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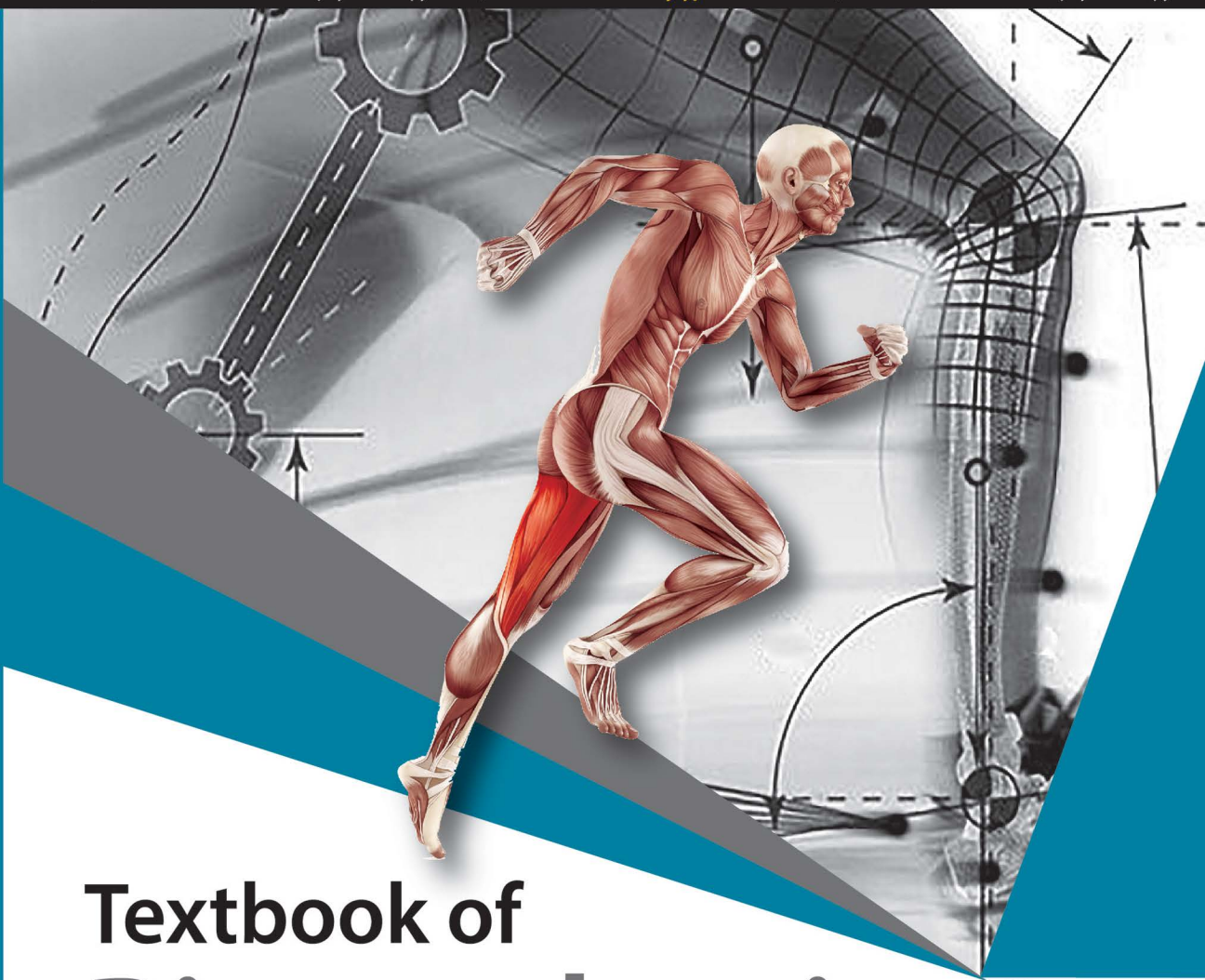

Textbook of Biomechanics & Kinesiology

(Detailed Analysis of Musculoskeletal Structure and Function)

Pavan Kumar G
Ilona Gracie De Souza

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CHAPTER 1

Basic Physics with Biomechanical Perspective

Chapter Outline

- Force: Classification, measurement, types
- Force systems
- Force couple
- Composition of forces
- Human motion: Types of motion
- Newton's law of motion
- Torque
- Friction
- Gravity
- Line of gravity
- Base of support
- Center of gravity
- Equilibrium
- Work, energy, power
- Springs
- Levers
- Elasticity-stress, strain

INTRODUCTION

This chapter is concerned with application of physical principles and methods to the human body. The concepts of force, motion, gravity, work, energy, power, and elasticity are overviewed. This chapter is useful in understanding the physical processes in human body.

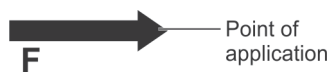
FORCE

Force is that agent, which when applied to a body changes or tends to change the state of rest or uniform motion of the body.

Force is the push or pull of body that causes motion.

Force can be explained on the basis of the following terminologies:

- **Magnitude:** It defines the amount of force applied to a body.
  For example, 40 pounds, 60 pounds, etc.
- **Direction:** Direction is the way in which the force is applied to a body.
  It is either perpendicular or inclined to the surface.
  For example, toward east, west, north or south.
- **Point of application:** It is the exact location at which the force is applied to a body.
- **Line of action of force:** It is the imaginary line that extends from the point of application along with the point of deviation.
- **Representation of force:**
  - A force is represented by an arrow of specific length.
  - An arrow indicates direction.
  - Length of arrow indicates magnitude.
  - Tail of arrow indicates point of application.



Classification of Force

Generally, a force can be classified as:

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- **Based on contact:**
  - *Contact force:* Contact forces are the forces that are produced via, contact either by pushing or pulling of a body. For example, pushing a desk across, kicking a ball, etc.
  - *Noncontact force:* Noncontact forces are those produced without contact of a body. For example, attraction and repulsion of electrically charged particles.
- **Based on production:**
  - *External force:* External forces are those which exert a push or pull on a body and are produced outside the body.
    - Types:
      - Gravitational
      - GRF
      - Frictional
      - Impedance
  - *Internal force:* Internal forces are produced inside the body. For example, contraction of muscle produces tension which acts on the point of attachment and causes movement of bone at joint surfaces.

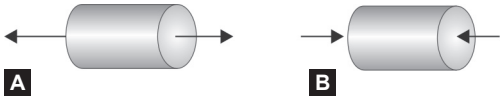
Measurement of Force

Forces can be measured using various units:

- **MKS system:**
  - The unit of meter kilogram second system is newton.
  - One newton is defined as the force applied to a body of mass 1 kg, produces an acceleration of 1 m/sec^2.
- **CKS system:**
  - The unit of centimeter second kilogram system is dyne.
  - One dyne is defined as force applied to a body of mass 1 g produces an acceleration of 1 cm/sec^2.
- **FPS system:**
  - The unit of foot pound second system is pound (lb).
  - One lb is defined as force applied to a body of mass 1 pound, produces an acceleration of 1 ft/sec^2.

Types of Forces

- **Tensile force (Fig. 1.1A):** Tensile force is an external force acting on a body causing elongation of the body. The line of action of forces is always opposite to each other. Mechanical, e.g., when a child sits on a swing, tension force acts along the chains of the swing. Anatomical, e.g., when capsule of a joint is stretched, tension force acts along the joint surfaces.
- **Compressive force (Fig. 1.1B):** Compression force is an external force acting on a body causing shortening of the body. Line of action of force is always toward each other. Compression forces are always opposite to tensile forces. Mechanical, e.g., compression of a sponge occurs, when a stone is placed on a sponge. Anatomical, e.g., in standing position, compression force act on hip, knee, and ankle joint. When both palms are placed together, compression force acts on both the palms.
- **Bending force (Fig. 1.2):** Bending force is an external force acting on a body causing the body to bend. Mechanical, e.g., when a pipe is subjected to bending forces, it causes curving of the pipe. Anatomical, e.g., during forward bending of trunk, tension force develops on the posterior side, while compression force develops on the anterior side. Bending occurs because of the three points force system acting on the object or four points force system acting on the object.
- **Shear force (Figs. 1.3A and B):** Shear force is an external force acting on a body, causing the body to slide over the surface on which it is placed. Mechanical, e.g., using a scissor for cutting paper, the two handles put force in different directions on the pin that holds the two parts together. The force applied to the pin is called shear force.



Figs. 1.1A and B: (A) Tensile stress; (B) Compressive stress

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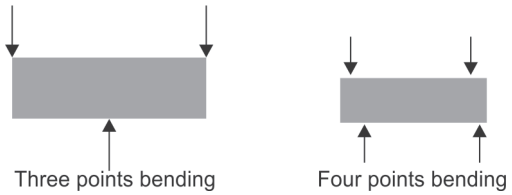


Fig. 1.2: Bending force

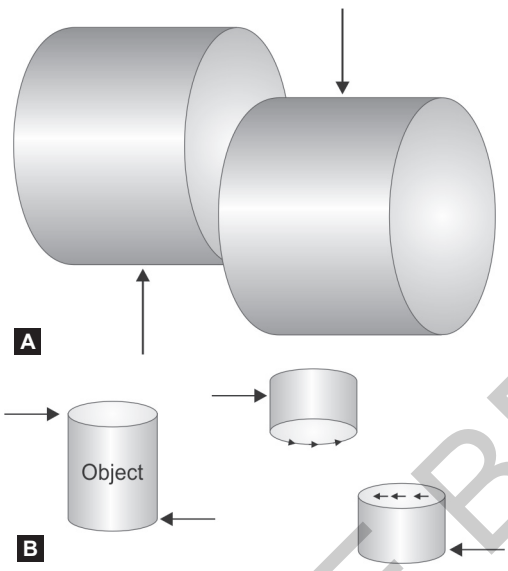


Fig. 1.3A and B: Shear force

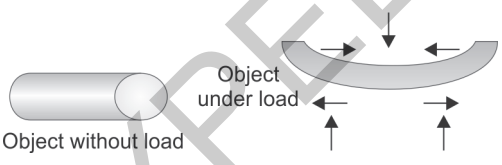


Fig. 1.4: Depicts combination of compressive and tensile forces that results in bending forces

Anatomical, e.g., when person sits from standing position, the femoral condyles slide over the tibial plateaus.

Figure 1.4 depicts combination of compressive and tensile forces that results in bending forces.

- **Torsion force (Fig. 1.5):** Torsion force is an external force acting on a body, causing the body to twist along its long axis. Mechanical, e.g., whenever we turn a key in a lock, the handle of the key is in torsion—when opening a lid of the bottle. Anatomical, e.g., during pronation and supination of forearm, torsion force is developed by pronators and supinators.

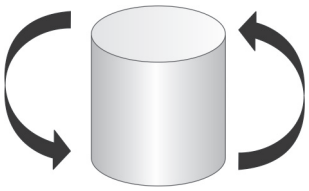


Fig. 1.5: Torsional force

FORCE SYSTEMS

A force system is defined as summation of all the forces influencing a particular body.

There are four types of force systems:

1. Coplanar force system
2. Colinear force system
3. Concurrent force system
4. Parallel force system

Coplanar Force System

In coplanar force system, all forces act in the same plane either in the same or opposite direction.

Mechanical, e.g., coplanar force system can be applied to a lever which has a fixed axis along its length **(Fig. 1.6)**.

- If two forces of equal magnitude act on lever, the lever is maintained in a state of equilibrium.

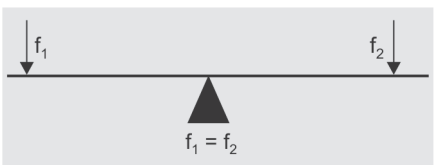
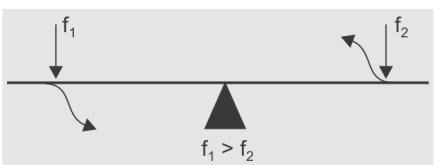


Fig 1.6: Coplanar force system

- If two unequal forces act on lever, the lever moves with respect to the greater force in downward direction while the lighter forces move upward, e.g., see-saw.



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- Anatomical/clinical, e.g., when right and left rectus abdominis muscle contract together, they cause forward flexion of the trunk.

Example: Pushing a wheelchair

- If two forces of equal magnitude act on a wheelchair, the resultant force will be in linear direction along with movement of wheelchair.



- If one force is greater than another, the resultant force moves away from the greater force (unequal force causes rotational movements).



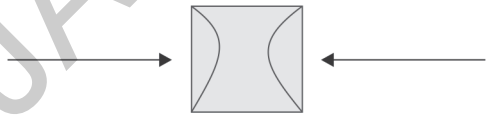
Colinear Force System

It is a specialized form of force system where forces act in the same line along the same plane.

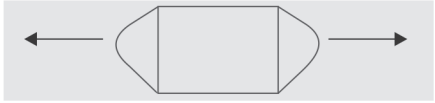
- When greater number of colinear forces act on a body in same direction a pulling or pushing effect is seen.



- When colinear forces act toward each other, the body undergoes compression.



- When colinear forces act away from each other, the body undergoes distraction and tension.



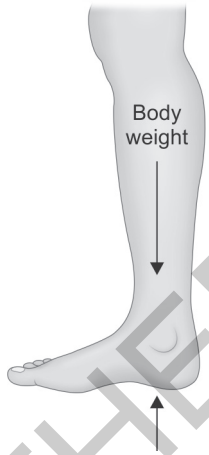


Fig. 1.7: Ground reaction force

Mechanical, e.g., two people standing at the opposite ends of a rope and pulling it.

Anatomical, e.g.,

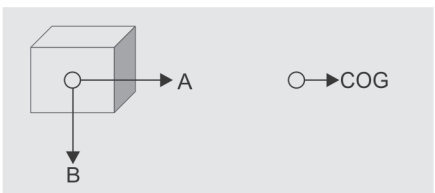
- In standing position, the joint usually undergoes tension and compression.
  Here, the body weight forms the downward force while the ground reaction force signifies the upward force **(Fig. 1.7)**.
- In upper extremity, tension force acts on the shoulder joint.
  Here, the weight of the upper extremity forms the downward force while the muscles of scapula form the upward force.

Any imbalance in these forces causes dislocation of shoulder joint.

Concurrent Force System

In the concurrent force system **(Fig. 1.8)**, the force acting have same point of application but different line of action.

- Mechanical, e.g., a box pulled by two people at the level of center of gravity (COG).



- Anatomical, e.g., action of deltoid muscle at shoulder joint. Deltoid muscle consists

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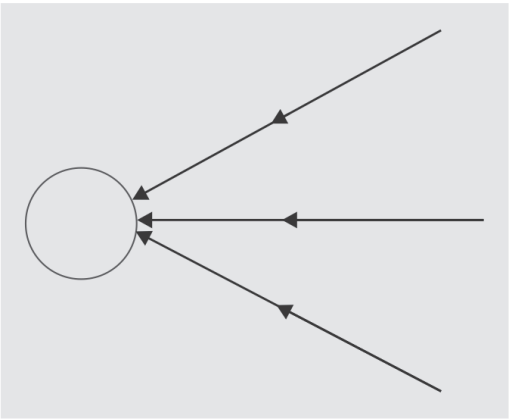


Fig. 1.8: Concurrent force system

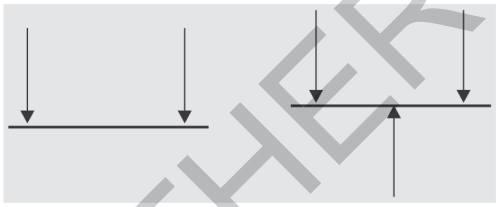
of three fibers, i.e., anterior, middle, and posterior fibers. Anterior fiber causes flexion, middle fiber causes abduction, and posterior fiber causes extension at the shoulder joint, respectively. However, when the anterior and posterior fiber contract together, they causes abduction of the shoulder. Their common point of application is at the deltoid tuberosity **(Fig. 1.9)**.

- Another example of concurrent force system is the action of the quadriceps at the knee joint. Quadriceps is made up of rectus femoris, vastus medialis, vastus intermedius, and vastus lateralis meeting at the common point on the patella **(Fig. 1.10)**.

Parallel Force System

In parallel force system, the line of action of the forces is always parallel to each other and lies in the same plane. They never converge at a joint.

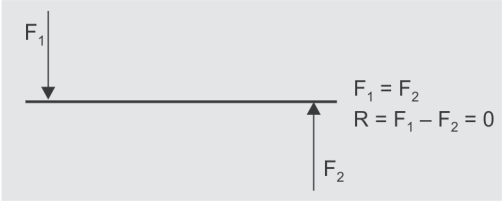
- A parallel force system exists when two or more forces act at some distance from each other.



- Mechanical, e.g., common balance, see-saw.
- Anatomical, e.g., coordinated action of tibialis anterior and gastrocnemius **(Fig. 1.11)**.

FORCE COUPLE

A specialized example of parallel force system occurs when two forces of equal magnitude act at a distance in opposite direction producing a force couple.



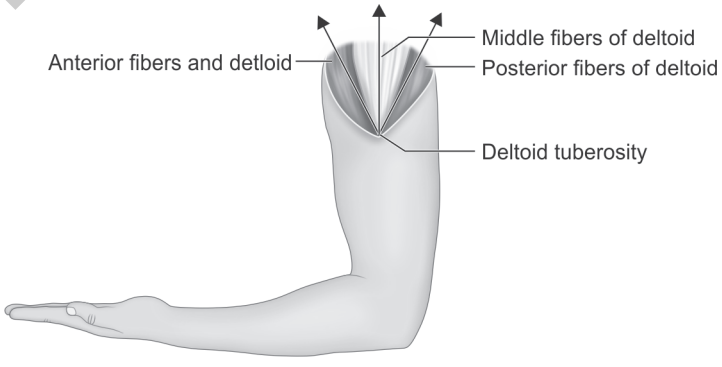


Fig. 1.9: Concurrent force system in upper extremity

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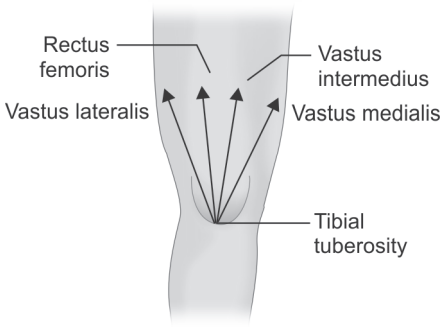


Fig. 1.10: Concurrent force system in right leg

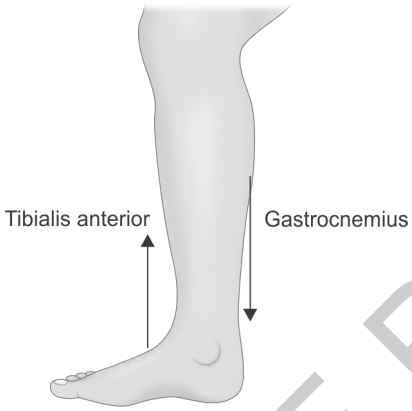
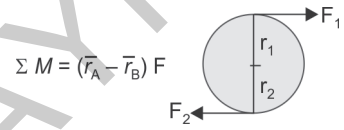


Fig. 1.11: Parallel force system

As the forces are equal and opposite, the body turns without linear displacement or oscillation.

- $F_R = 0$ but



  - Mechanical, e.g., closing or opening a water tap, steering a wheel.
  - While steering toward right side, a downward force is produced by the right hand. At the same time, an upward force is produced by the left hand. The resultant force produced is zero but the wheel turns around its axis.
  - Anatomical, e.g., during shoulder abduction, force couple causes lateral rotation of the scapula **(Fig. 1.12)**.

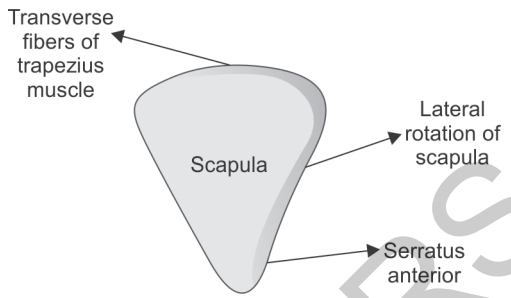
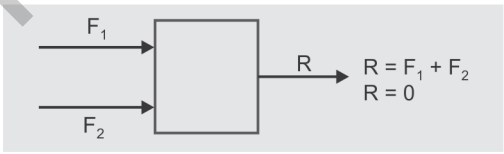


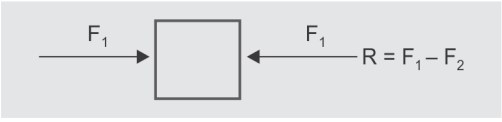
Fig. 1.12: Anatomical example of force couple

COMPOSITION OF FORCES

- It is a process of combining all the given forces to calculate a resultant force.
- If the resultant force calculated is zero, then the body is said to be in a state of equilibrium.
- When the forces acting on a body are in the same direction, the resultant force is calculated by adding all the given forces.



- When the forces acting on a body are in opposite direction, the resultant force is calculated by subtraction of one force from another.



  - Practically, as forces are multidirectional, it cannot be calculated by methods of simple addition or subtraction.
  - In such cases, resultant force is calculated using graphical methods.
  - Following graphical methods are used:
- **Triangle method:** The triangle method states that *"If two forces act on two sides of a triangle, then the resultant force is represented by third side of the triangle taken in opposite order."*

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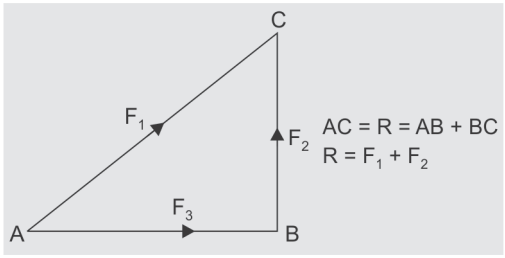
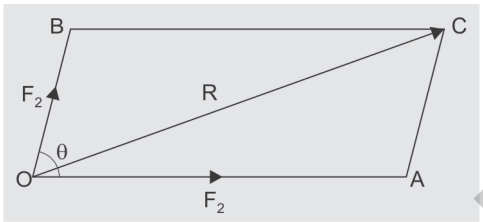
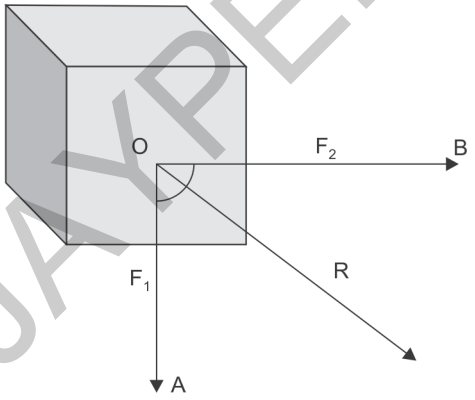


- **Parallelogram method:**
  - It states that *"If two forces are represented by adjacent sides of a parallelogram, then the resultant force is represented by the diagonal of the parallelogram drawn from the same point."*



$$R = \sqrt{f1^2 + f2^2} + 2f1.f2\cos\theta$$

  - Mechanical, e.g., when a wooden box is pulled from both the sides, the box moves in the direction of the diagonal of the parallelogram (resultant force).



- **Anatomical:** The action of right upper trapezius and left upper trapezius, acting together will result in the resultant force of neck extension **(Fig. 1.13)**.
- **Polygon method:** This method is used when more than two forces act on a body.

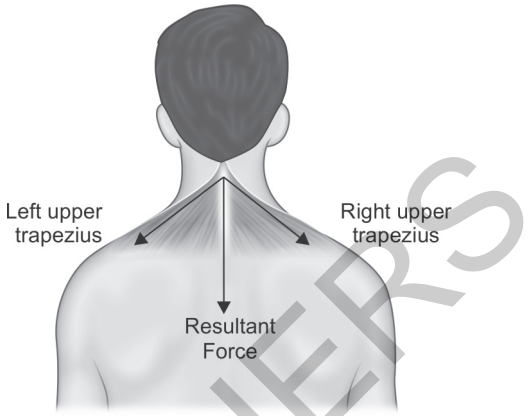
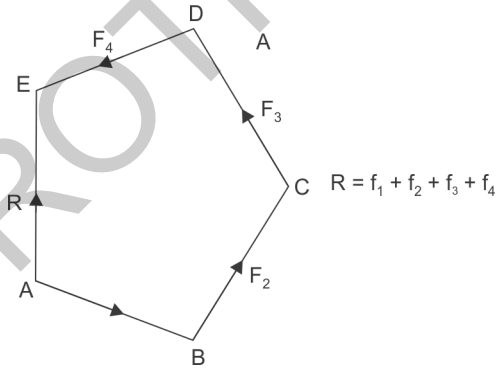


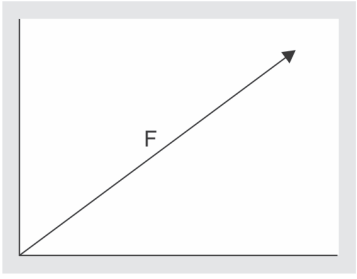
Fig. 1.13: Composition of force of upper trapezius



RESOLUTION OF FORCES

Forces Acting on Human Body

It is a process by which a single force or a resultant force is replaced by two perpendicular components.



The two components are:

1. **Vertical component:** Vertical component is also called as rotatory component. It causes rotation and is always perpendicular to the bone.

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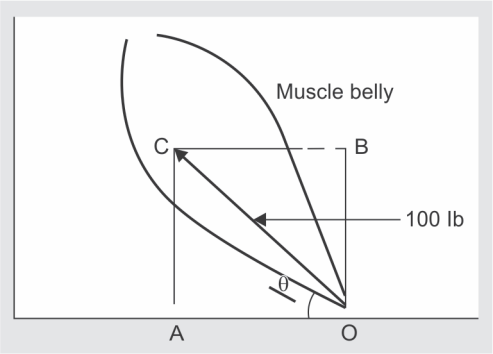


Fig. 1.14: Resolution of forces into its components

2. **Horizontal component:** Horizontal component is also called as stabilizing component. It causes either tension or compression and acts along the long axis of the bone.

For example, a muscle is pulling a bone with magnitude of 100 lb (pound) and at an angle of 60° to the long axis of the bone. Find out the value for vertical and horizontal component.

OC = 100 lb
OC = R
OB - Vertical component
OA - Horizontal component
Angle or θ = 60°

$$\text{Sin } 60° = \frac{AC}{OC} = \frac{OB}{100lb}$$

$$= \frac{\sqrt{3}}{2} = \frac{OB}{100lb}$$

$$OB = 50\sqrt{3} \text{ lb}$$

$$\text{Cos } 60° = \frac{OA}{OC} = \frac{OA}{100lb}$$

$$\frac{1}{2} = \frac{OA}{100lb}$$

$$OA = 50 \text{ lb}$$

HUMAN MOTION

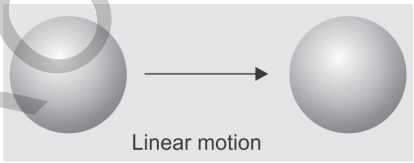
Motion

Motion is an action of an object with respect to a reference point.

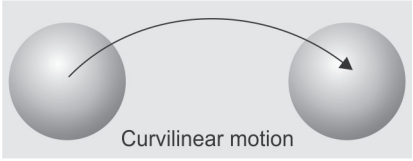
Types of Motion

Classification based on path of motion

- **Translatory motion (linear motion, translation):** A motion in which all parts of the moving body move toward the same direction.
  Here, the body moves in one direction or follows a linear path.
  For example,
  - Walking on a straight bar
  - Elevation, depression, protraction, and retraction of scapula
  - Pushing or pulling of bone at joint surfaces
- **Linear (or rectilinear) motion:** A motion in which all parts of a moving body move in the same direction and the path follows a straight line.



- **Curvilinear motion:** A motion in which the net motion of a moving body move toward the same direction although the path follows a curved line, e.g., the path of the center of mass of the body during level walking.



  - Curvilinear motion is the combination of linear and circular motions. For example,
  - Curvilinear motion is commonly found in almost all joints.
- **Circular motion:** When a body moves in a circular path around a fixed point, the body is in angular motion. For example,
  - Movement of fan
  - The movement of major joints in upper and lower extremity (hip, knee, ankle, elbow, wrist joints).

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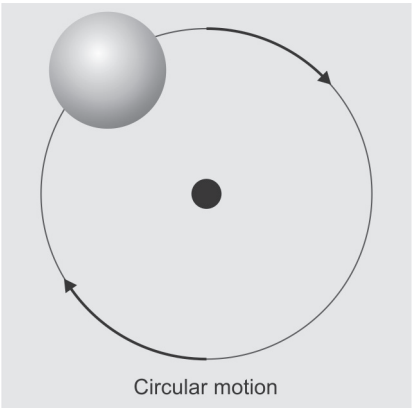


- **Rotary motion (angular motion, rotation):** A motion in which the object acts as a radius and all parts of the moving object rotate in the same angular direction and follow a circular path about a pivot point.
- **Angular motion:** The rotary motion with one side of the moving object fixed, e.g., rotation of a limb.
- **Spin:** The rotary motion with the axis of rotation around the center of mass.

Figure 1.15 shows difference between angular motion and spin.

Classification based on repetition of motion

- **Single motion:** Movement performed only once
- **Reciprocal motion:** Same movement pattern that is done many times in a given time reciprocal motion **(Fig. 1.16A)**.
- **Oscillation:** Repeated motions in a small amplitude **(Fig. 1.16B)**.
- **Pendulum motion:** Repeated motions like a pendulum **(Fig. 1.16C)**.

Classification based on degree of freedom

Degree of freedom (DOF): A minimum number of kinematic variables required to

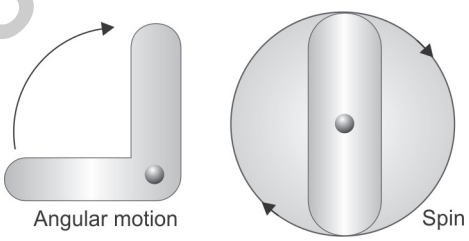
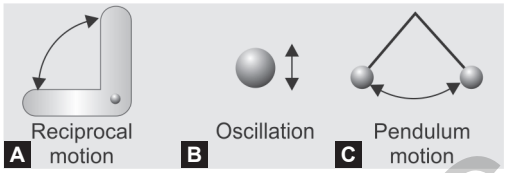


Fig. 1.15: Difference between angular motion and spin



Figs. 1.16A to C: Human motion classification based on repetition of motion. (A) Reciprocal motion; (B) Oscillation; (C) Pendulum motion

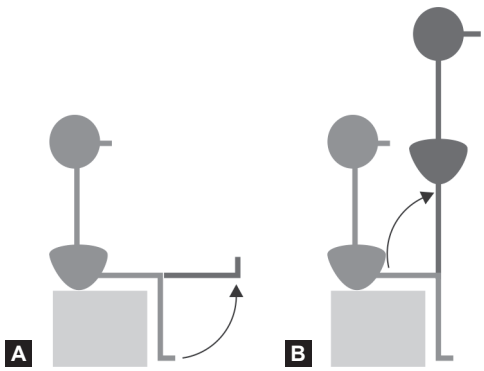
specified all positions and orientations of the segments in a body system, i.e.,

- The number of planes in which the segments move
- The number of the primary axes which the segments possess, e.g.,
  - The joint that moves in one plane possesses one axis and has one degree of freedom.
  - For the glenohumeral joint, there are three angular degrees of freedom and three linear degrees of freedom.

Classification based on relative segment kinematics

Kinematic chain: A series of connected segment links

- **Open kinematic chain motion (Fig. 1.17A):** The joint motion where the distal segment moves free in space, e.g., raising lower leg or throwing a ball.
- **Closed kinematic chain motion (Fig. 1.17B):** The joint motion where the distal segment is fixed, e.g., standing up or squatting down.



Figs. 1.17A and B: (A) Open kinematic chain; (B) Closed kinetic chain

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ANGULAR MOTION

Basic Terminologies Used in Context of Motion

- **Displacement:**
  - It defines the amount of motion of a body.
  - It is denoted as "s".
  - It is measured in meters and centimeters.
- **Velocity:**
  - It is defined as rate of change of displacement.
  - It is denoted by "v"
  - It is measured in m/sec and cm/sec.
- **Acceleration:**
  - Acceleration is defined as rate of change of velocity.
  - It is denoted as "a".
  - It is measured in m/sec^2 and cm/sec^2.

NEWTON'S LAW OF MOTION

Newton's law of motion is the three physical laws describing the relationship between a body and the forces acting on it, and its motion in response to those forces.

The three laws of motion were compiled by Newton in his Mathematical Principles of Natural Philosophy and were first published in 1687.

The three laws described by Newton are as follows:

Newton's First Law

- It is also called as *"law of inertia/law of equilibrium".*
- It states that *"Every object continues to remain in a state of rest or uniform motion unless and until it is acted upon by an unbalanced force".*
- It can be restated as *"When an object is in equilibrium, sum of all the forces acting on it is zero".*

And to maintain this state of equilibrium at least two forces are required.

Determination of equilibrium of a body

- Consider a patient lying on a table in equilibrium. Gravity acts on the patient in downward direction and the force exerted by the upper surface of the table is in upward direction.
- Let the magnitude of these forces be, upward force $F_{1,}$ and downward force $F_{2,}$ respectively.
- As the forces are in same plane, same line but in opposite direction, it forms a colinear force system.
- According to force convention, forces acting on the right and in upward direction are considered as positive and the one acting downward and in left are considered as negative.
- Resultant force is zero ($F_2 - F_1 = 0$).
- Hence, the patient is said to be in equilibrium.

Newton's Second Law

- It is also called as law of acceleration.
- It states that *"Forces acting on a body produces acceleration which is inversely proportional to mass and directly proportional to force".*

$$a \propto F$$

$$a \propto \frac{1}{m}$$

$$a \propto \frac{F}{m}$$

$$a = K\frac{F}{m} \qquad K = 1$$

$$F = ma$$

Clinical, e.g.,

Consider two patients A and B of weight 50 and 30 kg respectively, sitting on a wheel chair.

When equal amount of force is exerted, more acceleration is produced in patient B, than in patient A.

Also as force increases, acceleration also increases.

Newton's Third Law of Motion

- It states that *"For every action, there is equal and opposite reaction."*
- In other words, when one body applies a force on another, the second body in turn applies a force which is equal in magnitude but in opposite direction of the first body.

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Mechanical, e.g.,
- When both the palms are placed against each other, one palm applies acting force while the other applies the reacting force.
- In tug of war, acting and reacting force are applied on the rope.

Anatomical, e.g.,
- When a paraplegic patient is made to lie on a table, the body weight of the patient exerts an acting force in downward direction while the upper surface of the table provides a reacting force.
- In standing position body weight passes in downward direction forming the acting force while gravity provides the reacting force.

TORQUE (MOMENT OF FORCE OR MOMENT)

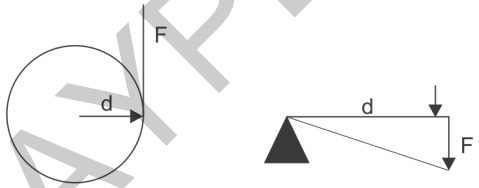
Torque is a force which causes rotation of a body or turning of a lever around a fixed axis.

In human body, it is seen when a bone rotates around a joint.

It is also called as rotatory effect of force.

Mathematically, it is defined as product of force and the perpendicular distance from the axis of rotation to the line of action of force. It is denoted by "τ"

$\therefore \quad \tau = F \times perpendicular\ distance$



Units:
- **MKS system:** It is measured in Newton.
- **CGS system:** It is measured in Dyne.
- **FPS system:** It is measured in Pounds (lb).

Moment Arm

It is the perpendicular distance from the axis of rotation of a joint to the line of action of force.

$\therefore$ From the above mentioned equation,

τ = Force × Moment arm

Movement According to Joint Position

In human body, joint acts as a fulcrum or axis of rotation and the force is supplied by weight of the body part or by muscle work.

Consider abduction movement of the shoulder joint from the neutral position.

Here, the shoulder joint acts as a fulcrum or axis of rotation.

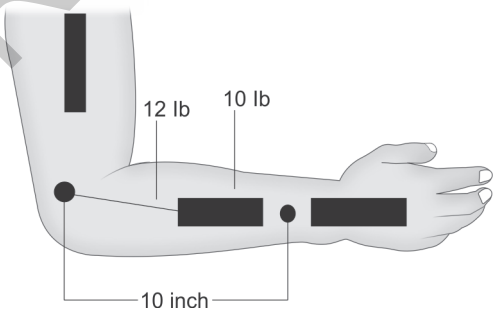
Weight of upper extremity is the force acting ⅓rd at distance from the shoulder joint.

τ depends upon the momentum and is directly proportional to momentum.

Mechanical, e.g., Opening and closing of door

Anatomical, e.g., Knee extension by the quadriceps, where knee joint is the fulcrum, body weight is the COG of the leg **(Fig. 1.18)**.

If the weight of forearm and hand is 10 lb acting at a distance of 10 inch from the joint axis, Then,



τ produced by biceps brachii muscles

T_B = 120 lb × 1 inch = 120 lb inch (negative)

τ produced by weight of forearm and hand

T_G = 10 lb × 10 inch = 100 lb inch (positive)

In anticlockwise direction is negative while in clockwise direction is positive.

Net τ

τ_R = –120 lb inch + 100 lb inch = –20 lb inch

τ_R = 20 lb inch in anticlockwise direction.

It indicates that elbow joint is in the direction of flexion.

If τ_R = 0, the lever system will be in a state of equilibrium (there is no movement at elbow joint).

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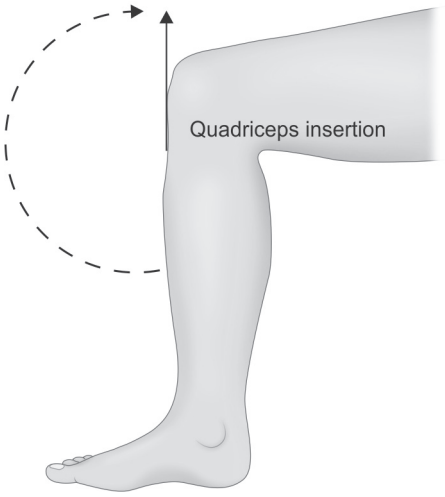
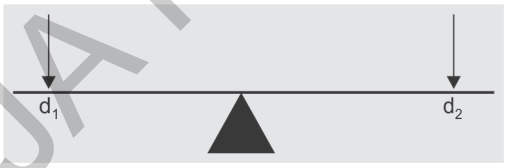


Fig. 1.18: Torque force by the quadriceps

PRACTICAL APPLICATION OF TORQUE

- This effect is seen in balance board or equilibrium board.
- It is a rectangular or a circular board resting on a curved surface.
- It is usually used for strengthening the muscles of lower extremity or for re-education of balance.
- Balance board is based on the principle of moment.
- When a person stands on the balance board, there is equal distribution of weight by both legs. Also the distance is equal from the axis of rotation or fulcrum.

So, $F_1 \times d_1 = F_2 \times d_2$



When a muscle is inserted far from the joint axis, it has more rotational effect on the bone than the muscle inserted close to the joint axis.

FRICTION

- Friction is the force that opposes motion between two surfaces.
- It is measured as coefficient of friction.
- It is denoted by "μ"

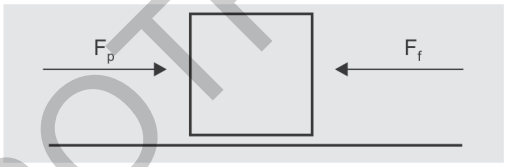
Coefficient of friction is the ratio between force of limiting friction and the normal reaction between them.

$$\mu = \frac{F}{R}$$

F = Force of limiting friction
R = Normal reaction

Frictional force depends upon the nature of the contact surfaces and the normal reaction.

Rough surfaces provide more coefficient of friction while smooth surfaces provide less coefficient of friction.



As friction is produced when one body slides over another, it is a shear force.

Units: Newton, Dyne.

It satisfies all the properties of force, such as magnitude, direction, line of action, and point of application.

Properties

- Magnitude
- **Direction:** It is always opposite to the movement of the body.
- Line of action of frictional force: It is always parallel to the contact surface.

Classification

Basically, friction is classified into two types:

1. Static or limiting friction
2. Dynamic or kinetic friction

Dynamic friction is further classified into:

- Sliding friction
- Rolling friction

Static friction: Produced at a point when body tends to move.

Dynamic friction: Produced when a body moves or is in motion.

Sliding friction: It is obtained when a body slides on another.

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Rolling friction: It is obtained when one body rolls on another. For example, when a tyre rolls on another.

- Static force > Dynamic force
- Sliding force > Rolling force

For example, it is easier to pull a cylinder by rolling than sliding because rolling friction is lesser than sliding friction.

Application of Friction

- As rough surface have more friction than smooth surface, there is less chances of falling on rough surface.
- Rubber tyre has many grooves that increases friction.
- In axillary crutch, rubber tip is attached to the distal end that increases the friction.
- Oil or powder is applied during massage reduces friction between skin and hand.
- Oil is used in machines to reduce friction.
- In human body, the articulating surfaces of the joints are covered by articular cartilage and lubricative synovial fluid that reduces friction.

GRAVITY

Gravity is a force which attracts all body toward the center.

The weight of the body is the force produced by the gravity and it depends upon the quantity of matter, such as mass.

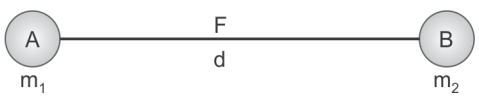
$\therefore$ $W = mg$

Where, m = mass of body

G = acceleration due to gravity

Newton's Law of Gravity

It states that every particle in universe attracts every other particle and the force is directly proportional to the total mass and inversely proportional to the square of distance between them.



$$F \propto m_1 m_2$$

$$F \propto \frac{1}{d^2}$$

$$F \propto \frac{m_1 \cdot m_2}{d^2}$$

$$F = \frac{G \cdot m_1 \cdot m_2}{d^2}$$

Where,

$G = 6.67 \times 10^{-11}\ N\ m^2/kg^2$

Gravitational constant = G

Anatomical, e.g., when shoulder is in abduction from neutral position.

- Movement occurs against gravity; here muscular force is greater than gravitational force.
- Shoulder wall remains in abduction as long as if, muscular force = gravitational force.
- When shoulder is brought back to neutral, movement occurs with the help of gravity and muscles relax.

Line of Gravity (LOG)

It is an imaginary vertical line that passes through COG of the body **(Fig. 1.19)**.

In normal anatomical position, from lateral view (side) it passes:

- Skull
- Through external ear
- Midpoint of cervical vertebra
- In front of thoracic vertebra
- Midpoint of lumbar vertebra
- Anterior to the 2nd sacral vertebra
- Through midpoint of hip joint axis
- Anterior to the knee joint axis
- Anterior to the ankle joint axis
- Then touches the ground at the level of midtarsal joint.

Base of Support (BOS)

It is an area covered by a body.

- **Mechanical example:**
  - When a book is placed on a table, the lower surface of the book is the BOS.
  - When a table is placed on the ground, the BOS is outer border of the four legs of the table.

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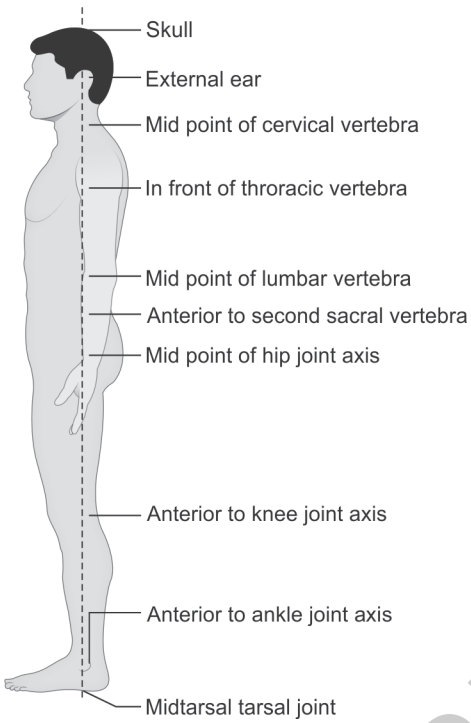


Fig. 1.19: Line of gravity of human body

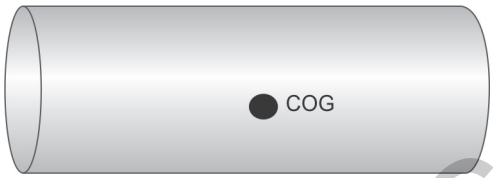
- **Anatomical example:**
  - When a person is standing, the BOS is outer border of both legs. It can be increased by spreading of legs laterally or anteriorly.
  - When person is supine position, the BOS is posterior part of body.
- LOG and BOG, the stability factors of the body

Center of Gravity

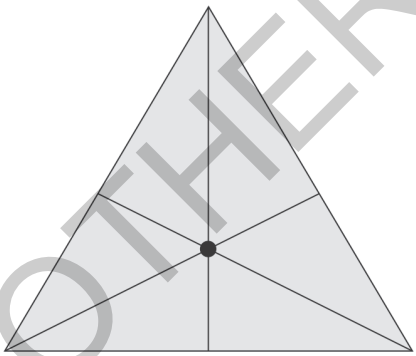
- It is a point where all body masses are assumed to be concentrated.
- COG is a point where all body mass and weight are balanced in all direction.
- It is a point where three planes intersect each other (sagittal, frontal and transverse plane).

COG of Geometrical Objects

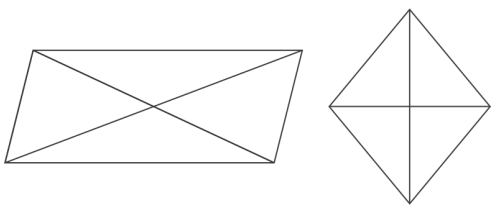
- COG of uniform cylindrical rod; lies on the MP of its axis.



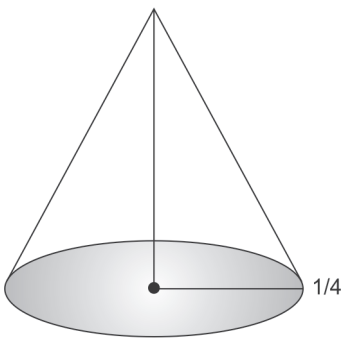
- COG of a triangle; lies at the intersection of median



- COG of parallelogram, rectangle, rhombus and square; lies at the intersection of diagonals.



- COG of solid circular cone; lies on its axis at a 1/4th distance from plane base.



- COG of hollow cone lies on its axis at 1/3rd of distance from the plane base.

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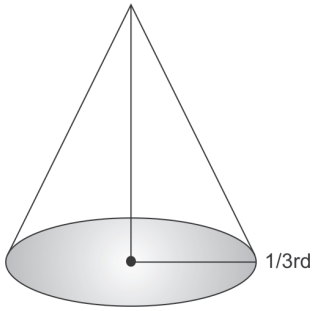
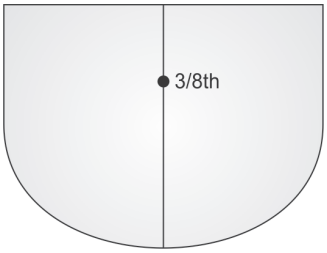
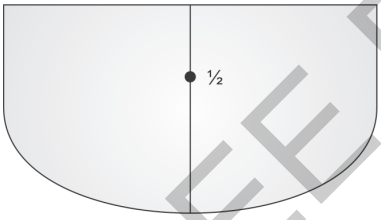


- COG of solid hemisphere lies on its central radius at a distance 3/8th from plane base.



- **COG of hollow hemisphere:** Lies on its central radius at the midpoint.



Segmental Weight of Human Body

Segment	*% of weight of the segment to the whole body weight*	
Head	6.9%	59%
Head and neck	7.9%	
Head, neck and trunk	59%	
Arm	2.7%	UL = 4.9%
Forearm	1.6%	
Hand	0.6%	
Thigh	9.7%	LL = 15.6%
Leg	4.5%	
Foot	1.4%	

- Segmental COG
- Human body consists of number of segments and each segment has its own COG.

Segment	*COG*
Head	At the level of sphenoid sinus
Head and neck	Just below the occipital bone
Head, neck and trunk	Anterior to the 11th thoracic vertebra
Arm	5 mm proximal to the insertion point of the deltoid muscle
Forearm	11 mm proximal to the insertion point of pronator teres muscle
Hand	Lies on the axis of 3rd metacarpal that is corresponding to the transverse proximal common crease
Upper limb	Just above the elbow joint
Thigh	29 mm below the apex of femoral triangle on the adductor grevis muscle
Leg	35 mm below the popliteus muscle
Foot	In between 2nd and 3rd cuneiform bone
Lower limb	Just above the knee joint

COG of Human Body

When all the segments are combined together and entire body is considered as a single object, in normal anatomical position COG lies slightly anterior to the 2nd sacral vertebra. It is a not a constant point. It changes according to the change in posture.

For example, forward bending of trunk, COG moves anteriorly and falls outside the body.

Relocation of COG

- When there is plaster cast in the right leg and person is walking by the support of crutch, the COG moves down and right.
- When a person is carrying suitcase in right hand, the COG moves up and to the right.
- When both hands are parallel, COG moves up.
- When both hands are vertical, COG moves up.
- During forward bending of trunk, COG moves anteriorly.
- When person is bending toward left side, COG moves toward left side.
- When person standing on right leg COG moves toward weight-bearing side (right side)

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- **COG of any segment:** 45% of length from proximal end and 55% of length from distal end.

EQUILIBRIUM

Equilibrium occurs when forces acting on object are perfectly balanced and object remains at rest.

Condition of the Equilibrium

- Summation of all forces is equal to 0, i.e., $\varepsilon f = 0$
- No tendency to move in any direction.
- Summation of all torque = 0, $\varepsilon\tau = 0$
- No tendency to rotate in any direction.

Types of Equilibrium

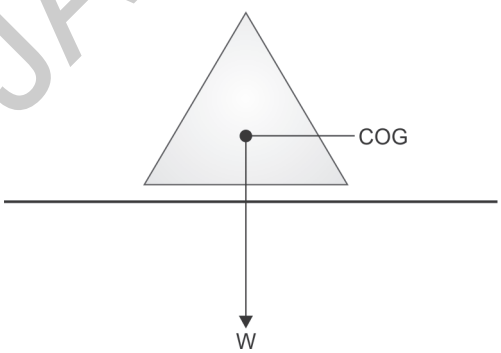
- Stable equilibrium
- Unstable equilibrium
- Neutral equilibrium

Stable Equilibrium

If a body returns to its original position after being displaced by external forces, this state of equilibrium is called stable equilibrium.

Conditions

- If the position of COG is lower, the object is more stable. The LOG moves to the center of BOS.
- If the position of COG is high, the LOG moves toward the periphery of BOS and the object is less stable.
  For example, when a solid cone is placed on a base



Here, COG is low and the LOG passes within the BOS.

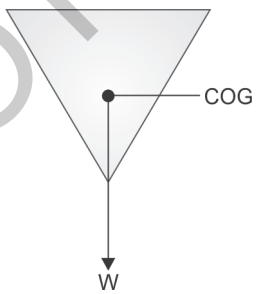
For example, person is in bilateral stance.

Unstable Equilibrium

If the body gets displaced from its original position, with the COG remaining at the same level when subjected to external forces, the state of equilibrium is called as unstable equilibrium.

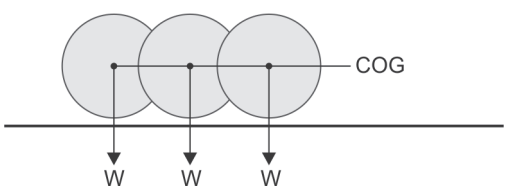
Conditions

- COG is high and LOG falls outside BOS. For example, when a cone is placed at its apex.
- Toe standing



Neutral Equilibrium

If the body does not get displaced from its original position and if the COG remains at the same level when subjected to external forces, this state of equilibrium is called neutral equilibrium. For example, when a ball moves on a plane surface.



Stability of body: Depends on:

- Size of BOS
- Height of COG
- Position of LOG

Size of base of support: Stability is directly proportional to base of support. In normal anatomical position, maximum stability is

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attained. When the legs are separated or moved laterally, the base of support increases. As the feet come close together, the base of support decreases and the body becomes less stable. In single leg standing or toe standing, the body is least stable as the base of support is minimum.

Height of COG: The lower the COG, more stable is the body. In comparison to various positions, such as supine lying, standing and sitting, the supine lying position is most stable.

Position of LOG: The distance between the LOG and center of base of support is inversely proportional to stability.

WORK, ENERGY, AND POWER

Work

- Work is said to be done when the point of application of force applied is in same or opposite direction.
- It is measured as product of force and magnitude of its direction.

Consider the work done by the force as positive and work done against it as negative.

Then mathematically,

Work done = F × S
Where S = Magnitude of direction of force
F = Force
WD = Work done

For example,

- When a bucket is drawn into a well, the bucket and the force acting on it are in the same direction. Hence, the work done by the force is positive.
- When the bucket is fetched out of well, the weight of the bucket is in downward direction while the bucket moves in upward direction. Hence, the work is done against the force and is taken as negative.

Anatomical, e.g., when shoulder is abducted, the work is done against gravity and is negative.

When abducted shoulder is brought back to the neutral position, work is done by the force and it is positive.

Measurement of Work

In MKS system, the unit of work is Joule. It measures the work being done when a force of 1 Newton acts through a distance of 1 meter.

1 Joule = 1 Newton × 1 Meter.

In CGS system, it is measured in ERG. It measures the work being done when a force of 1 Dyne acts through a distance of 1 centimeter.

1 Erg= 1 Dyne × 1 centimeter.

In FPS System, it is measured in Calorie.

ENERGY

Energy is defined as capacity to do work.

Principle of Conservation of Energy: It states that "Energy can neither be created nor destroyed, rather it can be transformed from one form to another."

Types of Energy

Mainly, there are two forms of energy, i.e., potential energy and kinetic energy.

Potential Energy

- Energy produced by a body due to its rest is called potential energy.
- It is also called as stored energy.

Potential energy = mgh

Where, m = mass of body
g = acceleration due to gravity
h = height of body

- For example, when a rubber band is stretched and waiting to be released.
  - Anatomical, e.g., sitting posture.

Kinetic Energy

- Energy produced by a body due to its motion, is called as kinetic energy.

Kinetic energy = $\frac{1}{2}mv^2$

Where, m = mass of body
v = velocity of body

For example, when a rubber band is zinged from the fingers.

- Anatomical, e.g., running, walking.

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POWER

Power is defined as rate at which work is done.

$$P = \frac{W}{t}$$

Where, P = Power
W = Work
t = Time

Units:

- In MKS System, Power is measured in Watt.
- 1 watt is equal to one joule per second.
- In CGS System, it is equal to one erg per second.

SPRINGS

A spring consists of a number of uniform coils of wire which are used either in tension or compression.

When subjected to tension, the length of the spring increases and vice versa.

Therapeutic Use

It is used either to resist or to assist the force of muscular contraction or to produce passive movements at joints.

In physiotherapy, it is used in suspension therapy, hand grip exercises, and also in multiple gym equipment.

Properties of Spring

- **Extensibility:** Elongation is directly proportional to the applied force. When force is applied to one end of a spring with its other end fixed, the spring elongates in a direction along its long axis.
- **Recoiling of spring:** After the removal of force, the spring returns to its original position. During extension of the spring, potential energy is converted into kinetic energy while the reverse occurs during recoiling.
- **Weight of spring:** The standard springs are available in various weights, e.g., 10, 20, 30 lb (pounds). Internally, the spring consists of a cotton tape which becomes tight when the spring reaches its maximum length thereby, preventing the over stretching of the spring. The weight of the spring depends on the material used, diameter, and thickness of coil.
- **Oscillatory movement produced by spring:** When forces are applied vertically to one end of the spring, and released oscillatory movements are produced. The amplitude of oscillation gradually decreases as the spring comes back to its resting position.

Springs in Series (Figs. 1.20A and B)

It is obtained when springs of equal weight are connected end-to-end.

For example,

Suppose a spring of 5 cm is elongated with 5 kg of weight separately.

Here the force acting is unidirectional.

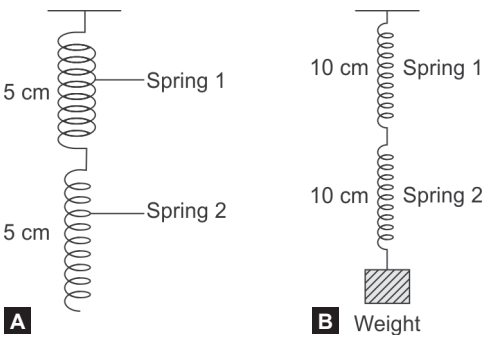
∴ The total elongation is 5 cm + 5 cm = 10 cm and the resistance offered by the spring is 10 pounds (resistance offered by the spring in series = weight of any one spring).

Springs in Parallel (Figs. 1.21A and B)

It is obtained when springs of equal weight are connected side-to-side.

Here, weight is divided by the spring and 2.5 kg of force is acting on each spring and the elongation is 2.5 cm.

∴ The total elongation offered by the spring in parallel is 2.5 cm and the resistance applied is equal to the sum of weight of the spring, i.e., 10 lb + 10 lb = 20 lb.



Figs. 1.20 A and B: Springs in series

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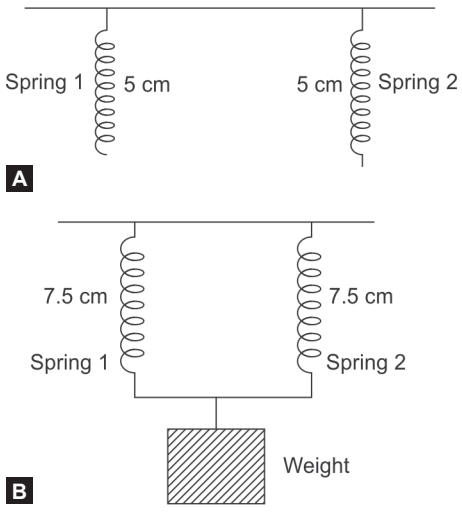


Figs. 1.21A and B: Spring in parallel

LEVERS

A lever is a rigid body which rotates around a fixed axis.

Here, the axis of rotation is called fulcrum and the two forces acting along the length of the lever at particular distance are effort and weight/resistance/load.

In simple terms, it is a simple machine used to transmit force, alter direction and magnitude of force, or to speed up movement.

- Effort tends to produce movement while weight or resistance resists the movement.
- Effort arm is the perpendicular distance from fulcrum to effort.
- Resistance arm is the perpendicular distance from the fulcrum to the resistance applied.

Classification

A lever is classified according to the relative position of fulcrum, effort, and resistance.

There are three types of lever:

1. First order lever
2. Second order lever
3. Third order lever

First Order Lever

In this type, fulcrum lies between effort and resistance. It may be either situated in center or toward effort or resistance.



Conditions

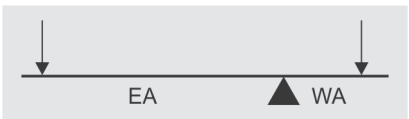
- When fulcrum is at center, effort arm is equal to resistance arm.



- When fulcrum is nearer to the effort arm, then effort arm is less than resistance arm.



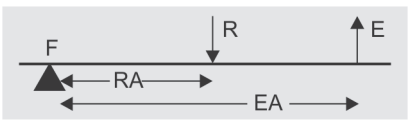
- When fulcrum is nearer to the resistance arm, the effort arm is greater than resistance arm.



Second Order Lever

In this, resistance lies between fulcrum and effort.

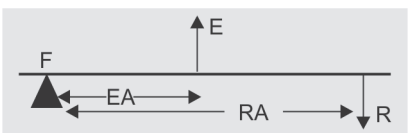
∴ Effort arm is always greater than resistance arm.



Third Order Lever

In this type, effort lies between fulcrum and resistance.

∴ Resistance arm is always greater than effort arm.



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Mechanical Advantage

It is defined as the ratio of resistance to the effort.

OR

It is defined as the ratio of effort arm to the resistance arm.

$$MA = \frac{W}{E} = \frac{EA}{WA}$$

When the value is greater than one, the lever has mechanical advantage and when the value is lesser than one, the lever has mechanical disadvantage.

Mechanical advantage for first order lever: Mechanical advantage for first order lever may be lesser, greater, or equal to one.

Conditions:
- When fulcrum is at the center, EA = RA and MA = 1
- When fulcrum is near to the effort, EA < RA and MA < 1
- When fulcrum is near to the resistance, EA > RA and MA > 1

Mechanical advantage for second order lever:
- As EA > RA
- Mechanical advantage for second order lever is greater than one.
- It is also called as lever of advantage.

Mechanical advantage for third order lever:
- As EA < RA
- Mechanical advantage is lesser than one.
- It is also called as lever of disadvantage.

Mechanical Levers

Example:
- **For first order lever:** See saw, scissors, common balance, cutting player.
- **For second order lever:** Nut cracker, shoulder wheel, closing a door.
- **For third order lever:** Lifting a ladder which rests against a wall, forceps.

Principle of Lever

- If the product of effort and effort arm is equal to the product of resistance and resistance arm, the lever is said to be in equilibrium or mechanical advantage = 1.
- If effort arm is greater than resistance arm then the lever is called as lever of advantage and the mechanical advantage is greater than 1.
- If effort arm is less than resistance arm then the lever is called as lever of disadvantage and the mechanical disadvantage is lesser than 1.

Analysis of Lever

- Find out the fulcrum
- Locate the effort and resistance
- Find out the effort arm and the resistance arm
- Justify the type of lever

LEVERS IN HUMAN BODY

In human body, lever is represented by bone, fulcrum (f) is represented by joint, effort (e) is the contraction of muscle force applied at insertion point, and weight (w) may be either COG of the moving part or the weight placed on the bony segment.

First Order Lever (Figs. 1.22A and B)

- This is the lever of stability and equilibrium with/without mechanical advantage.
- Nodding movement of the head
- Lever—skull
- Fulcrum—atlanto-occipital joint
- Weight—COG of the head
- Effort—insertion point of posterior neck muscles

Second Order Lever (Fig. 1.23)

- This is the lever of power with mechanical advantage.
- Plantarflexion of ankle
- Lever-foot
- Fulcrum-ankle joint
- Weight—COG of the foot
- Effort-insertion point of plantar flexors, i.e., gastrocnemius and soleus.

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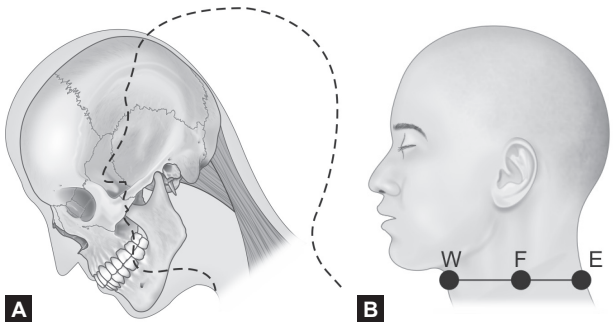

Figs. 1.22A and B: Atlantoaxial joint example of first order lever

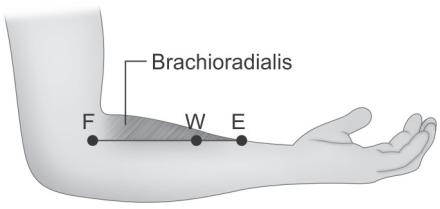

Fig. 1.23: Example of second order lever elbow flexion by brachioradialis

- Lever—forearm
- Fulcrum—elbow joint
- Weight—COG of forearm
- Effort—insertion point of brachioradialis

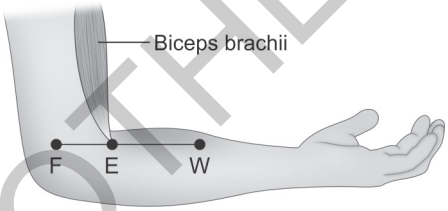

Fig. 1.24: Third order lever

Third Order Lever (Fig. 1.24)

This is the lever of inconvenience with mechanical disadvantage. But this is the most common lever system found in the human body

- Flexion of elbow by biceps brachii
- Lever-forearm and hand
- Fulcrum-elbow joint
- Weight—COG of forearm and hand
- Effort—insertion point of biceps brachii at radial tuberosity.

ELASTICITY

When a body is subjected under load, it may undergo change in shape or size. After removal of force, the body regains its original position. This property is known as elasticity.

Elasticity is expressed in stress or strain.

Stress

It is a force within the body. It is measured as force per cross sectional area.

$S = F/A$

Where, F = force

A = cross-sectional area, and

S = stress

Anatomical example:

Units of stress:

- In MKS system, the unit of stress is Newton/m^2.
- In CGS system, the unit of stress is Dyne/m^2.

Strain

It is defined as ratio of change in shape or size of a body to the original shape and size of a body.

- **There are three types of strain:**
  1. **Linear strain:** Change in length per unit length.
  2. **Shear strain:** Change in area per unit area.
  3. **Volume strain:** Change in volume per unit volume.
     - Strain has no dimensions and units.
     - Strain depends on the applied force, cross sectional area, structure, and design of material.
     - Stress and strain increase with increase in force while it decreases with increase in cross-sectional area.

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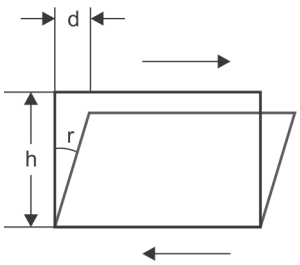

- Unit normal strain = % (dimensionless quantity) or mm/m shear strain = rad
- Tensile strain is positive while compressive strain is negative.
- Factors affecting the extent of deformation:
  - Mechanical properties
  - Size of the body
  - Shape of the body
  - Temperature
  - Humidity
  - Magnitude, direction, and duration of applied forces.

Application of Stress-Strain Curve

Stress-Strain Curve (Fig. 1.25)

- **Elastic region:** When the magnitude of the stress is small, the elastic force can be represented by the relation for an ideal spring (Hooke's law), i.e., the elastic force exerted by the viscoelastic material is proportional to the amount of deformation

$$F = kx$$

where F = elastic force
k = spring stiffness which is a constant
x = amount of deformation

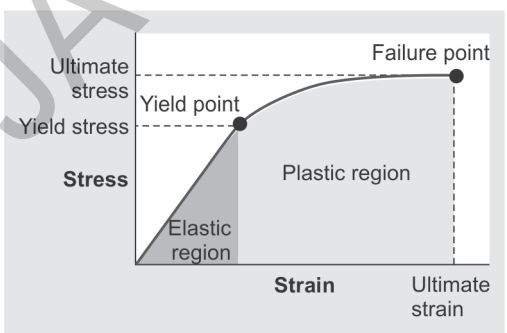

Fig. 1.25: Stress strain curve

- Plastic region
- Yield point
- Failure point

Strength

- Maximum stress that a body can be loaded (ultimate stress).
- Maximum strain that a body can be deformed (ultimate strain).
- Maximum energy stored.

Stiffness

- **Modulus of elasticity (Young's modulus):** For both tensile and compression stress
  - The ratio of the stress to strain in the elastic region of the stress-strain curve

$$E = \sigma/\varepsilon$$

  - Named after Thomas Young (1773–1829, English scientist)
  - *SI unit:* Pascal
  - *USCS:* psi
- **Hooke's law:** Only for tensile stress
  - For an elastic material, the strain is a linear function of the stress applied
  - Named after Robert Hooke (1653–1703, English scientist)
- **Modulus of rigidity (shear modulus of elasticity)**

$$G = \tau/\gamma$$

where $\gamma = d/h$

- **SI unit:** Pascal
- **USCS:** psi

Poisson's Ratio

- When a material is under a tensile stress, the tensile strain and the lateral contraction is proportional.

$$\nu = \varepsilon_{lateral}/\varepsilon_{longitudinal}$$

  - *Assumptions:*
    - The material is homogeneous
    - The material is isotropic
  - *Named after Simeon Denis Poisson (1781–1840)*
- **Unit:** Dimensionless
- $0 \leq \nu \leq ½$
- Relationship between the modulus of elasticity and that of rigidity

$$G = E/2(1 + \nu)$$

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- **Brittle vs. ductile materials:**
  - *Brittle material:* The material whose failure occurs at a very low strain, e.g., ceramic or glass.
  - *Ductile material:* The material that is able to resist a very high strain before failure, e.g., aluminum alloys.
- **Creep phenomenon:** Progressive deformation of a material with time as the amount of load remains constant **(Fig. 1.26)**.
- **Load relaxation phenomenon:** Progressive decrease in load with time as the deformation of the structure remains constant **(Fig. 1.27)**.
- **Hysteresis:**
  - Energy stored in a viscoelastic material when a load is given and then relaxed **(Fig. 1.28)**.
  - *Aged heel pad:* Poor ability to absorb the shock **(Fig. 1.29)**.
  - Elastic vs. plastic materials
- **Elasticity:** The ability of a body to resume its original size and shape on removal of the applied loads **(Fig. 1.30A)**.

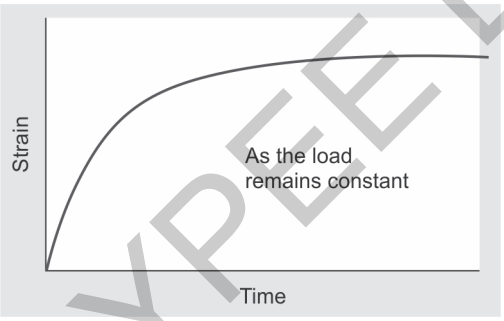

Fig. 1.26: Creep phenomenon

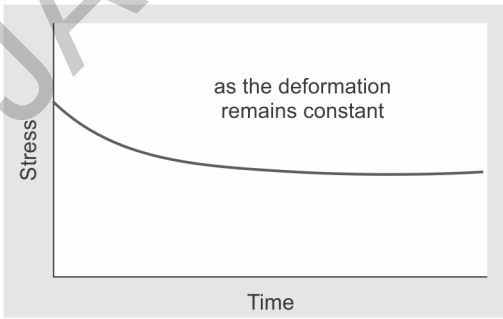

Fig. 1.27: Load relaxation phenomenon

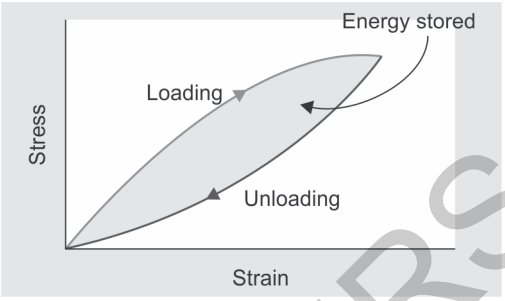

Fig. 1.28: Hysteresis

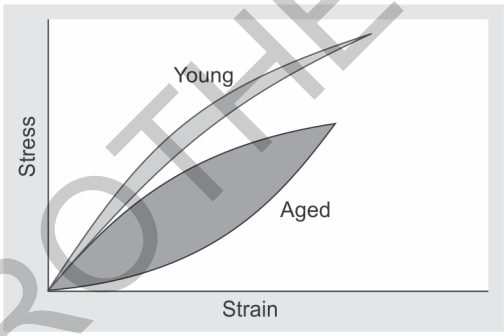

Fig. 1.29: Hysteresis of heel pad

Note: The elastic material is not necessary to have a linear relationship on the stress-strain curve.

- **Plasticity:** When a tissue is stretched to the plastic region and then released, the tissue will assume a new resting length that is longer than the initial length because of plastic changes in its structure **(Fig. 1.30B)**.
- **Clinical application:** Flexibility exercise or joint mobilization.
- **Allowable stress:**
  - When a structural member or mechanical element is designed, the stress must be restricted in a material to a level that will be safe. This is the allowable stress.
  - *Factor of safety (FS):* The ratio of a theoretical maximum load that can be carried by the member until it fails in a particular manner divided by an allowable load

$$FS = F_{fail}/F_{allow}$$

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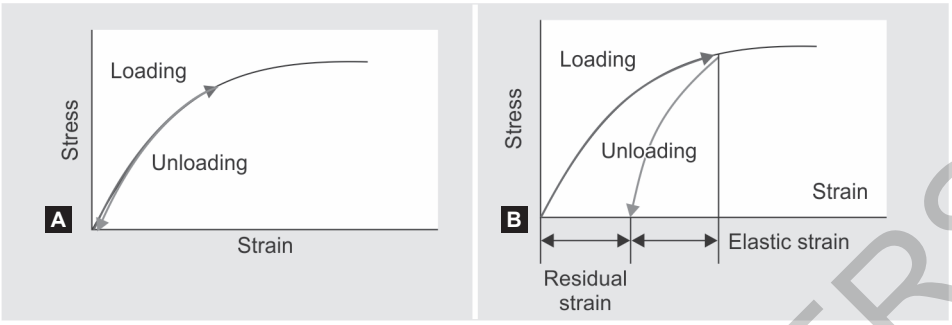

Figs. 1.30A and B: (A) Elastic behavior; (B) Plastic behavior

- The factor of safety is chosen to be greater than 1 to 10 in order to avoid the potential for failure.

When a body is under strain, the deformation produced is directly proportional to the load and the body thus, undergoes the following phases:

- Elastic region
- Plastic region
- Strain hardening
- Necking region
- Rupture/failure point

- **Elastic region:**
  - When a body is subjected to load, it undergoes deformation.
  - It regains its original position after removal of the load.
  - However, when the elastic limit is reached, the body does not regain its original position.
- **Hooks law:** It states that stress is directly proportional to strain within its elastic limit.

$$\therefore \quad \frac{\text{Stress}}{\text{Strain}} = Y = E$$

Where Y = constant = modulus of elasticity.

- **Yield point:** Yield point is achieved when a body stretches for a period without addition of any further load.
- **Plastic region:** Here the deformation produced is permanent and the body attains a new shape.
- **Strain hardening:** During the later stages of plastic phase, molecular changes occur within the body providing resistance to the deformation.
- **Necking region:**
  - This effect is seen when the body is subjected to linear tensile stress.
  - As the body stretches, the cross sectional area of the body decreases reducing the ability of the body against stress.
  - Thus, rupture or point of failure occurs.
- **Rupture or failure point:** This occurs when the tissue breaks. In human body, muscles, ligaments, tendons and other soft tissues are torn whenever injury occurs and this causes weakening of the soft tissues.
- **Result of time on strain:**
  - If a constant pressure is applied to a body, there may be change in shape and size of the body.
  - It can be attributed to the elastic and viscous property of the body.

Viscous property is a slow reaction to stress. It occurs when a constant force is applied for a longer duration of time.

  - After removal of force, the object does not return to its original position.
  - Human body is a combination of elastic and viscous properties which is termed as viscoelasticity and the resulting deformation produced is called as creep.
- **Creep:**
  - It is defined as gradual deformation produced within a body when a force is applied for longer duration of time.
  - In human body, skin produces higher degree of elasticity.
  - In old age, wrinkling occurs due to loss of elasticity of skin.

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Springs, sorbo rubber, rubber elastic, and crepe bandage which are commonly used in physiotherapy department show elastic properties.

- **Sorbo rubber:** It is compressible as well as extensible and provides grip for hand movements.
- **Rubber elastic:** It is used either to increase or resist the movements of small joints of hand.
- **Crepe bandage:**
  - Used to control and reduce swelling of the limb.
  - When applied to a limb, muscle contraction occurs increasing the circumference of the limb.
  - When the muscle relaxes, the crepe bandage recoils removing the weight placed on the limb.

In human body, tendons, ligaments, and muscles show elastic properties.

PULLEYS

Definition: A pulley changes the direction of the force, making it easier to lift things.

Anatomic Pulleys

Frequently, the fibers of a muscle or a muscle tendon wrap around a bone or are deflected by a bony prominence. When the direction of pull of a muscle is altered, the bone or bony prominence causing the deflection forms an anatomic pulley. Pulleys (if they are frictionless) change the direction without changing the magnitude of the applied force. As we will see, the change in action line produced by an anatomic pulley (even without affecting force) will have implications for the ability of the muscle to produce torque.

Function of Anatomical Pulley

The function of any pulley is to redirect a force to make a task easier. The "task" in human movement is to rotate a body segment. Anatomic pulleys (in the majority of instances) make this task easier by deflecting the action line of the muscle away from the joint axis, thus increasing the moment arm (MA) of the muscle force. By increasing the MA for a muscle force, a force of the same magnitude (with no extra energy expenditure) produces greater torque.

Types

There are three types of pulleys:

1. **Fixed pulley** is the only pulley that when used individually, uses more effort than the load to lift the load from the ground.
   - The fixed pulley when attached to an unmovable object, e.g., a ceiling or wall, acts as a first class lever with the fulcrum being located at the axis but with a minor change, the bar becomes a rope.
   - The advantage of the fixed pulley is that you do not have to pull or push the pulley up and down.
   - The disadvantage is that you have to apply more effort than the load.
2. **Movable pulley** is a pulley that moves with the load.
   - The movable pulley allows the effort to be less than the weight of the load. The movable pulley also acts as a second class lever. The load is between the fulcrum and the effort.
   - The main advantage of a movable pulley is that you use less effort to pull the load.
   - The main disadvantage of a movable pulley is that you have to pull or push the pulley up or down.
3. **Combined pulley:**
   - Makes life easier as the effort needed to lift the load is less than half the weight of the load.
   - The main advantage of this pulley is that the amount of effort is less than half of the load.
   - The main disadvantage is that it travels a very long distance.

THE PATELLA AS AN ANATOMIC PULLEY

The classic example of an anatomic pulley is that formed by the patella. The quadriceps

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muscle belly lies parallel to the femur. The tendon of the muscle passes over the knee joint and attaches to the leg (tibia) via the patellar tendon at the tibial tubercle. For knee joint extension, the joint axis is considered to be located through the femoral condyles. The MA for the quadriceps muscle force (QLf) lies in space between the vector and the joint axis. Without the patella, the line of pull of the quadriceps muscle on the leg-foot segment would follow the patellar tendon at the tibial tubercle and would lie parallel to the leg-foot segment. However, the patella lies between the quadriceps tendon and the femur, changing the angle that the patellar tendon makes with the leg (tibia) and changing the line of pull of the quadriceps muscle away from the knee joint axis. The effect of changing the line of pull of the quadriceps muscle on the tibia (QLf) is to increase the MA.

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