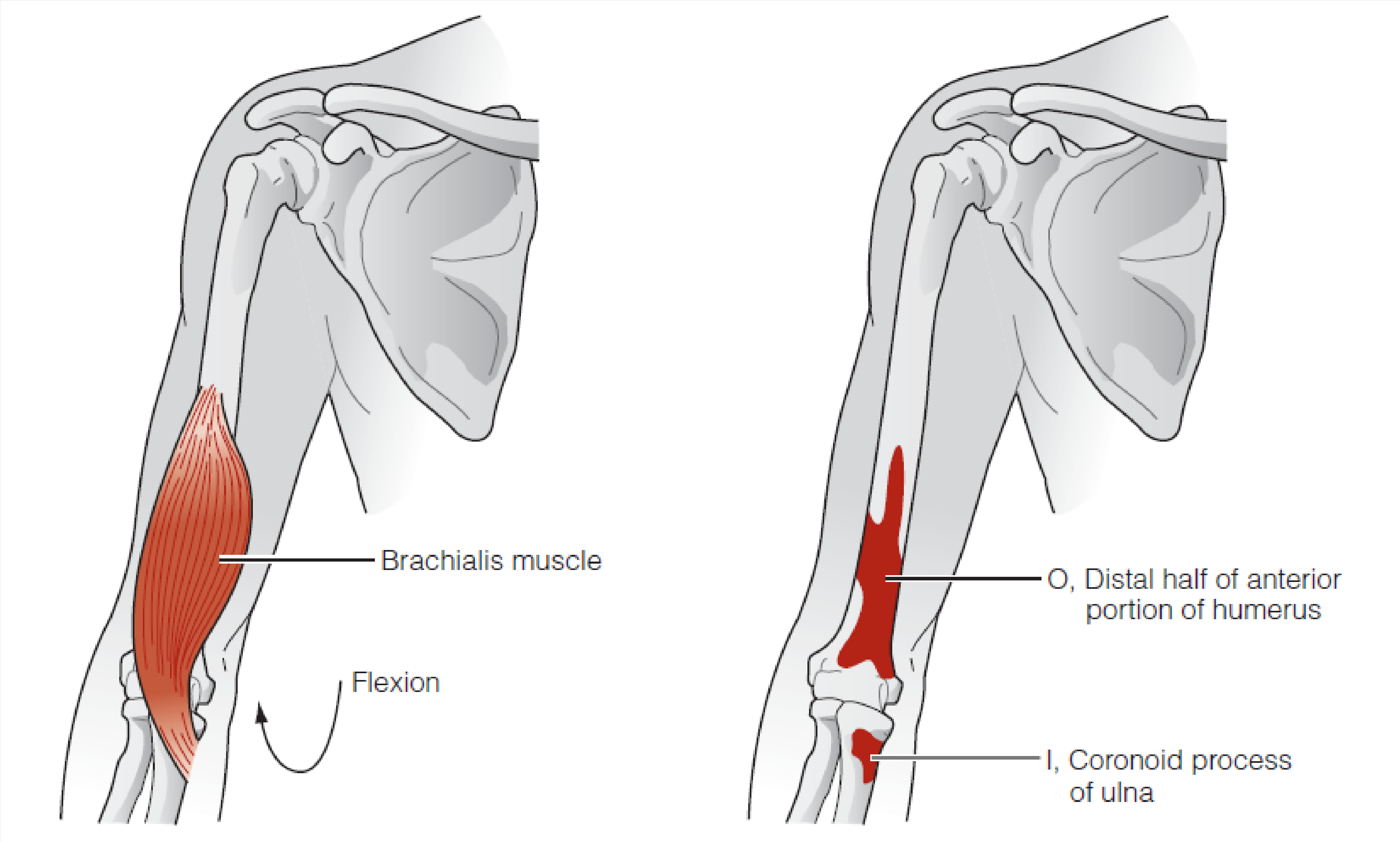
Uniarticular and Multiarticular Muscles

In addition to origin and insertion, a major factor related to the function of an individual muscle is the number of joints (articulations) that it crosses. A muscle can affect the actions of any joint that it crosses.

- **Uniarticular** (**single-joint**) **muscle** A muscle that crosses only a single articulation.
- **Multiarticular** (**multi-** or **compoundjoint**) **muscle** A muscle that crosses two or more articulations.

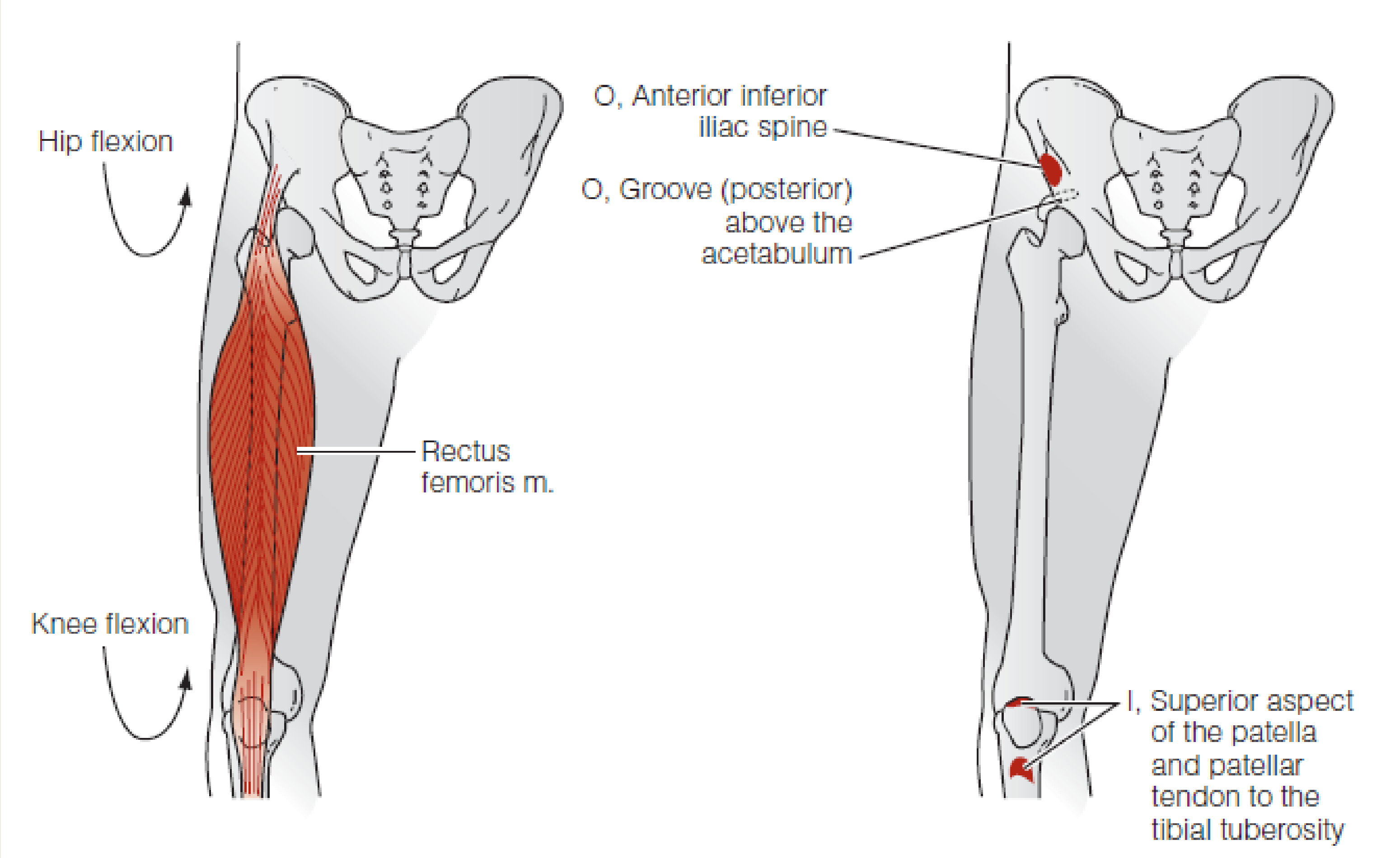
Uniarticular (single-joint) Muscles

Brachialis origin (O) and insertion (I)



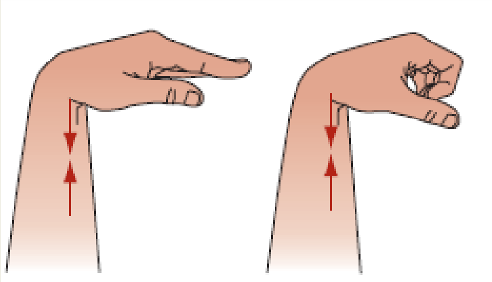
Multiarticular (multi- or compound-joint) Muscles

Rectus femoris origin (O) and insertion (I)

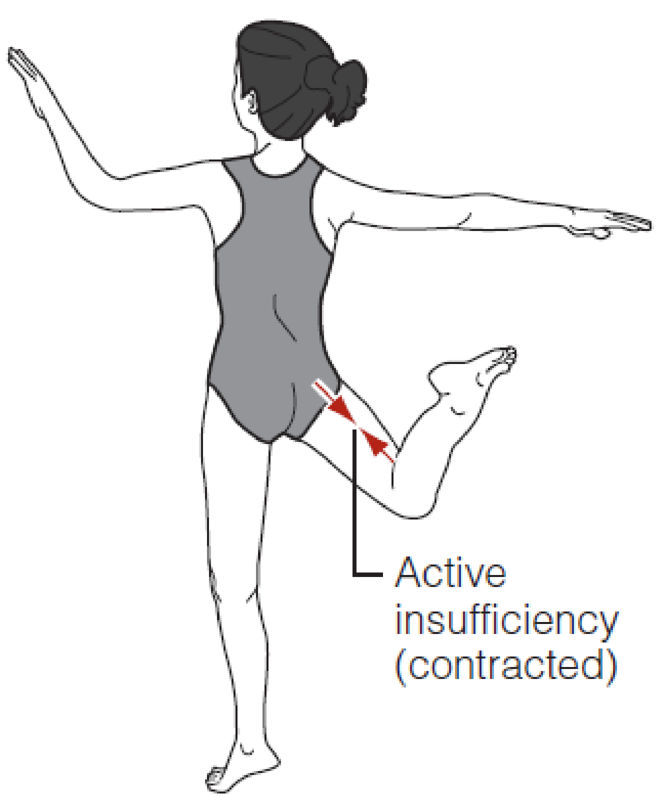


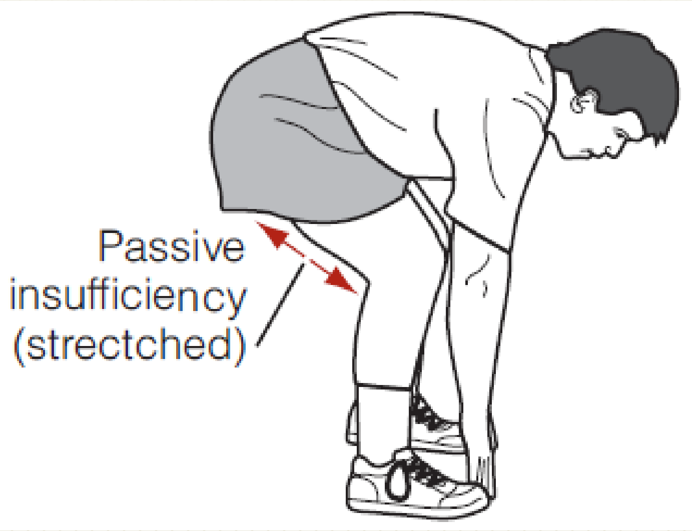
Active and Passive Insufficiency

- **Active insufficiency :** Inability of a multiarticular muscle to generate suffi cient force throughout all degrees of freedom.
- **Passive insufficiency :** Inability of a multiarticular muscle to lengthen to a degree that allows full range of motion at all of the joints that it crosses simultaneously.



Wrist and finger flexors in active insufficiency





Definitions

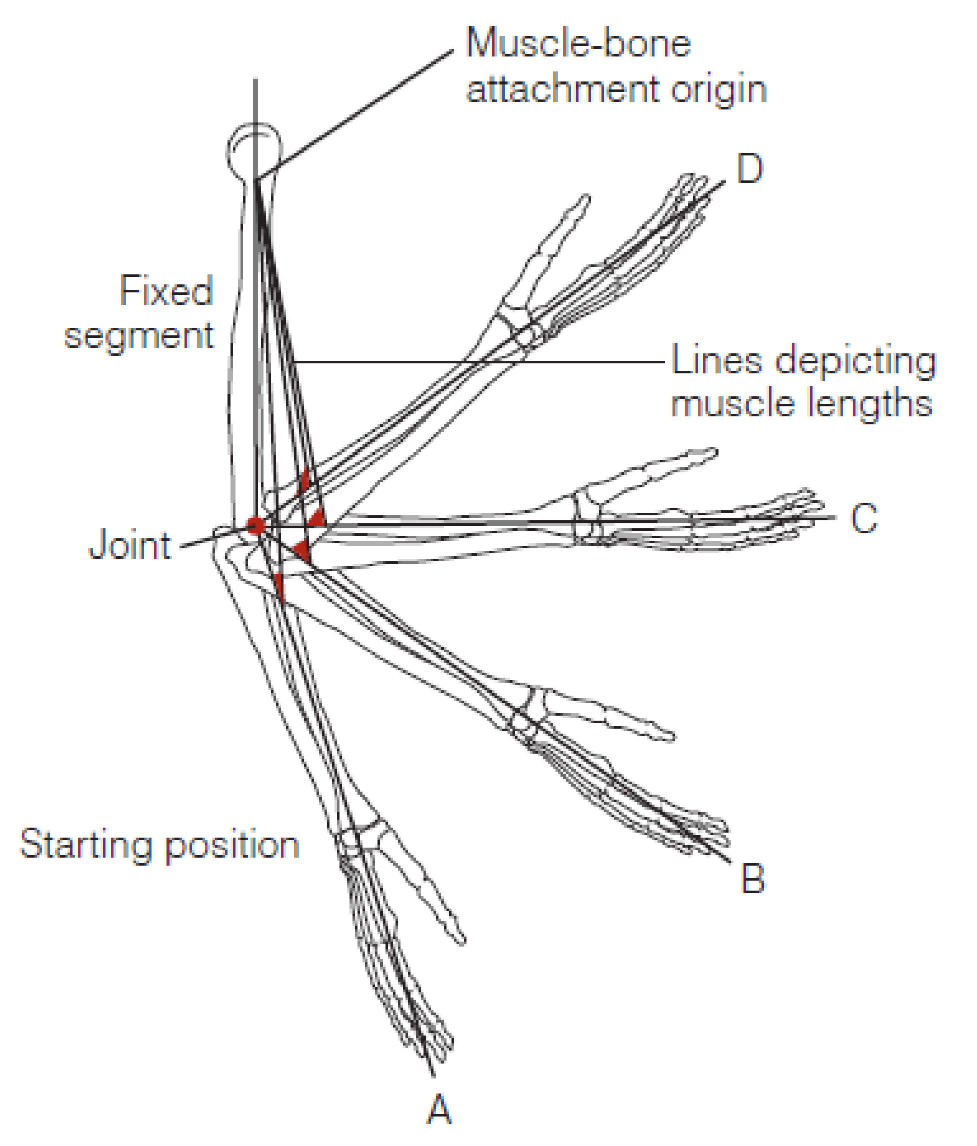
- **Agonists** The muscles that are responsible for causing a particular motion.
- **Prime movers** The agonist muscles that are most directly involved in causing the motion.
- **Synergists** The agonist muscles that are indirectly involved and play a more assistive role in bringing about the motion (i.e., stabilizers or neutralizers).
- **Antagonist** The muscle that performs the joint motion opposite that of the agonist.

The antagonist in the relationship is the muscle that performs the joint motion opposite that of the agonist. The antagonist is therefore usually located on the opposite side of the joint from the agonist. The relationship between the agonist and the antagonist is a fi ne balance.

Angle of Muscle Pull

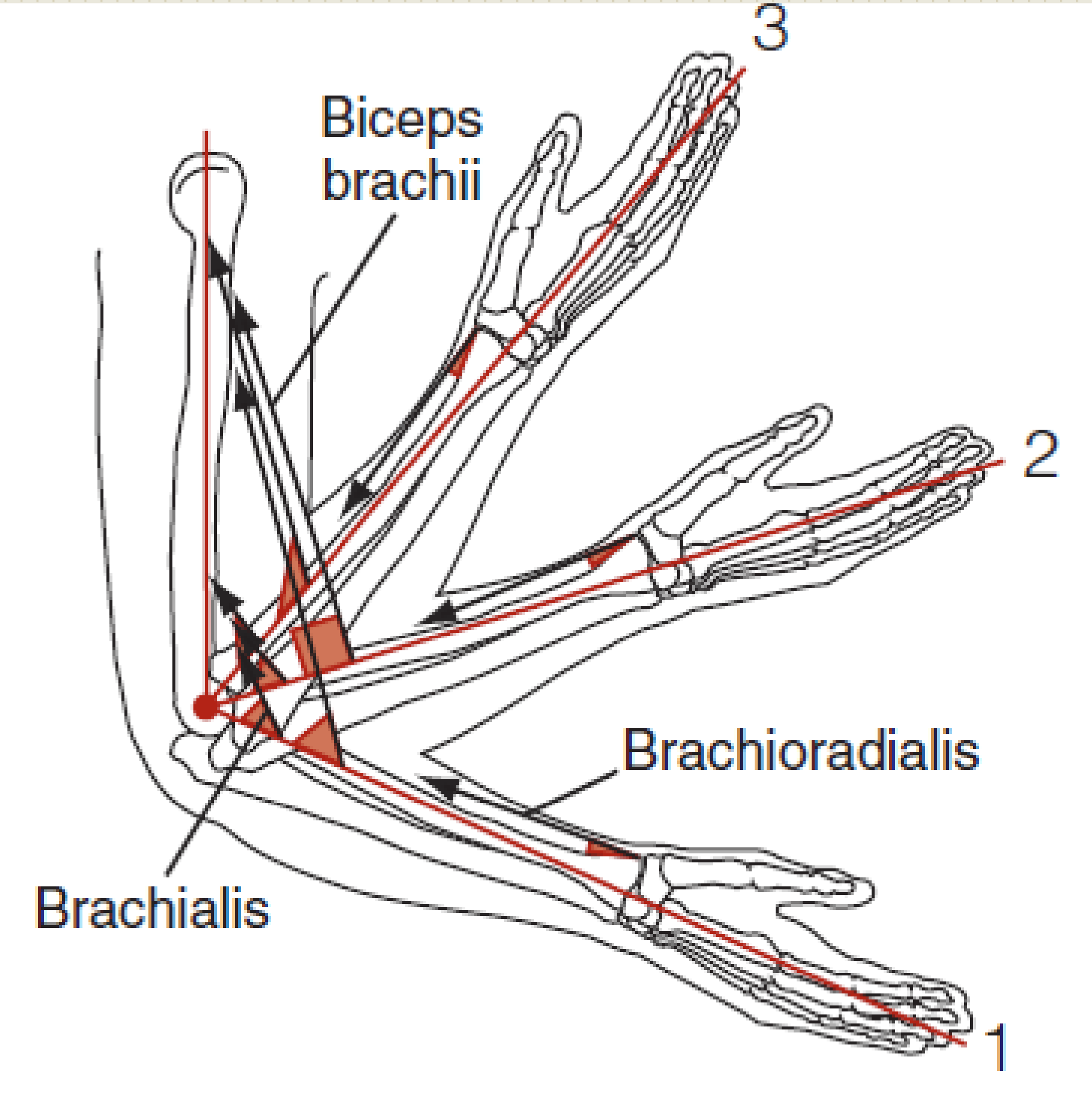
- The muscle’s angle of pull is the angle formed by the muscle force vector relative to the bone on which the muscle is attached. Distinguishing between the joint angle and the angle of pull is very important.

The joint angle is that formed by the bones of the articulation; the angle of pull is formed by the muscle and the bone of attachment. The angles are not necessarily the same, so do not make that assumption.



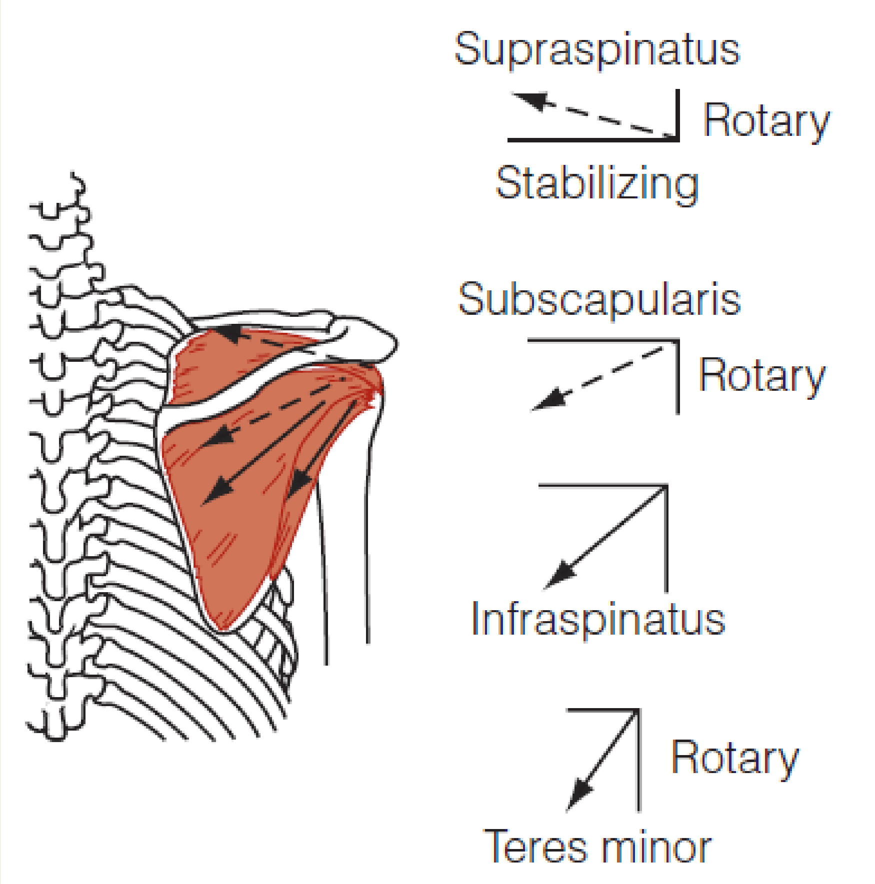
Angle of Muscle Pull

The angle of pull for each of the three elbow flexors at different joint angles



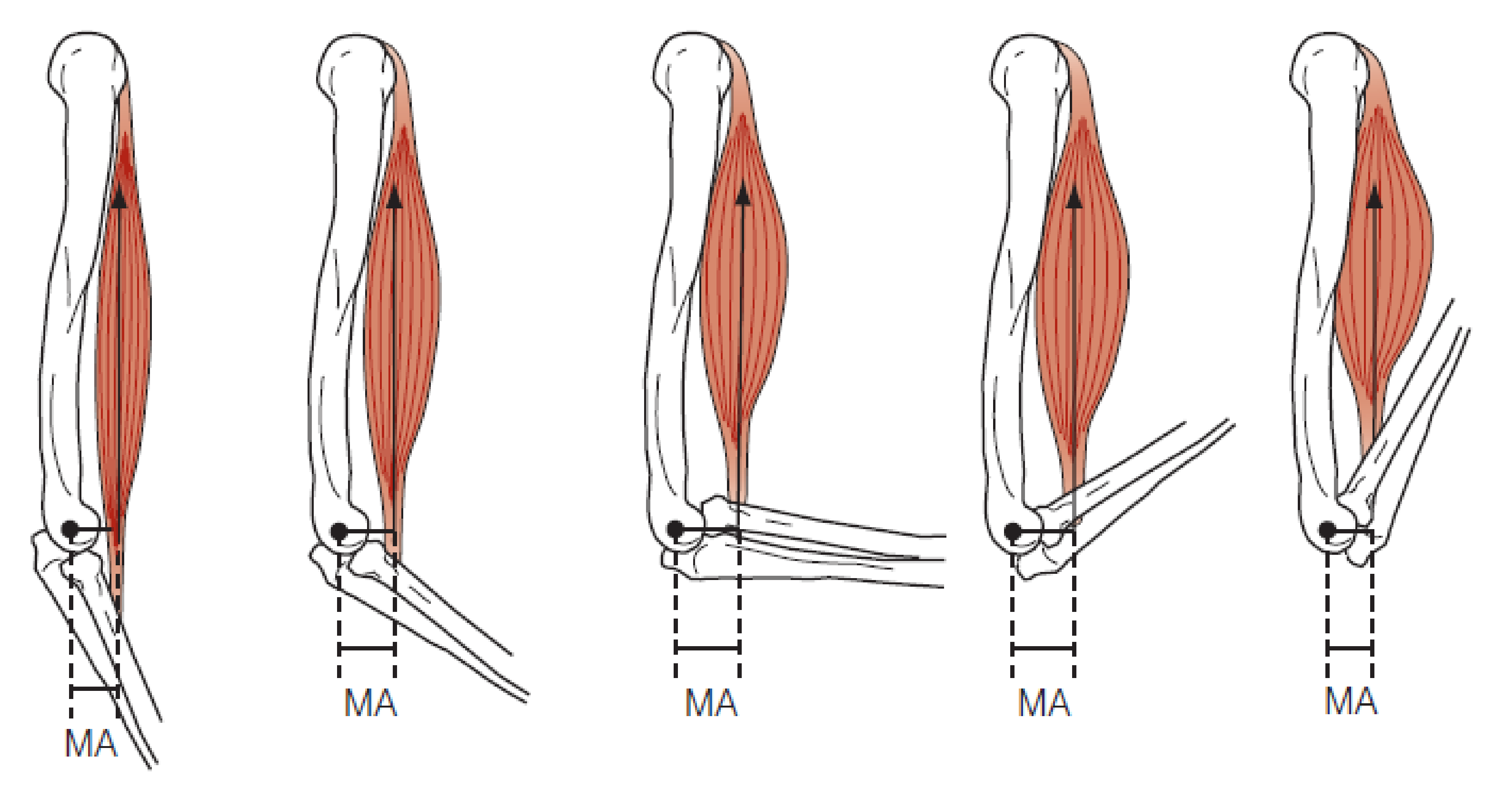
Rotator cuff

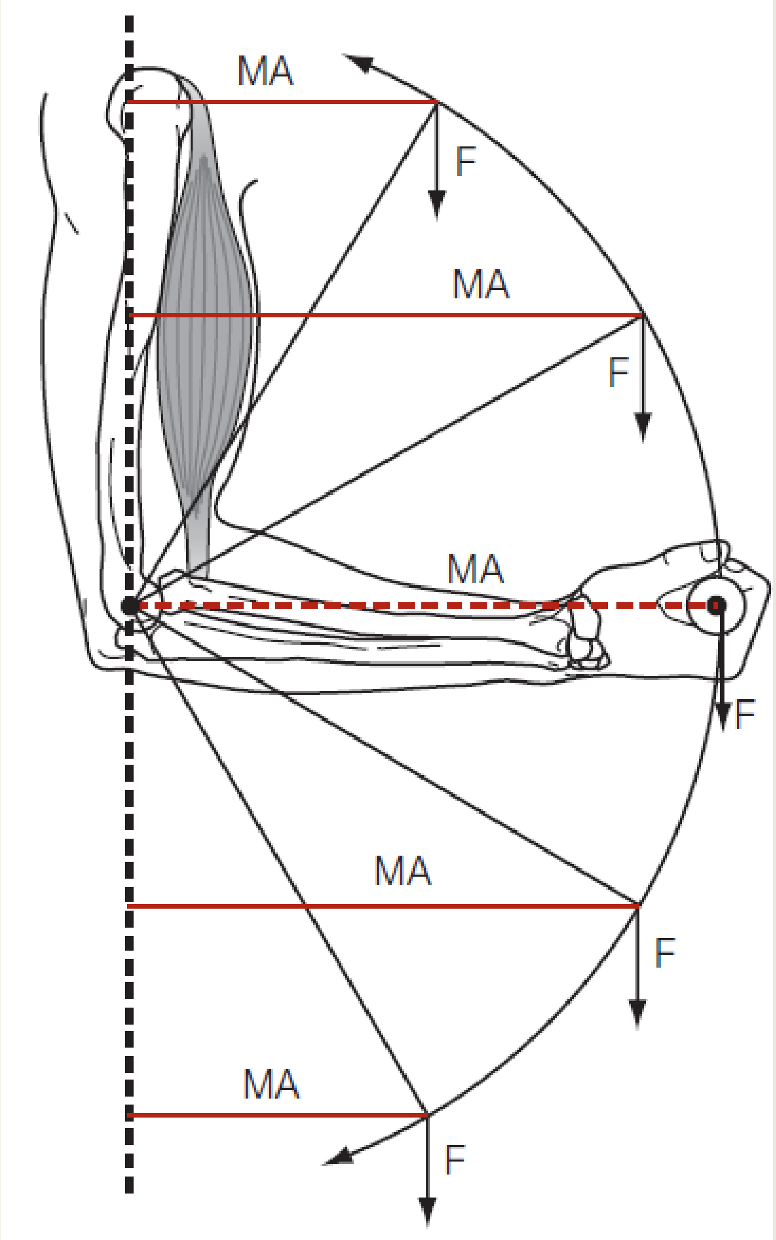
- **Rotator cuff** The muscle group comprised of the supraspinatus, infraspinatus, teres minor, and subscapularis.



Angles of pull of the rotator cuff muscles.

Moment Arm





Muscle Classification in Biomechanics

Muscles are classified in many different ways:

- Action, (flexor, extensor, levator),
- Direction (oblique, transverse),
- Location in relation to anatomical directions (anterior, posterior, medialis, lateralis),
- Location on the skeleton (brachii, femoris, gluteus, pectoralis, scapulae),
- Origin and insertion (brachioradialis, sternocleidomastoid),
- Number of heads (biceps, triceps),
- Shape (gracilis, rhomboid, teres, trapezius), and
- Size (maximus, medialis, minimus).

Muscle Classification in Biomechanics

Most names for muscles are derived from any number of combinations of these classifi cations (for example, biceps femoris, gluteus maximus, levator scapulae, pectoralis major, serratus anterior). Learning the names of muscles is important from a purely anatomical perspective.

However

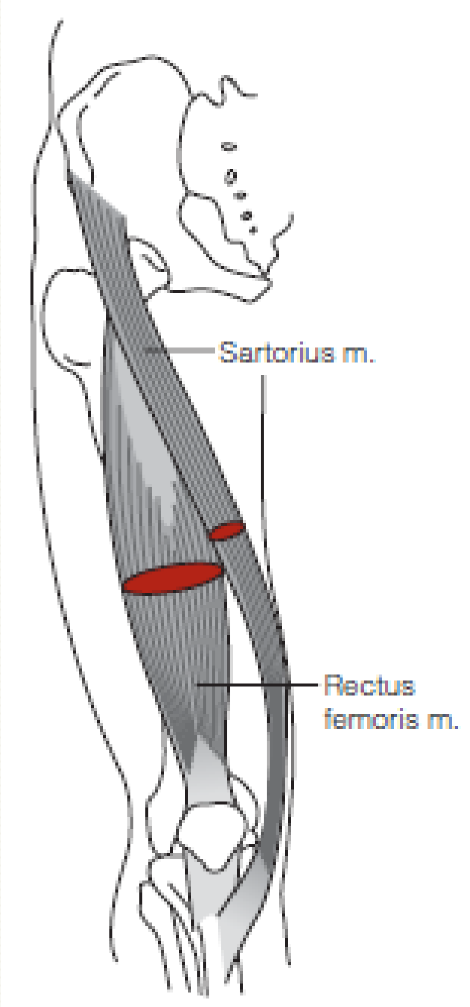
Biomechanics of Muscle Architecture

- In biomechanics we are more interested in muscle function arising from architecture.

- Whole muscles vary widely in their maximal force production capability. The reported values of stress exerted by a maximally contracting muscle usually range from approximately 10 N/cm2 to 50 N/cm2 of active cross-sectional area (the cross-sectional area of the fi bers actively producing tension).

Biomechanics of Muscle Architecture

- **Anatomical cross-sectional area** The cross-sectional area of a muscle measured perpendicular to the longitudinal axis of the whole muscle at its widest point.



Biomechanics of Muscle Architecture

- It only makes sense that the force produced by a muscle would increase with cross sectional area; greater area means more myofibrils with potential for contractile function.
- However, predicting force output cannot be as simple as measuring anatomical cross-sectional area. Many factors can affect muscle force production.
- A biomechanical factor that may contribute to the large variation noted above is the architecture of the muscle in terms of fiber arrangement and length. In other words, just looking at a cross-section perpendicular to the largest portion of the muscle may not provide the entire picture, because not all of the fibers in different muscles are arranged in the same way.

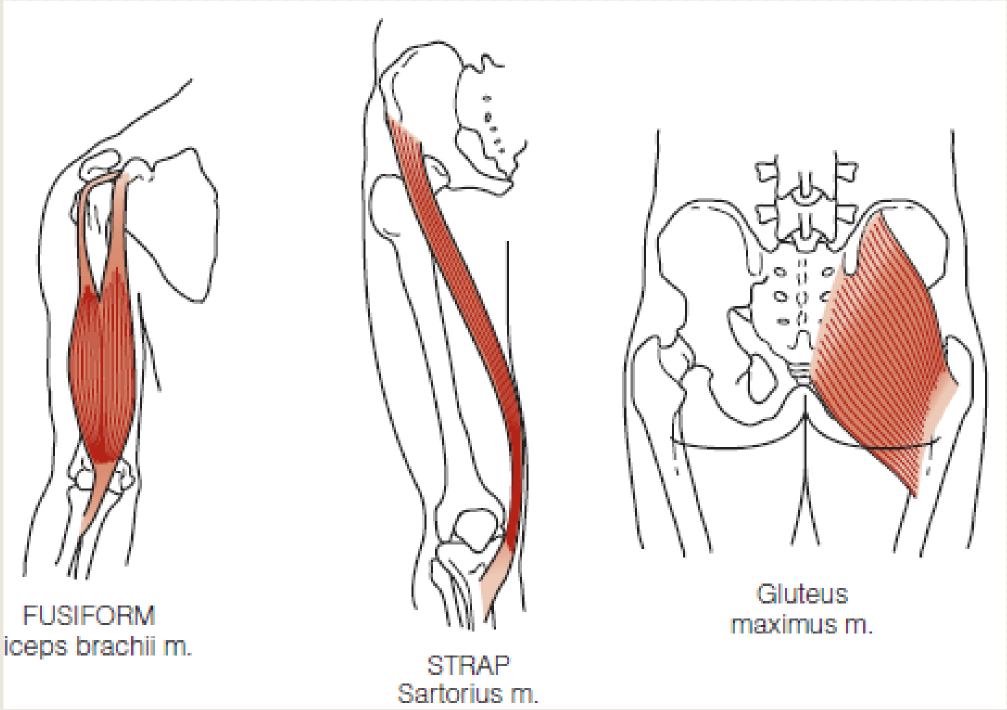
Biomechanics of Muscle Architecture

- A classification of a more biomechanical nature is according to fiber arrangement. Even within this system, many muscle classifications exist. But overall, two basic categories are used, based on fiber arrangement:

  (1) longitudinal (or fusiform) and (2) pennate (“feather-like”).

Biomechanics of Muscle Architecture

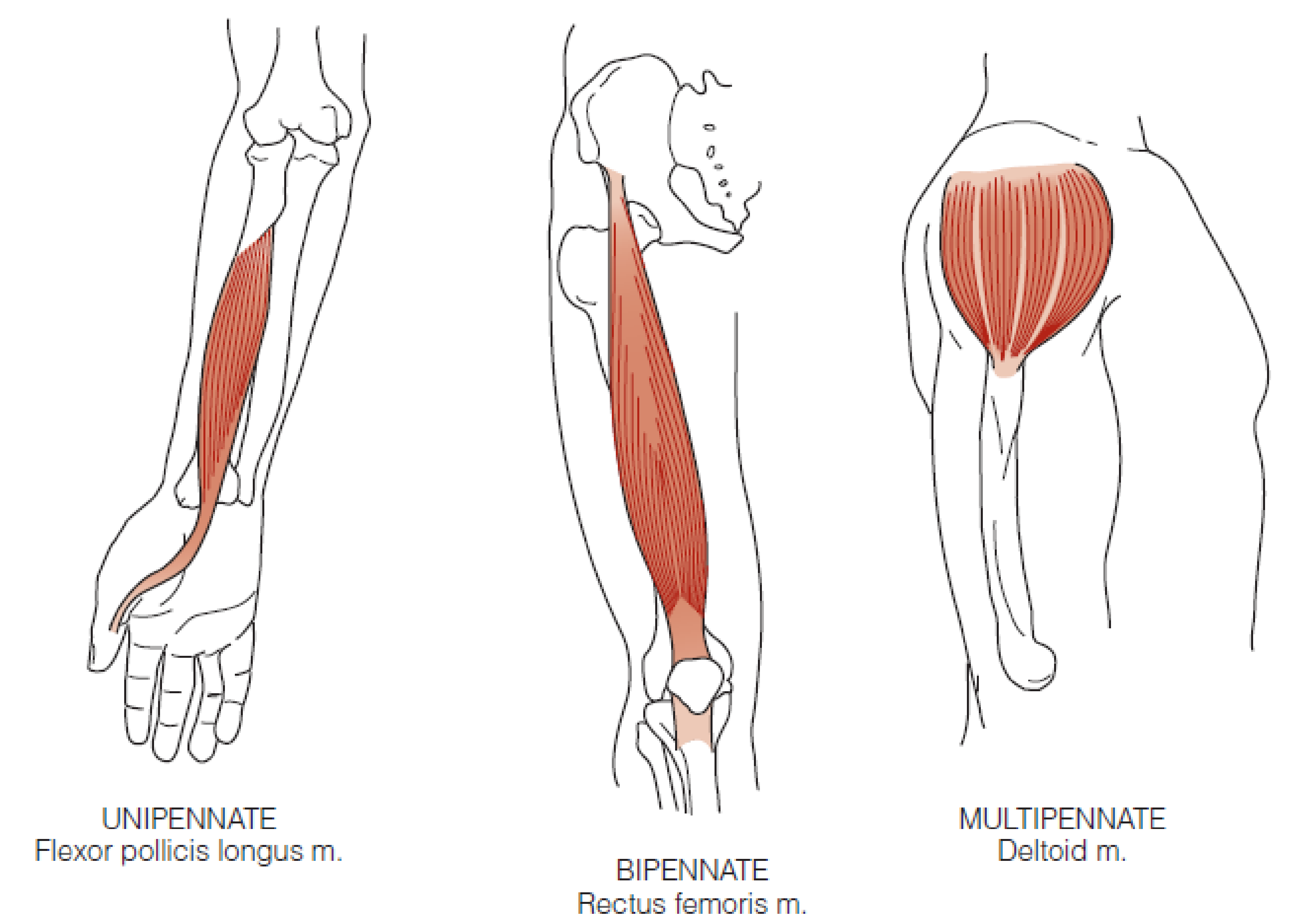
- **Longitudinal** or **fusiform fibers** Muscle fibers that run somewhat parallel to the muscle’s longitudinal axis.
- **Strap muscles** Longitudinal muscles that have less prominent tendons and therefore taper less.
- **Radiate muscles** A longitudinal muscle with an exaggerated taper to the tendon.



Biomechanics of Muscle Architecture

- **Pennate fibers** Fibers that are arranged obliquely to a tendon that runs along the longitudinal axis of the muscle.
- **Unipennate fibers** One set of pennate fibers, parallel to each other but oblique to the tendon.
- **Bipennate fibers** Two groups of pennate fibers, with the fibers in one group parallel to each other but oblique to the other group and to the tendon.
- **Multipennate** Arrangement in which two or more bipennate muscles converge on one tendon to form a single muscle.
- **Pennation angle** The angle at which fibers in a pennate arrangement are oriented relative to the longitudinal axis

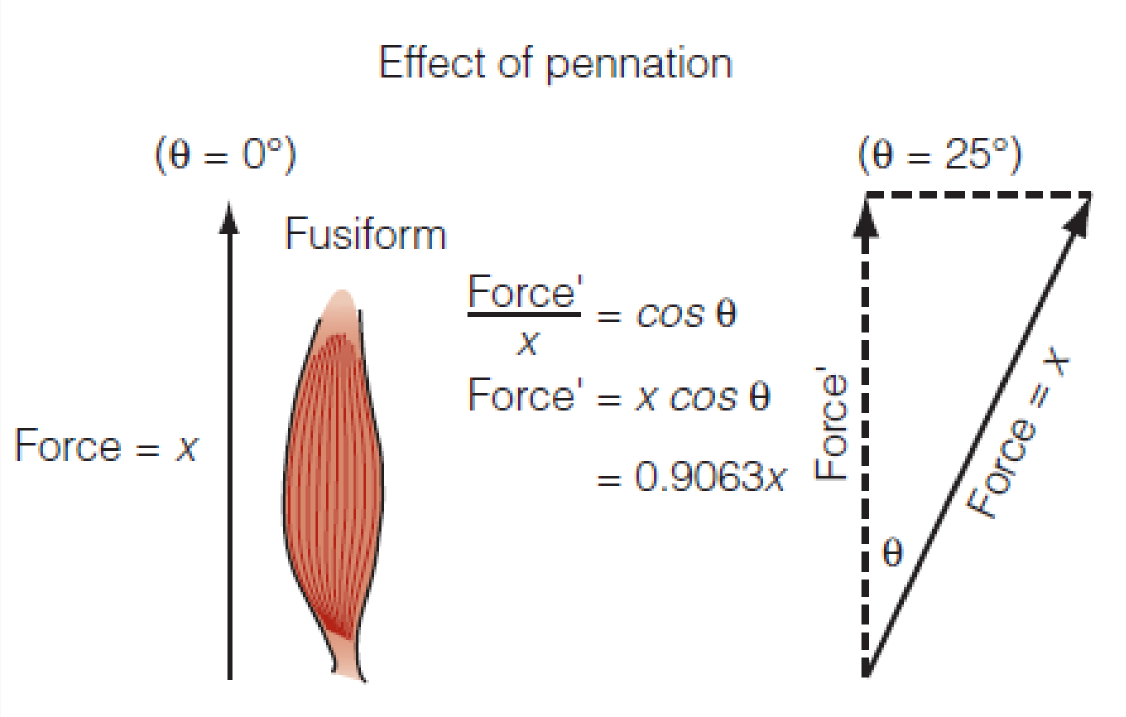
Biomechanics of Muscle Architecture

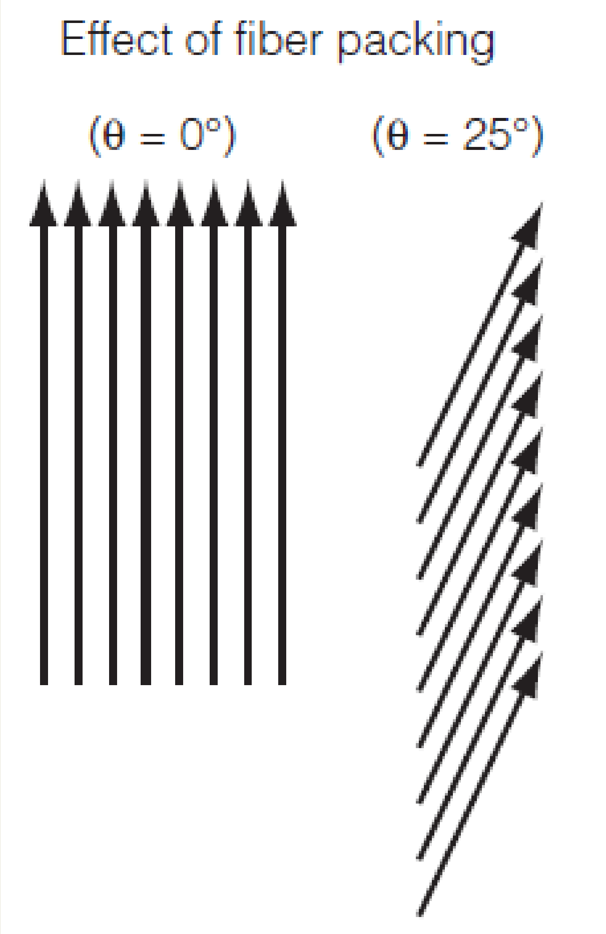


Biomechanics of Muscle Architecture

- The angle at which fibers in a pennate arrangement are oriented relative to the longitudinal axis (pennation angle) varies from muscle to muscle. Pennation angle can be as much as 30 but is rarely larger than 15.

Biomechanics of Muscle Architecture

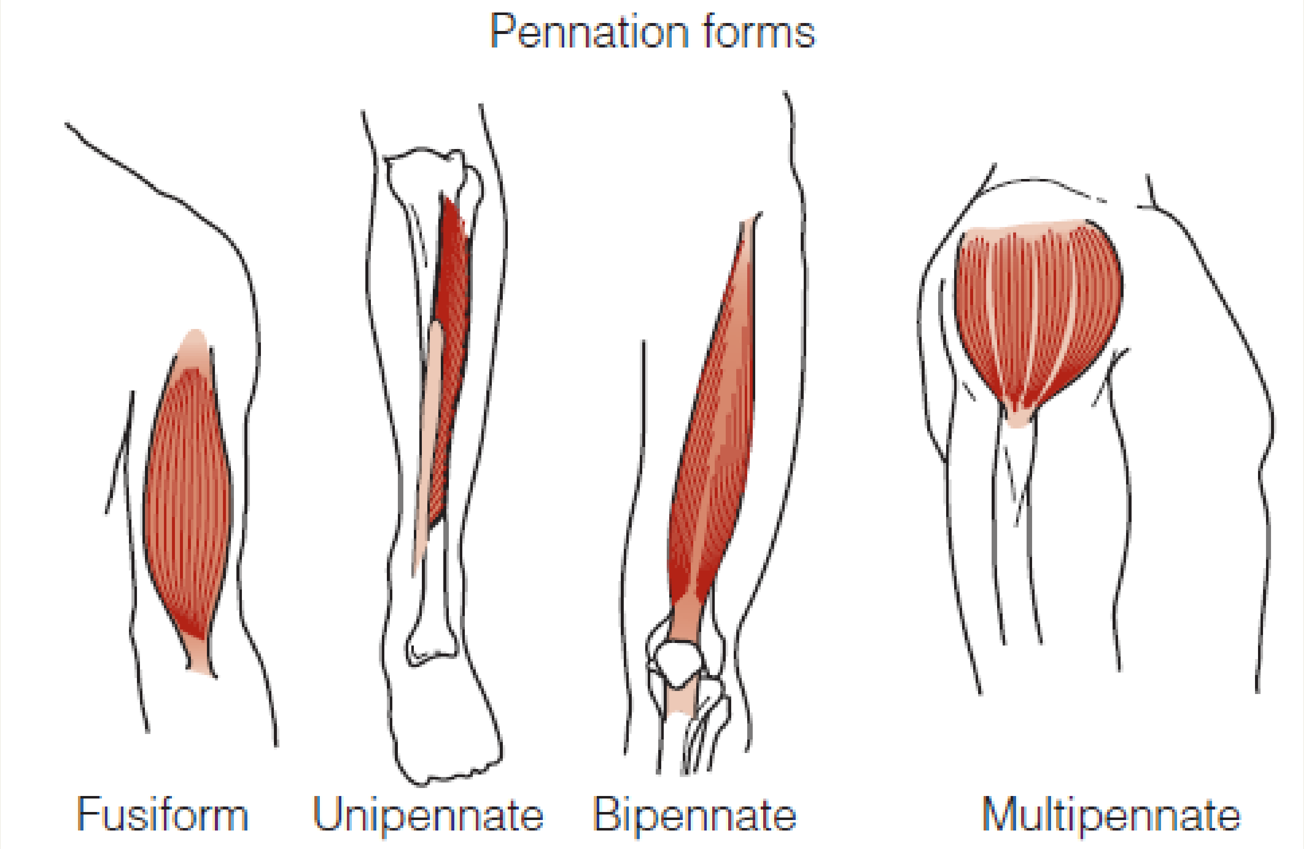




Fiber length = muscle length

Muscle fibers oriented parallel to the axis of force generation transmit all of their force to the tendon

Biomechanics of Muscle Architecture



Biomechanics of Muscle Architecture

- **Anatomical cross-sectional area** underestimates the number of total fibers in a pennated muscle. A better estimation of the force capacity of a muscle is *physiological* cross-sectional area. **Physiological cross-sectional area** (PCSA) is taken perpendicular to all of the fibers in the muscle and is therefore approximately equal to the sum of all of the cross-sectional areas of the individual fibers in that muscle. So, PCSA takes into account the angle of pennation of the fibers in the muscle. PCSA is calculated as follows

$$PCSA = \frac{m \times \cos\theta}{\rho \times l}$$

m = muscle mass in grams

θ = angle of pennation

ρ = density of the muscle in g/cm^3

l = fiber length in cm

$$PCSA = CSA \times \cos\theta$$

CSA = cross-sectional area (cm^2) of a cylinder with equal length to that of the fibers

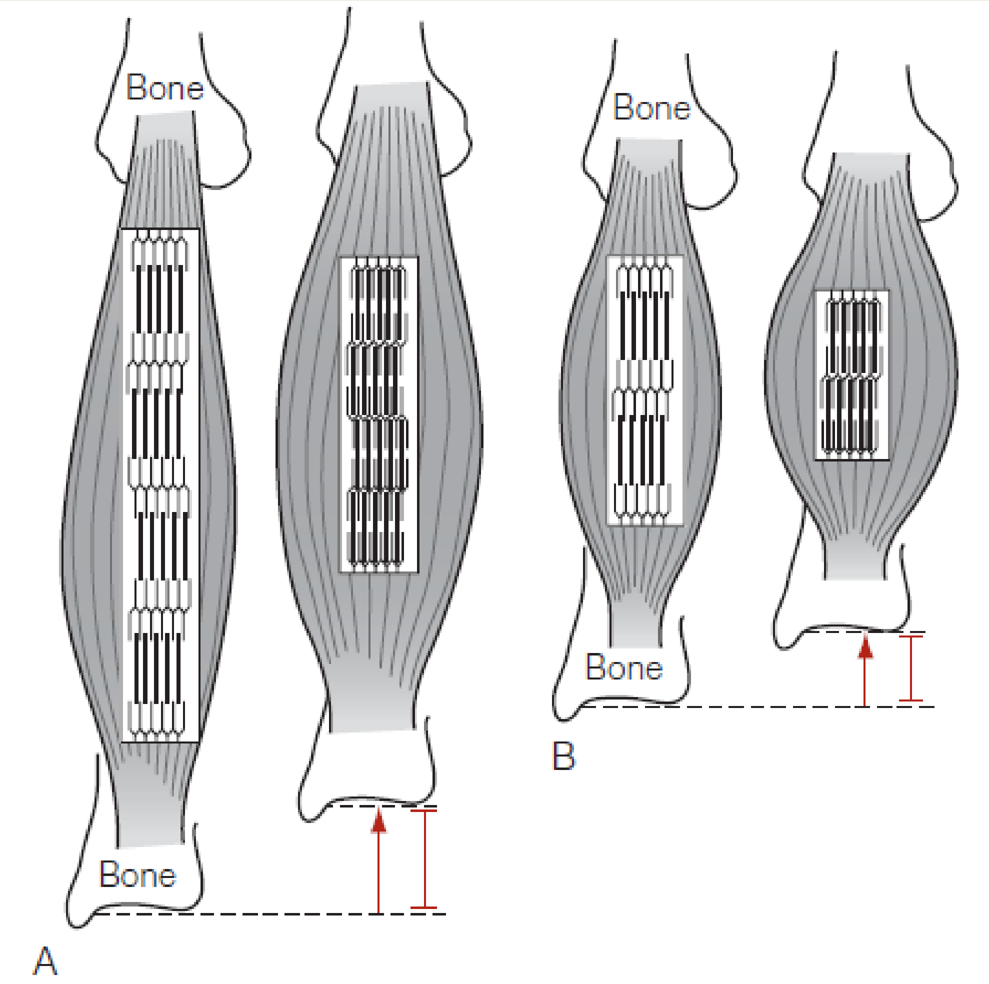
θ = angle of pennation

Biomechanics of Muscle Architecture

- In either equation, the key point is that pennation is taken into account; and the greater the angle of pennation, the greater the physiological cross-sectional area (with all other factors held constant). In a longitudinal fiber arrangement, the anatomical cross-sectional area is approximately equal to the physiological cross-sectional area. However, in a pennated fiber such as the rectus femoris, the physiological crosssectional area is significantly larger than the anatomical cross-sectional area. A large cross-sectional area means that more sarcomeres are contributing to contractile force.

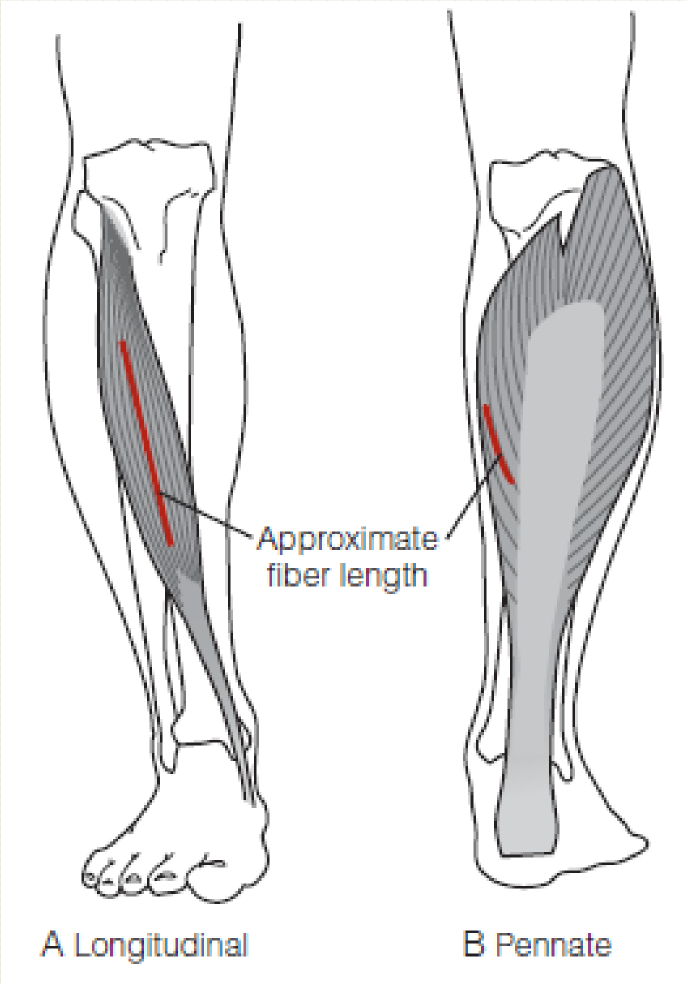
Biomechanics of Muscle Architecture

- More sarcomeres in series, the greater the total amount of fiber shortening that is possible.



Biomechanics of Muscle Architecture

- Fibers do not run the entire length of the muscle in longitudinal fiber arrangements, fibers are longer than those found in pennate arrangements.



Biomechanics of Muscle Architecture

- The fibers of a pennate muscle are arranged obliquely to a tendon that runs along the longitudinal axis of the muscle; as a result, longitudinal muscle fibers have more sarcomeres *in series* than pennate fibers, and are therefore capable of a greater degree of total shortening. The pennate fibers have more sarcomeres *per unit of cross sectional area*, and therefore produce more force. However, this additional force comes at the expense of total shortening capacity. Therefore, longitudinal fiber arrangements tend to be found in muscles designed for producing greater range of motion at a joint, or greater **joint excursion.**

The System

- The human skeletal system is a kinetic chain, a system of linked rigid bodies subject to force application. The links are in the form of various types of joints, and the bones are semi-rigid bodies. Force is applied to the segments by muscle contractions, causing motion at the joints. A lever system consists of a rigid or semi-rigid object (lever) that is capable of rotating about an axis called a fulcrum. Therefore, the human skeleton is analogous to a group of connected lever systems.

The System

- Three types of lever systems exist:

  first, second, and third class.

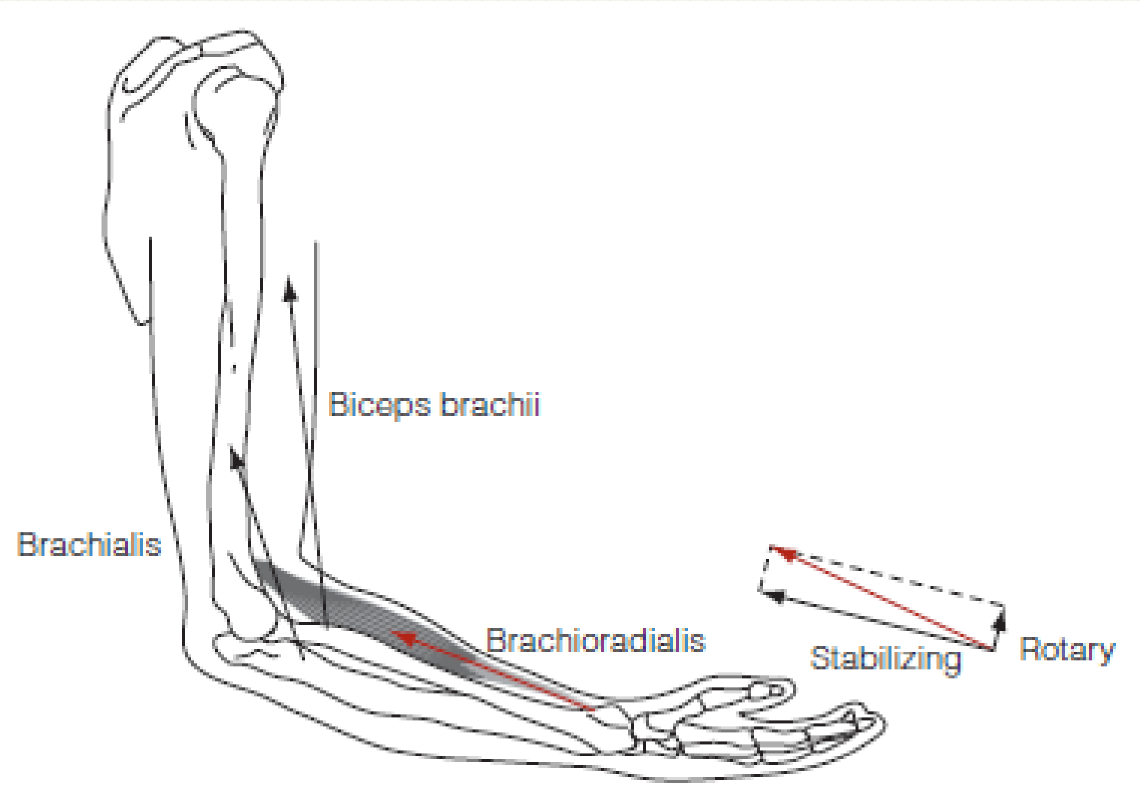
Many musculoskeletal arrangements in the human body can be classified as **third class lever systems**.

In a third class lever system, the motive force (muscle) is between the fulcrum (joint) and the resistive force (segment). Because the radius of rotation for the resistive force is larger than that for the motive force, its linear distance traveled is large relative to that of the motive end of the lever. Therefore, third class levers are used to gain an advantage in linear range of motion and velocity of movement.

Skeletal and Muscular System Interaction

- Because of the design of the skeletal system, the muscular system has certain constraints. Because an axis of rotation exists at each segmental link, the resolved muscle force vector will have components with specifically defined roles. We know that when resolving muscle force vectors, we define the perpendicular component as the rotary component, because if it were allowed to act *alone* it would cause joint rotation. The rotary component does not pass through the axis of rotation, so it always has a moment arm and is therefore torque-producing.
- Also, if the horizontal (parallel) component acted *alone*, it would cause the bones of the articulation to be either pushed tightly together or pulled apart. So, the parallel component of a muscle force vector is defined as either the stabilizing component or the destabilizing component. Because the parallel component always passes through the axis of rotation, it never has a moment arm and is therefore not capable of producing torque.

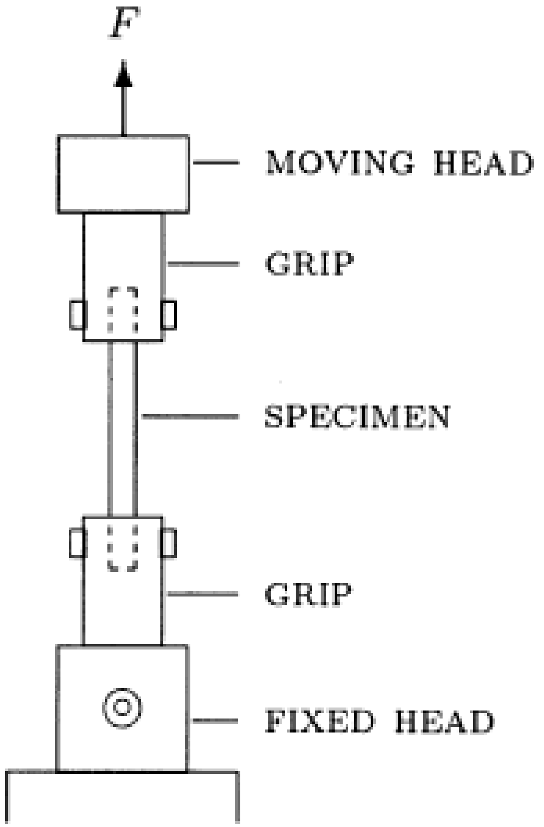
Biomechanics of Muscle Architecture



Brachioradialis muscle force components

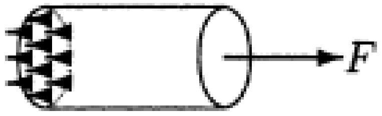
Strength of Materials

Uniaxial tension test



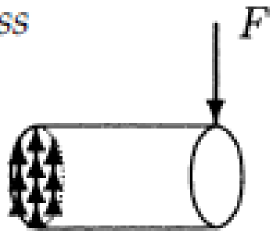
Normal stress

$$\sigma = \frac{F}{A}$$



Shear stress

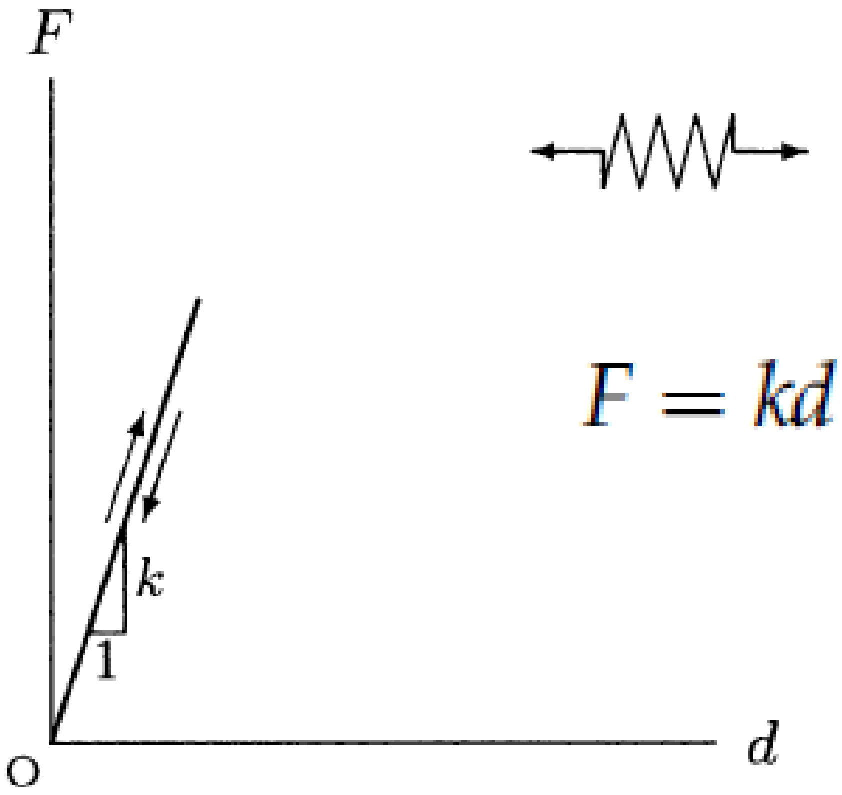
$$\tau = \frac{F}{A}$$



System	Units of stress	Special name
SI	N/m^2	Pascal (Pa)

Hooke's Law

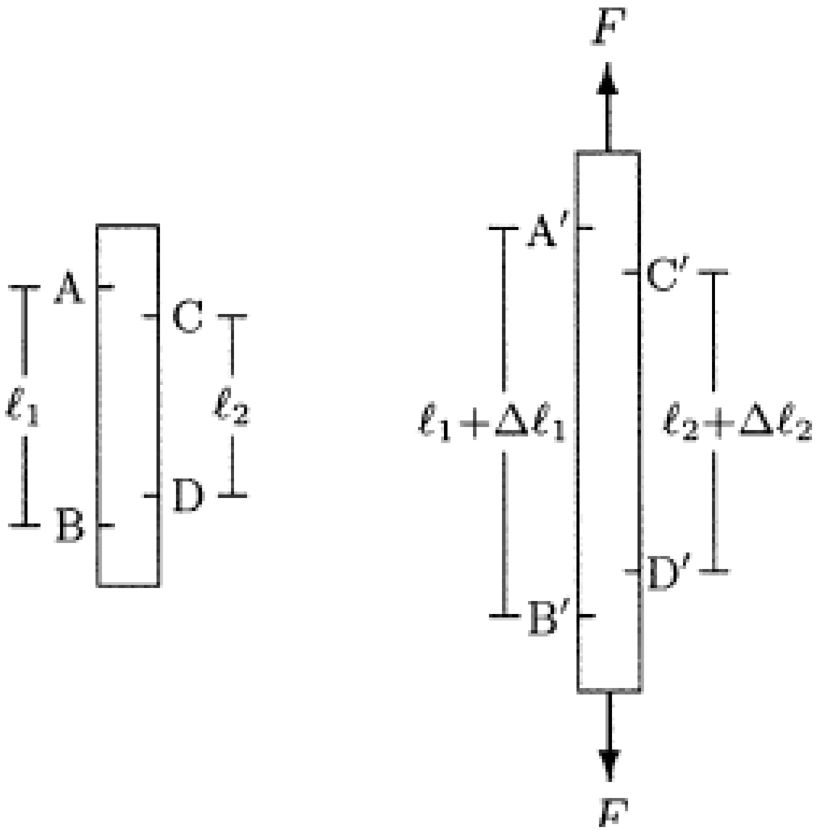
Load-elongation diagram for a linear spring



$$F = kd$$

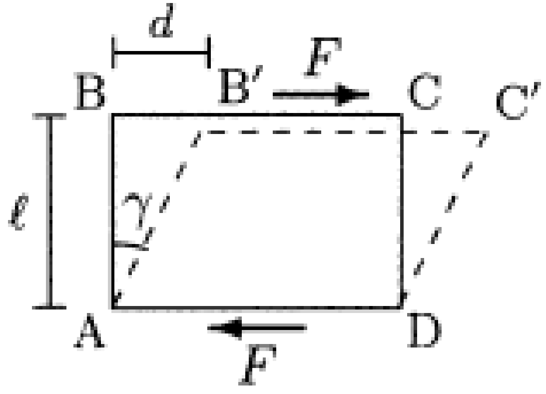
Normal strain

$$\epsilon = \frac{\Delta l}{l}$$



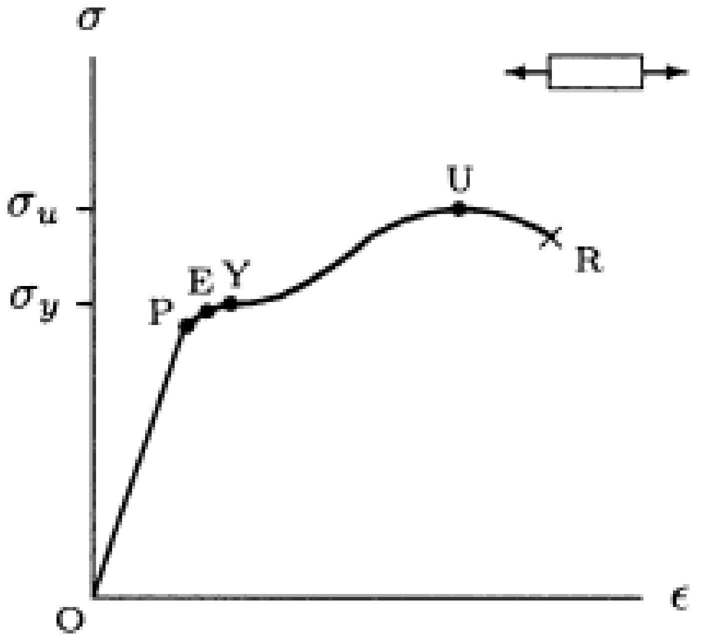
Shear strain

$$\gamma \cong \tan(\gamma) \cong \frac{d}{l}$$

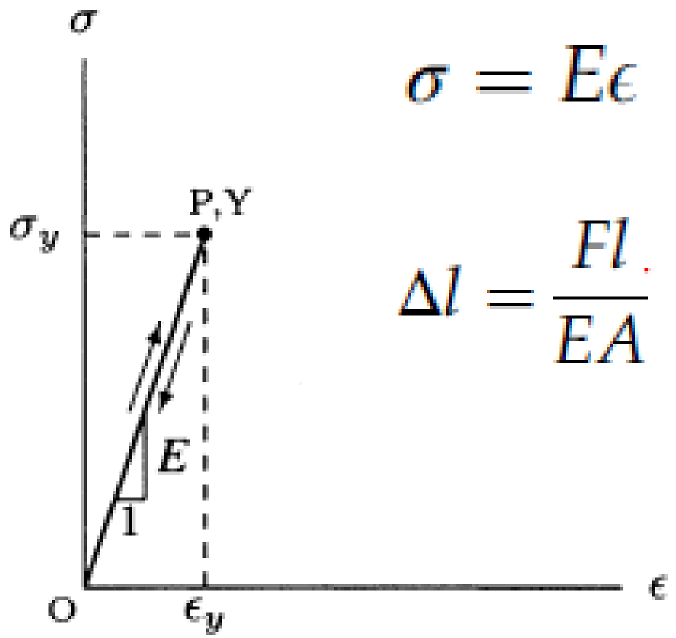


Stress-Strain Diagram

Stress–strain diagram
for axial loading



Stress–strain diagram
for a linearly elastic material
(↗: loading; ↙: unloading)



$$\sigma = E\epsilon$$

$$\Delta l = \frac{Fl}{EA}$$

Stress-Strain Diagram

There are six distinct points on the curve that are labeled as O, P, E, Y, U, and R.

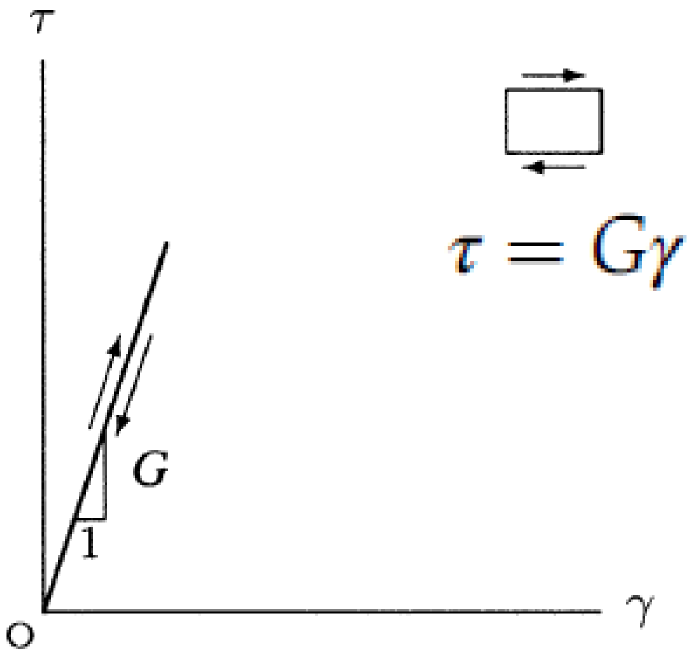
- Point O is the origin of the diagram (no deformation stage)
- Point P represents the proportionality limit. Between O and P, stress and strain are linearly proportional.
- Point E represents the elastic limit. The stress corresponding to the elastic limit is the greatest stress that can be applied to the material without causing any permanent deformation within the material. The material will not resume its original size and shape upon unloading if it is subjected to stress levels beyond the elastic limit.
- Point Y is the yield point, and the stress corresponding to the yield point is called the yield strength of the material. At this stress level, considerable elongation (yielding) can occur without a corresponding increase of load.

Stress-Strain Diagram

- U is the highest stress point on the curve. The stress is the ultimate strength of the material. For some materials, once the ultimate strength is reached, the applied load can be decreased and continued yielding may be observed. This is due to the phenomena called necking.
- R represents the rupture or failure point. The stress at which the rupture occurs is called the rupture strength of the material.

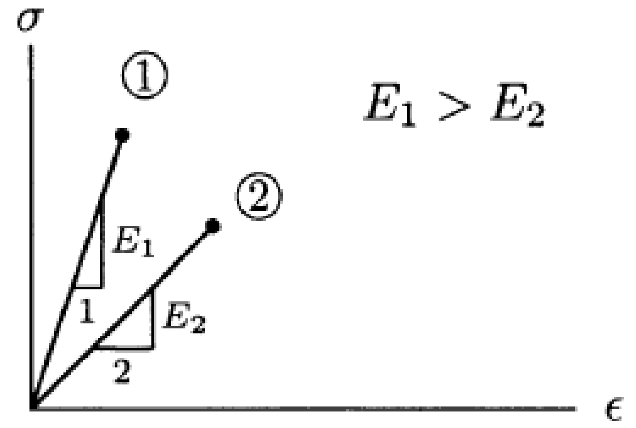
Stress-Strain Diagram

Shear stress versus shear strain diagram for a linearly elastic material

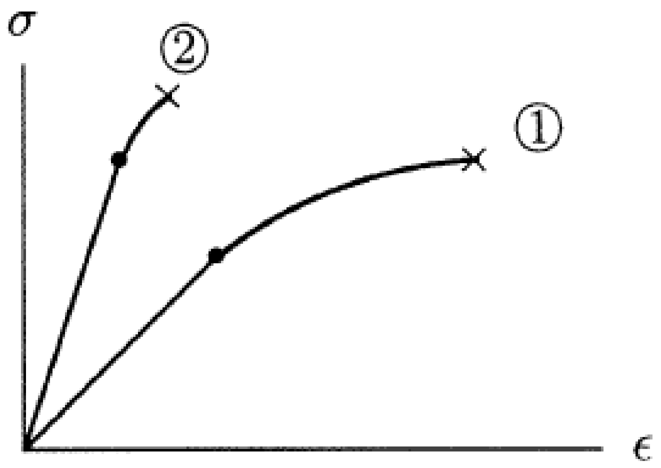


$$\tau = G\gamma$$

Properties Based on Stress–Strain Diagrams

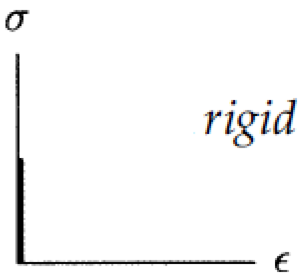


Material 1 is stiffer than material 2

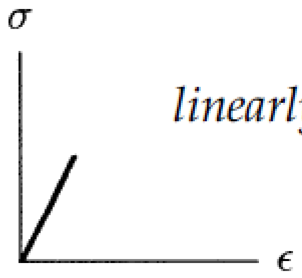


Material 1 is more ductile and less brittle than material 2

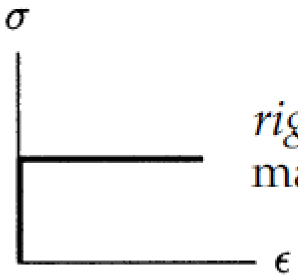
Idealized models of material behavior



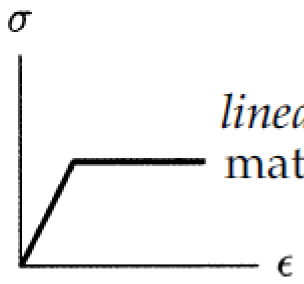
rigid material



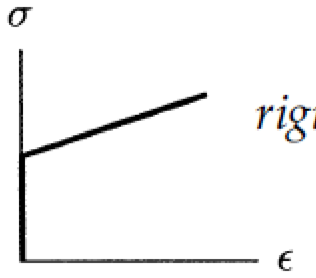
linearly elastic material



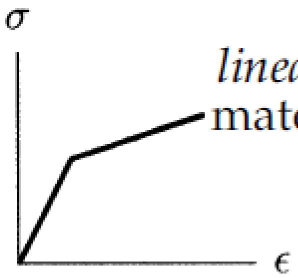
rigid-perfectly plastic material



linearly elastic- perfectly plastic material



rigid-linearly plastic material

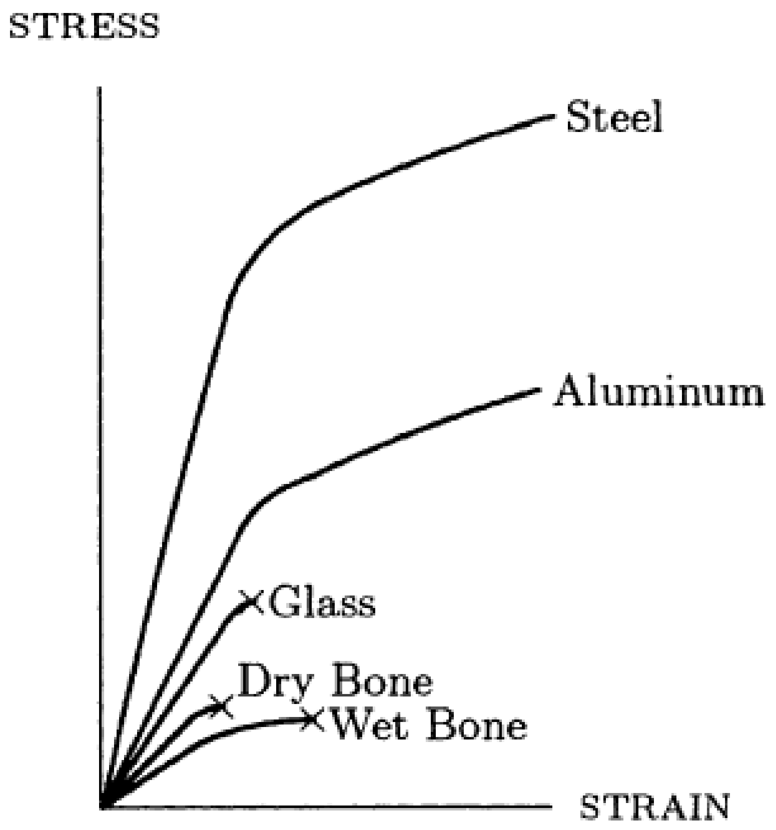


linearly elastic-linearly plastic material

Mechanical Properties of Materials

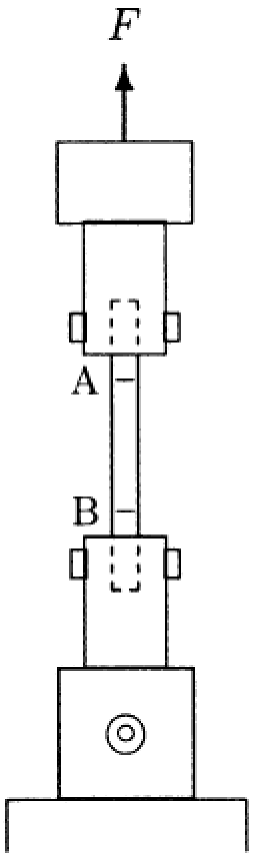
Average mechanical properties of selected materials

Material	Yield strength σ_Y(MPa)	Ultimate strength σ_U (MPa)	Elastic modulus E (MPa)	Shear modulus G (MPa)	Poisson's ratio v
Muscle	–	0.2	–	–	0.49
Tendon	–	70	0.4	–	0.40
Skin	–	8	0.5	–	0.49
Cortical bone	80	130	17	3.3	0.40
Glass	35–70	–	70–80	–	–
Cast iron	40–260	140–380	100–190	42–90	0.29
Aluminum	60–220	90–390	70	28	0.33
Steel	200–700	400–850	200	80	0.30
Titanium	400–800	500–900	100	45	0.34



Gross comparison of stress–strain diagrams of selected materials

Example 1



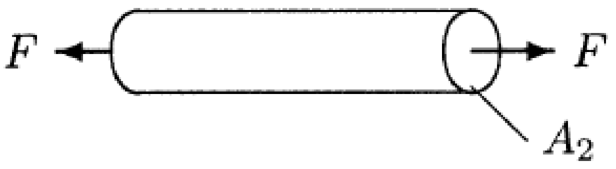
A circular cylindrical rod with radius $r = 1.26\,\text{cm}$ is tested in a uniaxial tension test. Before applying a tensile force of $F = 1000\,\text{N}$, two points A and B that are at a distance $l_0 = 30\,\text{cm}$ (gage length) are marked on the rod. After the force is applied, the distance between A and B is measured as $l_1 = 31.5\,\text{cm}$.

Determine the tensile strain and average tensile stress generated in the rod.

Example 2

Specimen 1: Aluminum Bar

Specimen 2: Steel Rod



Two specimens made of two different materials are tested in a uniaxial tension test by applying a force of $F = 20\,\text{kN}$ $(20 \times 10^3\,\text{N})$ on each specimen

Specimen 1 is an aluminum bar with elastic modulus $E_1 = 70\,\text{GPa}$ $(70 \times 10^9\,\text{Pa})$ and a rectangular cross-section (1 cm × 2 cm). Specimen 2 is a steel rod with elastic modulus $E_2 = 200\,\text{GPa}$ $(200 \times 10^9\,\text{Pa})$ and a circular cross-section (radius 1 cm).

Calculate tensile stresses developed in each specimen. Assuming that the tensile stress in each specimen is below the proportionality limit of the material, calculate the tensile strain for each specimen. Also, if the original length of each specimen was 30 cm, what are their lengths after deformation?

Example 3

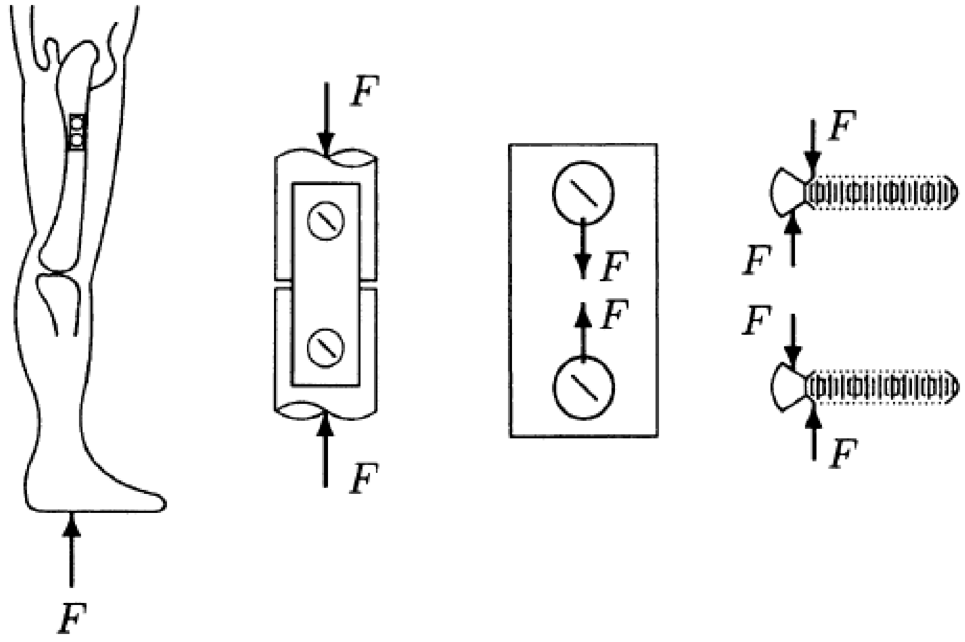


Figure illustrates a fixation device consisting of a plate and two screws, which can be used to stabilize fractured bones. During a single leg stance, a person can apply his/her entire weight to the ground via a single foot.

In such situations, the total weight of the person is applied back on the person through the same foot, which has a compressive effect on the leg, its bones, and joints. In the case of a patient with a fractured leg bone (in this case, the femur), this force is transferred from below to above (distal to proximal) the fracture through the screws of the fixation device.

If the diameter of the screws is $D = 5\,\text{mm}$ and the weight of the patient is $W = 700\,\text{N}$, determine the shear stress exerted on the screws of a two-screw fixation device during a single leg stance on the leg with a fractured bone.

End of the course