General Certificate of Education
(Advanced Level)
BIOLOGY

Handout for Support and Movement (unit 05)
Grade 13

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Support and Movement

The structure and functions of the skeletal systems of animals

In the animal kingdom, three major types of skeletons are found. They are hydrostatic skeletons, exoskeletons and endoskeletons.

Hydrostatic skeleton is a fluid filled body cavity which is enclosed by the body wall. In cnidarians, gastrovascular cavity acts as the hydrostatic skeleton. In some animals such as nematodes and annelids, the fluid filled cavity enclosed by the body wall (e.g., Pseudocoelom in Nematoda, Coelom in Annelida) consists of two muscle layers (longitudinal and circular muscles) which act antagonistically. The combined effect of muscle contraction and fluid pressure aids in locomotion and maintain the shape and form of the animal. In many animals, the spaces between cells are filled with fluid called interstitial fluid which provides support to these cells.

Exoskeleton is a rigid outer covering of the body of the animal which acts as a skeleton. Different types of exoskeletons are seen in the animal kingdom: Chitinous exoskeleton, calcium carbonate exoskeleton and bony plates. Arthropods possess the exoskeleton which is mainly composed of a non-cellular material, chitin. The chitinous exoskeleton is hardened by proteins or calcium carbonate. Exoskeletons that are made up of calcium carbonate are seen in the molluscs. In some reptiles, bony plates serve as the exoskeleton.

Endoskeleton is a hard skeleton which is buried in the soft tissues of the animal. Different types of endoskeletons are seen in the animal kingdom. These include plates of calcium carbonate (in echinodermates), bones and cartilage (in chordates).

Common functions of the skeletal systems in animals

- Support – All skeletons provide a rigid framework for the body and are resistant to compression and tension forces. They help to maintain the shape of body.

- Protection – The skeleton protects the delicate internal organs.
    - Movement – Most skeletons are composed of rigid materials which provide a means of attachment for the muscles of the body. Parts of the skeleton operate as levers on which the muscles can pull. When this occurs, movement takes place.

Functions of the human skeletal systems

- Support
- Protection
- Movement
- Storage and release of calcium under the influence of some hormones (refer competency level 5.7.1).
- Storage & release of phosphates under the influence of some hormones (refer competency level 5.7.1).
- Production of blood cells in the bone marrow

How animals move through water and air?

Swimming: *Different groups of animals swim in different ways. Some animals use their legs as oars to push against the water (e.g. insects and four legged vertebrates). Some animals are jet propelled taking water into the body and squirting it out in bursts (e.g. squids). Fishes swim by moving their body and tail from side to side. Aquatic mammals move by undulating their body and tail up and down (e.g. whales and dolphins). Fusiform body shape is a common adaptation for fast swimming animals.*

Movement through air: *Animals move through air mostly by flying. Gliding downward can occur in some instances. Flying animals use wings to lift the body against the gravity. Wings act as air foil: their shapes alter air currents in a way that helps flying. Fusiform shape of the wings helps to reduce drag force in air.*

The human skeleton

Human skeleton is divided into two main parts: axial skeleton and appendicular skeleton.

- Axial skeleton consists of skull, vertebral column, sternum and ribs.
- Appendicular skeleton consists of girdles (pectoral and pelvic) and limb bones.

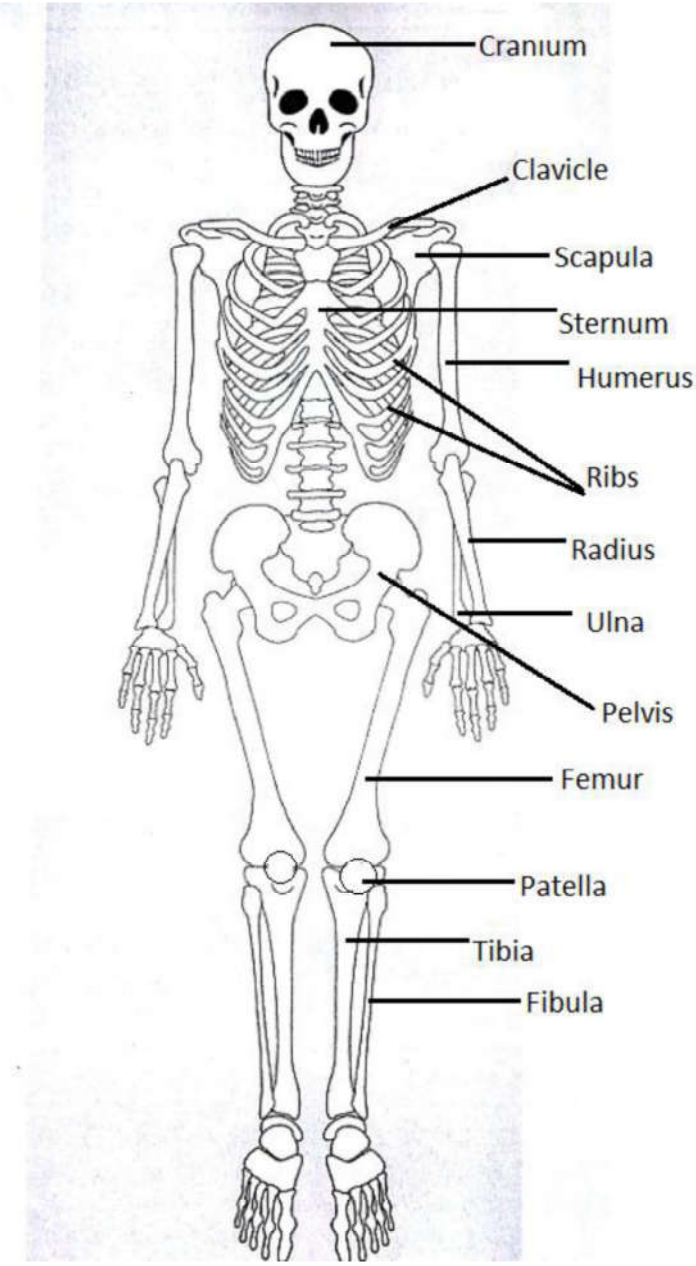


Figure: The anterior view of the human skeleton

Organization of the human axial skeletal system

Skull

In humans, the skull rests on the upper end of the vertebral column. The human skull consists of 21 bones which are mostly connected together by ossified joints (sutures). Skull is divided into the cranium (brain case) and the face. The bones in the cranium are the frontal bone, two parietal bones, the occipital bone, two temporal bones, the ethmoid bone and the sphenoid bone. In addition to the frontal bone, thirteen other bones form the skeleton of the face. They are two zygomatic bones (cheek), the maxilla (upper jaw bone), two nasal bones, two lacrimal bones, the vomer, two palatine bones, two inferior conchae and the mandible (lower jaw bone).

Human cranial capacity is nearly 1.5 L. Cranium protects and encloses the brain. It also protects the inner ear, middle ear, olfactory organs and eyes. Bony eye sockets provides attachment to the eye muscles that move them. On the inferior surface of the cranium there is foramen magnum to provide passage to spinal cord. Two smooth rounded knobs (Occipital condyles) on either side of the foramen magnum articulates with the first vertebrae (atlas vertebrae) which permits nodding movements.

In the cranium, soft membranous regions called fontanelles are present which allow slight compressions at birth facilitating parturition. Fontanelles become replaced by bones within 1-2 years of life. Immovable joints (sutures) are present between the skull bones to provide more protection. Several air filled cavities lined by ciliated mucous membrane are present in the skull (in the sphenoid, ethmoid, maxillary and frontal bones). They are called sinuses. They all communicate with the nasal cavity. Sinuses provide resonance to voice and reduce the weight of the skull.

Facial region is situated below the cranium. Some facial bones form the walls of the posterior part of the nasal cavity and form the upper part of the air passages. Maxilla and mandible provide ridges in which teeth are embedded. Upper jaw (maxilla) is fused with cranium. Lower jaw (mandible) is movable. Hard palate (bony) and soft palate (cartilaginous) separate the buccal cavity from nasal cavity. Lower jaw articulates with the cranium. Zygomatic arch (formed from parts of zygomatic bone and temporal bone) provides the surface for muscular attachment for moving the lower jaw. Lower jaw (mandible) contains two processes: Condyloid process which articulates with the temporal bone to form the temporal-mandibular joint; Coronoid process which gives attachment to muscles and the ligaments. At the base of the skull, occipital condyles (1 pair) are present on the two occipital bones to form a hinge joint with Atlas vertebrae. Temporal bone contains three processes: zygomatic process (which forms part of the zygomatic arch), mastoid process and styloid process. They provide surfaces for muscle attachment.

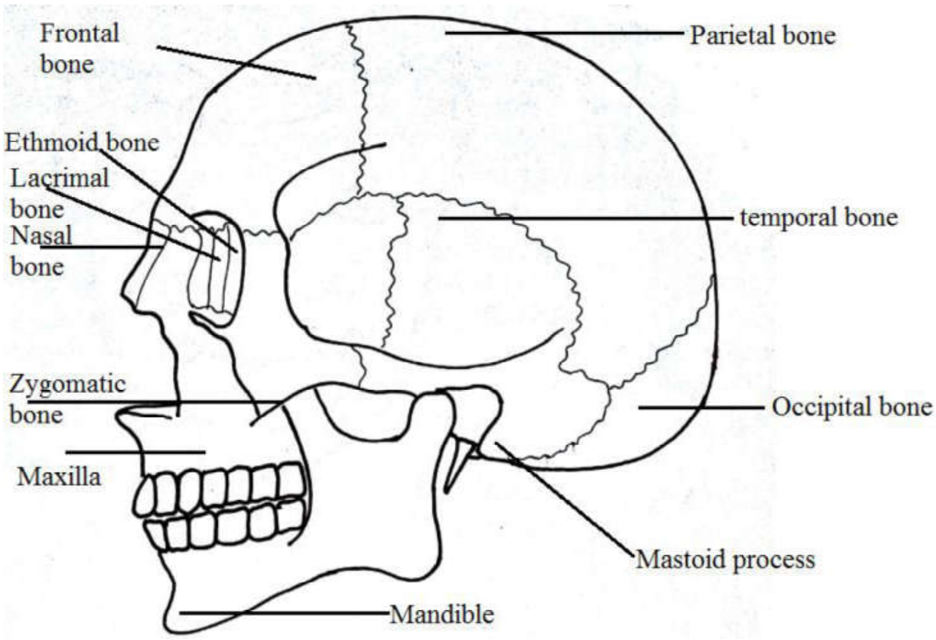


Figure: The bones of the human skull

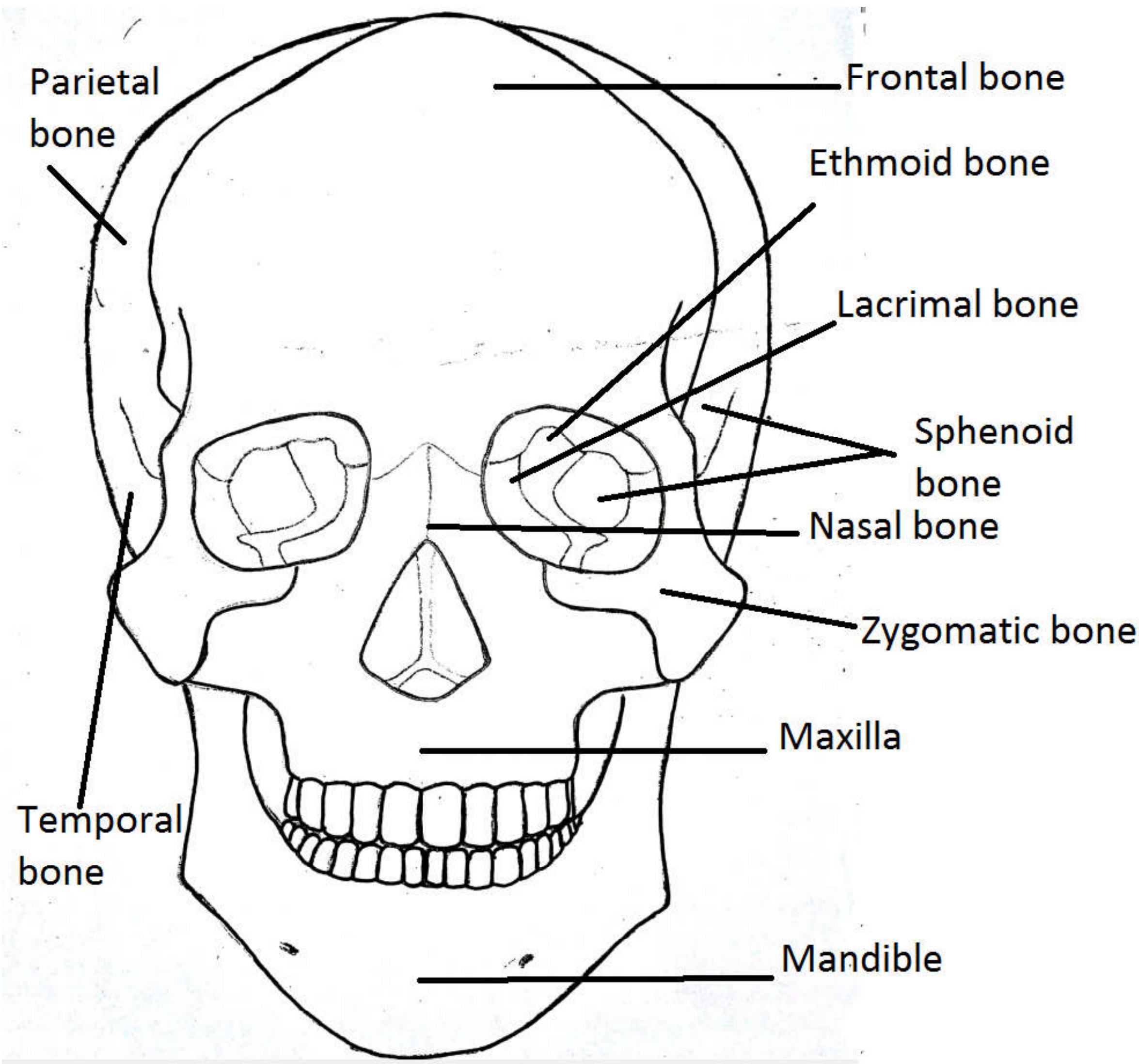


Figure: The anterior view of the human face (bones in the face)

Vertebral column

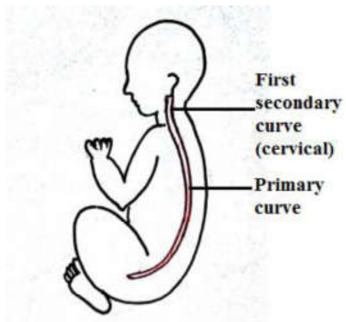
Vertebral column is a strong flexible rod consisting of 26 linearly arranged bones. It consists of 24 separate vertebrae extending downwards from the occipital bone of the skull, the sacrum (formed from 5 fused vertebrae) and coccyx (formed from 4 small fused vertebrae). The vertebral column is divided into different regions. There are 4 distinct regions: cervical spine (formed by 7 vertebrae in the neck), thoracic spine (formed by next 12 vertebrae), lumbar spine (formed by next 5 vertebrae), and the sacrum to which the lowest vertebrae of lumbar spine is articulated; the coccyx is situated at the end.

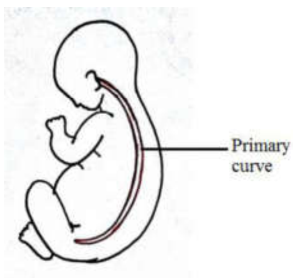
Curvatures of the vertebral column

In humans, there are 4 curves in the vertebral column: cervical, thoracic, lumbar and sacral. They can be categorized into two main types: two primary curvatures and two secondary curvatures. Main function of the curvatures is the maintenance of the erect posture.

Primary curvatures: In the foetus, there is only one curvature in the vertebral column. When secondary curvatures are formed the primary curvature is retained only in thoracic and sacral regions which are known as primary curvatures. They are concave towards anteriorly.

Secondary curvatures: Formed after birth, first cervical curvature develops at about 03 months of birth. Then the child can hold his head upright. Second, lumber curvature develops when the child is around 7-8 months. Then the child can hold his body upright. These secondary curvatures are convex towards anteriorly.





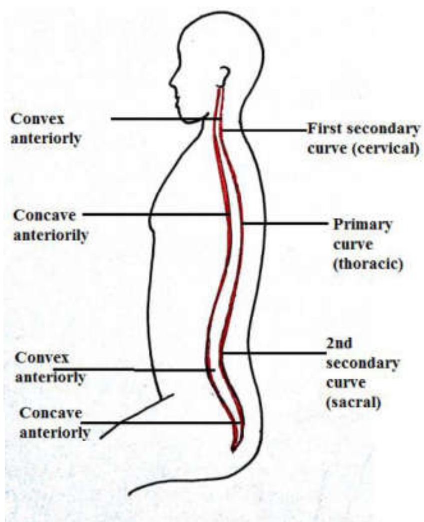


Figure :The development of curves in the human vertebral column

Types of vertebrae

Structure of the typical vertebra

A lumbar vertebrae can be considered as a typical vertebrae. The typical vertebrae consists of the body and the vertebral arch. The body is the largest, broad and flattened part of the vertebrae. The flatten surface of the body of each vertebrae articulate with the corresponding surface of adjacent vertebrae so that vertebrae are stacked together in the vertebral column. However the adjacent two vertebrae are not in direct contact with each other as there is a tough pad of cartilage called intervertebral disc between the two vertebrae. The size of the body of the vertebrae increases downwards of the vertebral column to support the body weight.

Vertebral arch encloses vertebral foramen which provides passage way for the spinal cord. Processes arise from the neural arch provide surfaces for muscle attachment. Two lateral processes are called transverse processes and posterior process is called spinous process. The vertebral arch has four articular surfaces: two superior articular surfaces (articulate with the adjacent vertebrae above) and two inferior articular surfaces (articulate with the adjacent vertebrae below).

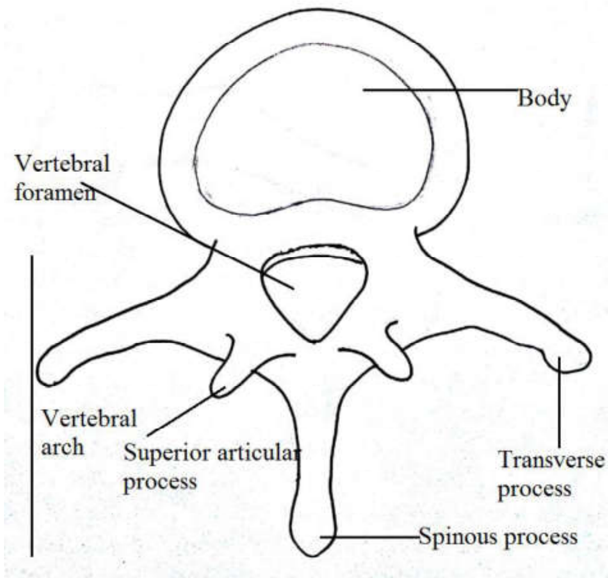


Fig 5: The structure of the typical vertebrae (lumbar vertebrae)

Region specific vertebral characteristics

Cervical vertebrae: Cervical vertebrae are the first seven vertebrae in the vertebral column. When compared to the other types of vertebrae, cervical vertebrae are the smallest. Body of the cervical vertebrae is smaller compared to the other vertebrae. In addition, transverse processes of cervical vertebrae have a foramen on each side to provide passage for the vertebral artery. The spinous process of these vertebrae is bifid.

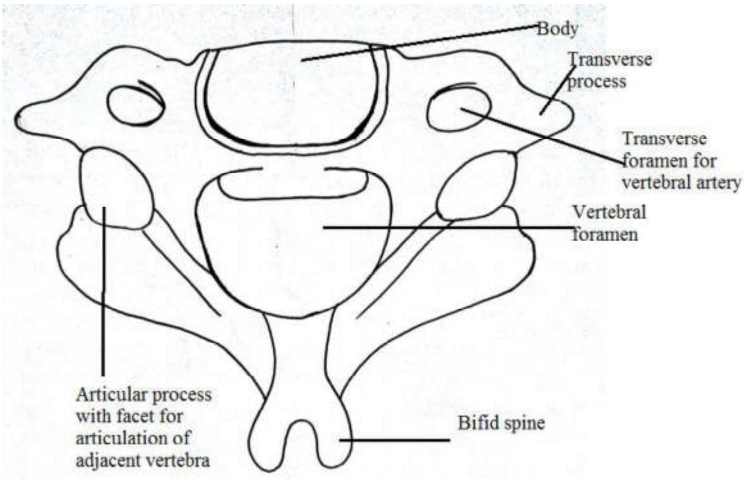


Figure: The structure of the typical cervical vertebra

The first cervical vertebrae is the atlas which is the bone on which the skull rests. It is a ring shaped vertebrae with no distinct body or spinous processes. It has two short transverse processes. The atlas contains two flattened facets which articulates with the occipital bone of the skull (Condyloid joints), permitting nodding movements. Vertebral foramen of this vertebrae is relatively larger to provide the passage of the larger anterior part of the spinal cord.

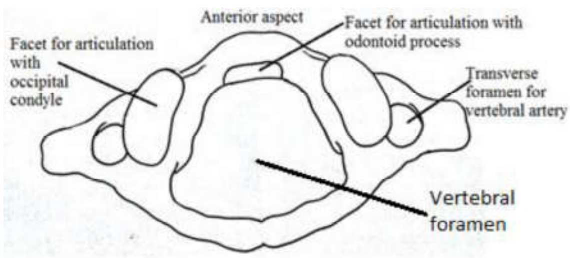


Fig 5: The structure of the atlas vertebrae

The second cervical vertebra is the axis. It has a small body with a superior projections called odontoid process which articulates with the atlas vertebrae above. The head pivots (turns on side to side) on this joint.

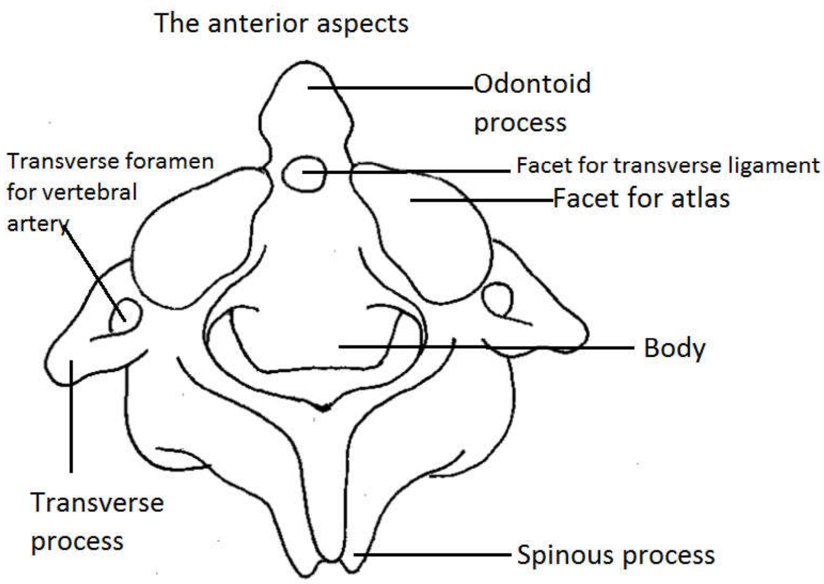


Figure: The structure of axis vertebrae

Thoracic vertebra: The twelve thoracic vertebrae are larger than cervical vertebrae as this region of the vertebral column has to support more body weight. The body and transverse processes of thoracic vertebrae have facets for articulation with the ribs.

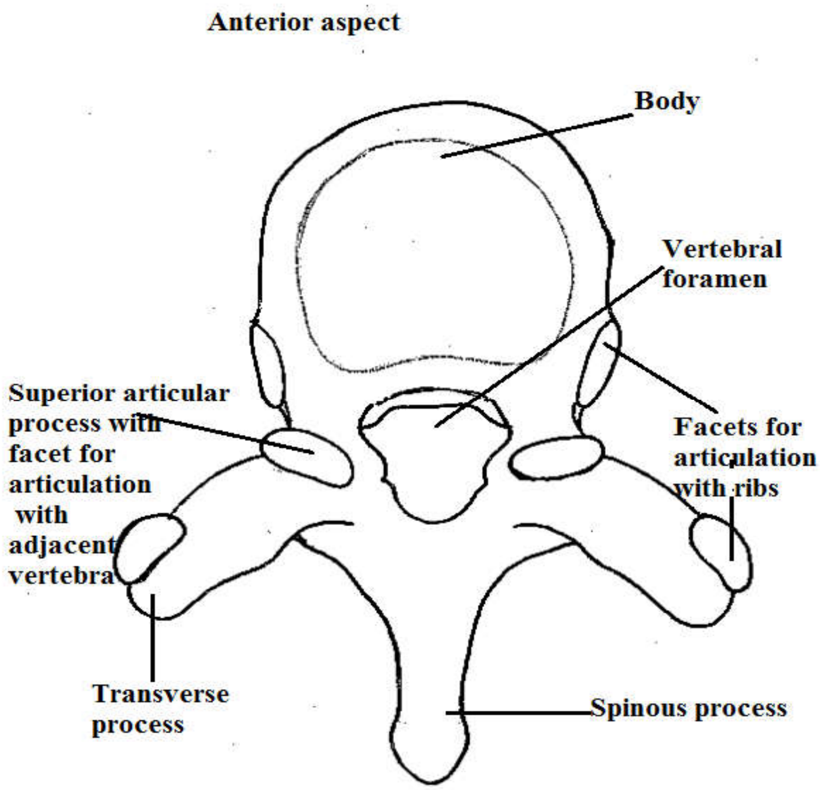


Figure: The structure of the thoracic vertebrae

Lumbar vertebrae: The five lumbar vertebrae are the largest of the vertebrae because they have to support the weight of the upper body. The size of the body of the lumbar vertebrae is larger compared to the other vertebrae. For attachment of the muscles of lower back the lumbar vertebrae have a relatively large spinal processes.

Sacrum and Coccyx: Sacrum is a triangular shaped large bone consisting of five fused rudimentary vertebrae. It has a concave anterior surface. The upper part articulates with the fifth lumbar vertebrae. On each side, sacrum articulates with the pelvic girdle. Inferior tip of the sacrum articulates with coccyx. A series of vertebral foramina are present on each side for passage of nerves. Coccyx consists of fused four terminal vertebrae to form a small triangular bone. The broad base of the coccyx articulates with the tip of the sacrum.

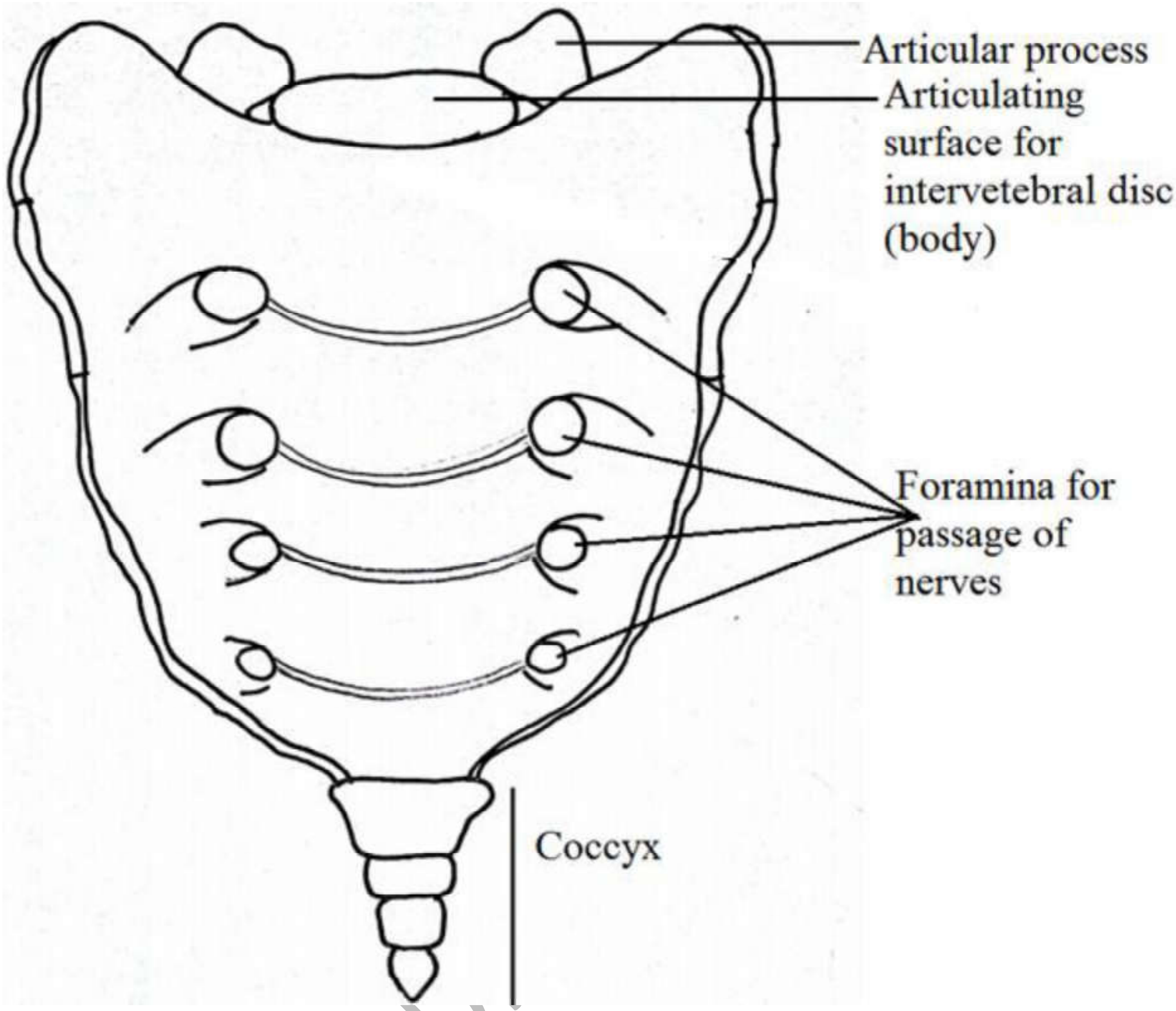


Figure: The anterior view of the sacrum and coccyx

Common functions of the human vertebral column

The vertebral column helps to maintain erect posture. It supports the skull and give attachments to ribs and girdles. It also provides the protection for spinal cord. Vertebral foramens provide spaces for spinal nerves and blood vessels and lymph vessels. The vertebral column allows flexibility in the body movements. The intervertebral discs act as shock absorbers and protect the spinal cord.

Sternum

Sternum is a long flat bone that forms anterior part of the thoracic cage (which is made up of sternum, ribs and thoracic vertebrae). The uppermost section of the sternum is the manubrium which articulates with the clavicles in the pectoral girdles and the first two pairs of ribs. The body, which is the middle part of the sternum gives attachment to the rest of the ribs. The xiphoid process is the tip of the bone which gives attachment to the diaphragm and muscles of the anterior abdominal wall. The sternum provides protection of the organs and blood vessels that lie behind it (heart and lungs) from physical damage. The red bone marrow in the sternum is one of the main sites for production of blood cells.

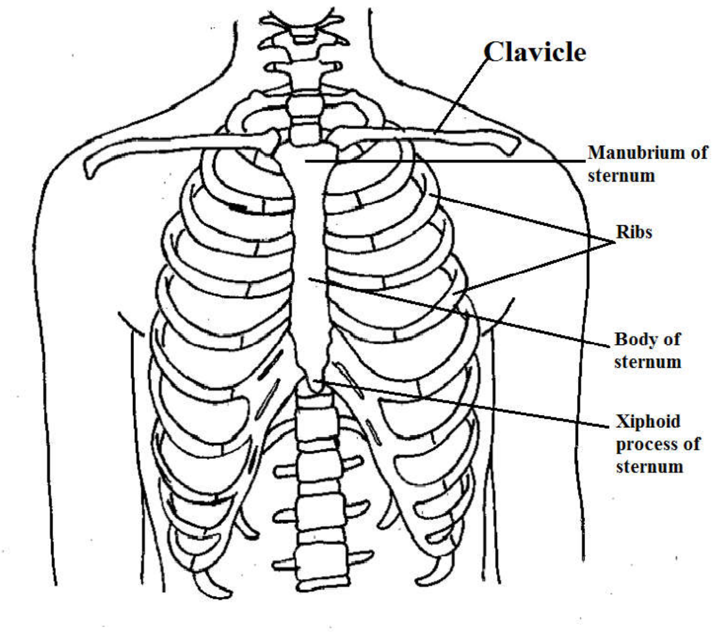


Figure: The thoracic cage and the location of the sternum

Ribs

The twelve pairs of ribs form the lateral walls of the thoracic cage. They are elongated curved bones. They articulate posteriorly with the thoracic vertebrae of vertebral column. Anteriorly 7 pairs of ribs articulate with the sternum (true ribs), next 3 pairs articulate with sternum indirectly. In both cases costal cartilages attach the ribs to the sternum. The lowest 2 pairs do not join the sternum (floating ribs). Head of the rib articulates with vertebral bodies, facets of tubercle articulate with transverse process of vertebrae. The thoracic cage which includes the ribs and sternum plays an important role in the mechanism of breathing. Between each ribs intercostal muscles are present which move the rib cage during breathing. The first rib is firmly fixed to the sternum and to the first thoracic vertebrae. Therefore it does not move during inspiration. Because it is a fixed point when the intercostal muscle contract they pull the entire rib cage upwards and towards the first ribs. Presence of 12 pairs of ribs and sternum provide protection to the organs such as lungs and heart in the thoracic cavity.

Contribution of human axial skeleton to maintain the upright posture

- Presence of two primary curvatures and two secondary curvatures in the vertebral column. Development of the two secondary curvatures in the vertebral column mainly contribute to maintain the erect posture. (Refer the section on curvatures of vertebral column).
- The size of the vertebrae (especially the body of the vertebrae) become larger towards the end of the vertebral column as they have to support the weight of the upper body (Refer the section on vertebrae).
- The sacral vertebrae are fused to form a triangular shaped large sacrum to support the weight of the vertebral column and internal organs of the body.
- The two occipital condyles (and the foramen magnum) are located inferiorly at the base of the skull close to the center. In the upright position, this arrangement permits proper balancing of the skull on the vertebral column.

The structure and functions of the human appendicular skeleton

Appendicular skeleton

The appendicular skeleton consists of upper limbs with pectoral (shoulder) girdle and lower limbs with the pelvic girdle. Through the pectoral girdle the upper limb forms the joints with the trunk. Pectoral girdle connects upper limb with the axial skeleton. Pectoral girdle consists of two scapulae (shoulder blades) and two clavicles (collar bones). The lower limb forms a joint with the trunk at the pelvic girdle. Pelvic girdle is formed from two hip bones and it is associated with the sacrum.

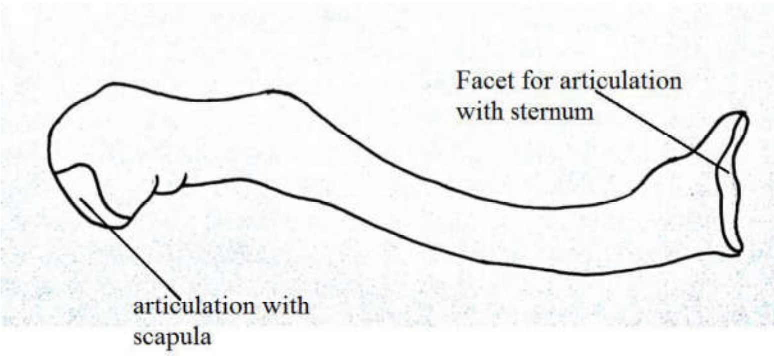


Fig 5: The right clavicle

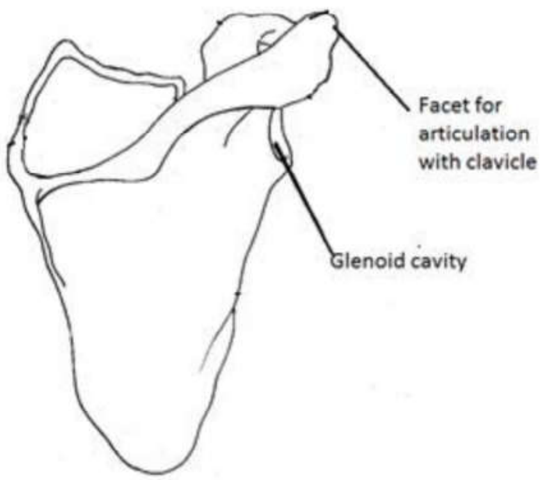


Fig 5: The right scapula

Upper limb

Upper limb consists of humerus, radius, ulna, eight carpal bones, five metacarpal bones and fourteen phalanges. Humerus is the bone of the upper arm.

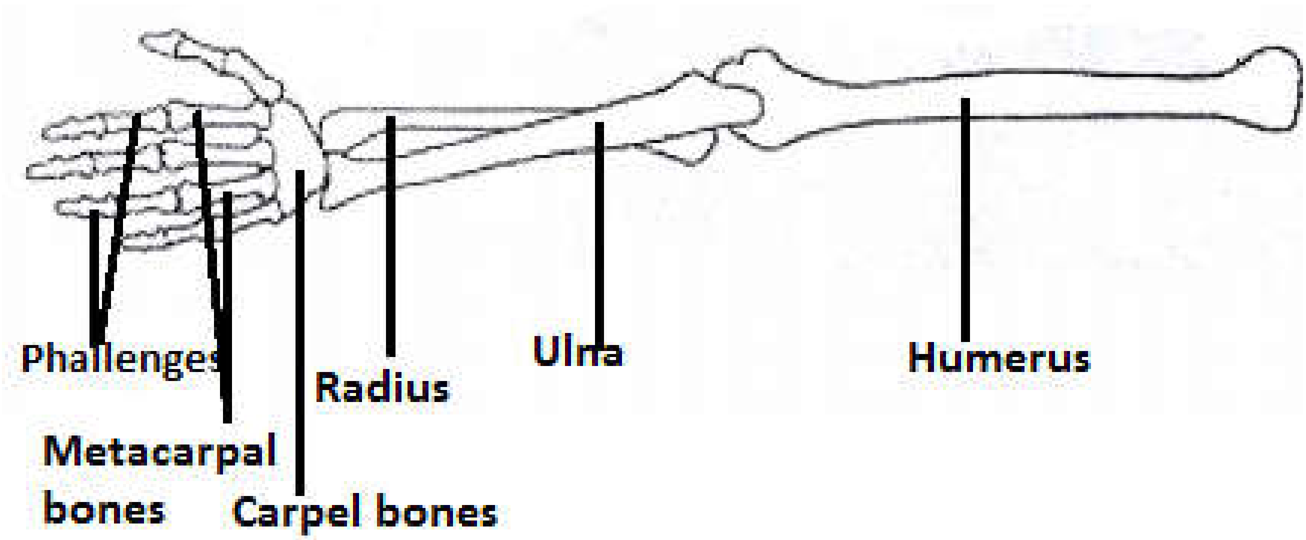


Figure: Bones of the upper limb

The adaptation of the human upper limb for movement of wide range

Structure of upper limb is adapted for grasping, weight lifting and movement over a wide range.

Head of the humerus (the bone of the upper arm) forms an incomplete ball and socket joint (shoulder joint) in glenoid cavity of the scapula permitting vast range of movements. The joint allows for flexion, extension, adduction, abduction, rotation and circumduction.

The distal end of the humerus has two articular surfaces. Through these surfaces, radius and ulna articulate with the humerus at the elbow joint. They articulate with the carpal bones at the wrist joint. Further ulna and radius are articulated with each other at the proximal and distal radio-ulna joints. In addition a fibrous joint connects the bones along their shafts which stabilize their association and maintain their relative position in spite of forces applied from the elbow or wrist. The elbow joint act as a hinge joint which permits only flexion and extension of the fore arm.

The carpal bones which are arranged in two rows (proximal row and distal row) are closely fitted together so that there is limited amount of movement between them. Proximal row bones are associated with the wrist joint and distal row bones form joints with metacarpal bones. Wrist joint is present between the distal end of radius and three proximal carpal bones. This arrangement allows pronation (palm down) and supination (palm up) of the lower part of the upper limb. In addition the wrist can be flexed, extended, abducted and adducted.

The proximal ends of metacarpal bones in the palm articulate with carpal bones and their distal ends articulate with phalanges. The joints between metacarpal and phalanges allow movement of the fingers and permits the power grip. Fingers may be flexed extended, adducted, abducted and circumducted with the first finger more flexible than the other. The joint present at the base of the thumb between a specific carpal bone and the first metacarpal bone allows more mobility to the thumb than the other fingers. This leads to opposable nature of the thumb which permits the thumb to move perpendicular to the other fingers. This articulation permits precision grip which is unique to man.

Lower limb

Lower limb consists of femur (thigh bone), tibia (shin bone), fibula, patella (knee cap), seven tarsal bones (ankle bones), five metatarsal bones (bones of the foot) and fourteen phalanges (toe bones).

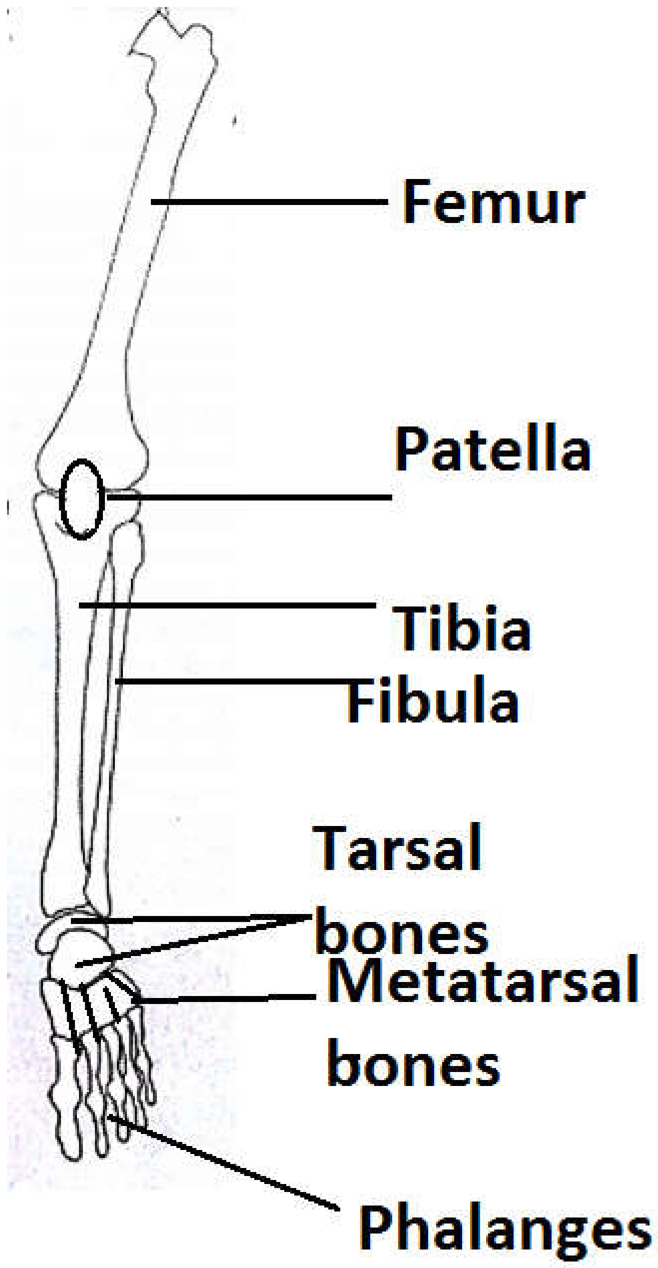


Figure: Structure of the lower limb

Adaptations of the lower limb for the erect posture, bearing of body weight and walking

Structure of the lower limb is adapted for strength, erect body posture, bearing body weight and walking.

Femur is the longest, heaviest and the strongest bone of the body. Head of the femur forms the hip joint (ball and socket joint) with the acetabulum of the hip bone of the pelvis. This hip joint is very sturdy and powerful as it bears all body weight when standing. The lower limb can be extended, flexed, abducted, adducted, rotated and circumducted at the hip joint.

Lower end of femur articulates with tibia and patella to form the knee joint. Tibia is the medial of the two bones. Possible movements at the knee joint are flexion, extension and a rotatory movement that locks the joint when it is fully extended. When this joint is locked it is possible to stand upright for long period of time.

Femur transmits the weight of the body through the bones below the knee to the foot. All the lower ends of both tibia and fibula articulate with a specific tarsal bone to form the ankle joint. The ankle joint allows rising in tip toe and lifting toes towards calf.

The arrangement of bones in the foot supported by associated ligaments and muscles gives the sole of the foot an arched or curved shape. There are two longitudinal arches and one transverse arch in the foot. Curve running heel to toe is called the longitudinal arch and the curve running across the foot is called the transverse arch. In the upright position, these arches of the foot are important in distributing the weight of the body evenly whether stationary or moving.

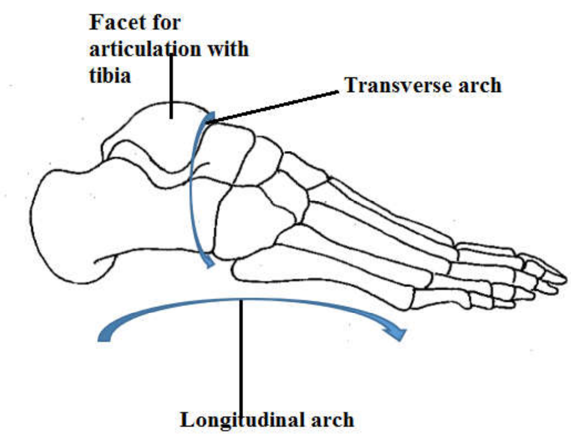


Fig 5: The arches of foot

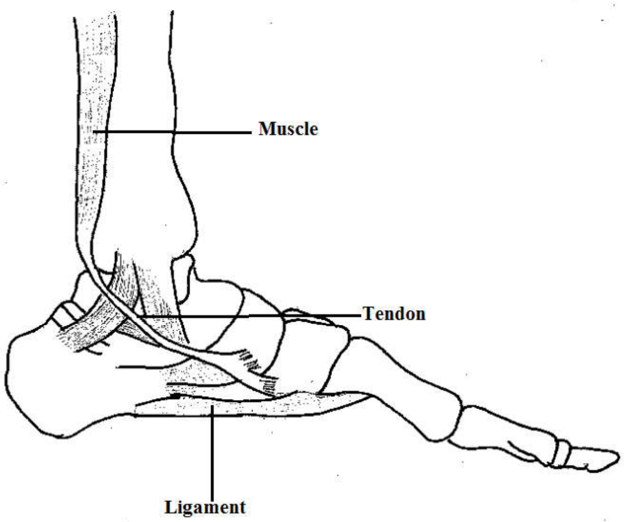


Fig 5: The tendons and ligaments in the foot

Some disorders and abnormalities associated with human skeletal system

Osteoporosis

Osteoporosis is a condition associated with the reduction of bone density due to the exceedance of the bone reabsorption rate over the deposition rate. This gives in fragility to the bone tissue. This condition leads to immobility in joints and may cause fractures, skeletal deformities and bone pain. Factors causing osteoporosis include hormonal imbalances (especially at menopause), calcium deficiency and environmental factors.

Osteoarthritis

Osteoarthritis is a degenerative non-inflammatory disease that causes pain and restricted movements in the affected joints. Articular cartilage at the joints gradually become thinner so that articular surfaces of the bones come in contact and eventually the bones begin to degenerate; the outcome is pain. The cause of osteoarthritis is unknown. But risk factors include excessive use of affected joints, female gender, increasing age, heredity and obesity.

Slipped disc

The bodies of adjacent vertebrae are separated by intervertebral discs which serve as shock absorbers. These intervertebral discs consist of an outer ring of cartilage and a central core of soft gelatinous material. An injury or weakness can cause the inner portion of the intervertebral disc to protrude through the outer ring. This condition is called ‘slipped disc’. This leads to pain and discomfort. If the slipped disc compresses a spinal nerve, there can be numbness and pain along the affected nerve. Slipped disc condition can arise when lifting heavy weights without bending knees.

Main types of joints in the human skeletal system

Main types of the joints in the human skeletal system are ball and socket joint, hinge joint and pivot joint.

- **Ball and Socket Joints**

In these joints, ball shaped head is connected with the cup shaped socket and allows for wide range movements such as flexion, extension, adduction, abduction, rotation and circumduction. There are two ball and socket joints available in the human body: Shoulder joint and Hip joint. (Refer upper limb and lower limb)

- **Hinge Joints**

The articulating ends of the bone fit together in such a way so it looks like a hinge of a door. This allows only restricted movements such as flexion and extensions. Examples for hinge joints are elbow joint, knee joint, ankle joint and joints between the phalanges of the fingers and toes. (Refer upper limb and lower limb)

- **Pivot Joints**

One bone fits in to a hoop shaped ligament that holds it close to another bone and allows it to rotate in the ring formed by the ligament. These joints allow a bone or limb to rotate. For example head rotates by the pivot joint formed by the axis vertebrae within the transverse ligament ring and odontoid process of the atlas. (Refer vertebral column)

Skeletal muscle and mechanism of contraction

Features of skeletal muscle tissue

The skeletal muscles are generally attached to the skeletal system and mainly cause voluntary body movements. Skeletal muscle tissue is composed of bundles of long cylindrical cells. These cells are aligned parallel to each other along the length of the muscle. Each cell contain multiple nuclei close to the cell membrane. Inside the cell, bundles of myofibrils containing contractile microfilaments are located longitudinally along the length of the cell. Myofibrils in the muscle cell form repeating sections called sarcomeres. The repeating arrangement of sarcomeres within the skeletal muscle cell gives its striated appearance under the microscope. Sarcomeres are the basic contractile units of the striated muscle cell. Like smooth muscle cells and cardiac muscle cells, skeletal muscle cells show excitability or irritability (ability to receive and respond to stimuli)**,** contractility (ability to contract or shorten)**,** extensibility (ability to stretch or contract) and elasticity (ability to return to its original length after being stretched or contracted). The skeletal muscle is under the voluntary control of the somatic nervous system.

Structure of the sarcomere, basic mechanism of skeletal muscle movement

Sarcomeres are the repeating contractile units present within a striated muscle cell. The sarcomere is composed of myofibrils containing contractile thick filaments and thin filaments which are made up of specific proteins. The thin filaments (formed mainly from actin protein) attached at the Z line, a dense stripe which forms the borders of the sarcomere. The thick filaments (formed from myosin protein) are fixed (at the M line) in the middle region of the sarcomere. Sarcomeres are found repeatedly between two Z lines in a skeletal muscle cell. At the resting stage of myofibrils, thick and thin filaments are partially overlapped. At the edge of the sarcomere there are only thin filaments while at the center of the sarcomere only thick filaments are present. Such arrangement of thick and thin filaments in the sarcomeres permits the shortening of the skeletal muscle cell during contraction and return to the original state during relaxation. The mechanical function arising from sarcomeres is produced by actin (found in thin filaments) and myosin (found in thick filaments) proteins.

The skeletal muscle contraction is mainly voluntary and under the control of the somatic nervous system. Upon stimulation, individual muscle cells in the skeletal muscle shortens due to the shortening of its sarcomeres, and thus the whole muscle may contract. Converting muscle contraction to movement needs a skeleton to which the muscles attach. Skeletal muscle contractions pull on the tendons attached to the bones. If contraction of the muscle causes the muscle to shorten, the bone and the body part will move. When the nervous stimulation is stopped, the muscles will return to the original length after being contracted.

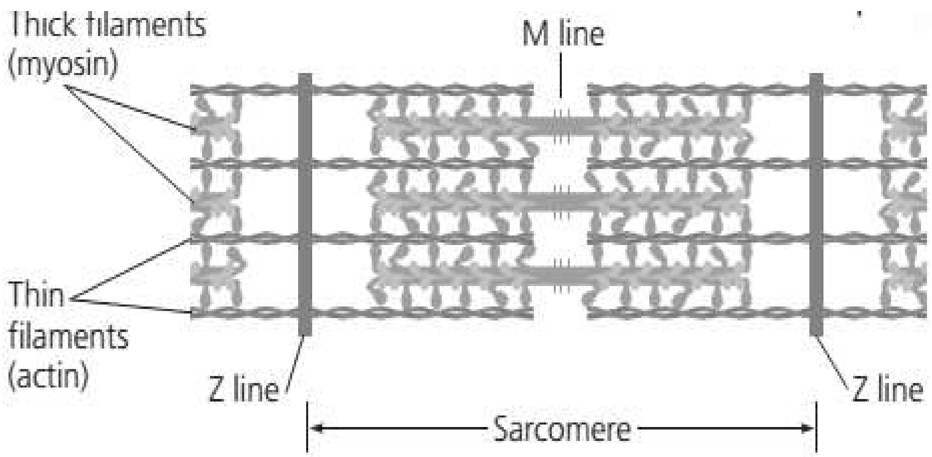


Figure: The arrangement of a sarcomere

Sliding filament theory is the currently accepted model of striated muscle contraction. According to this theory, when a skeletal (or cardiac) muscle cell contracts, the thick (myosin) filaments and thin (actin) filaments in each sarcomere slide past each other pulling the Z lines at each end of the sarcomere closer to one another shortening the sarcomeres and thus the muscle cell, while the two groups of filaments in the sarcomere remain at relatively constant length. Myosin is the motor protein that does muscle contraction by pulling on thin filaments (actin) in muscle cells. Each myosin molecule is composed of 'tail' region and 'head' region. In the thick filaments, these 'tail' regions are bundled together while the 'heads' are sticking out. The thin filaments are composed of actin molecules which have binding sites for the 'head' region of the myosin molecules. The head region of the myosin can also bind with an ATP molecule when its 'low energy state'.

When the ATP molecule is hydrolyzed to form ADP and phosphate while releasing energy, the myosin head enters into the 'higher energy state'. At this state, the myosin head binds to myosin binding site of actin forming a cross bridge. Thereafter the myosin head returns to its lower energy state by releasing ADP and phosphate, which pulls (slides) the thin filament toward the center of the sarcomere and so shortening the sarcomere. When a new molecule of ATP binds to the myosin head, the cross bridge is broken, myosin head detaches from actin. A new cross bridge cycle begins again. The contraction of muscles require many number of repeated cycles of binding and releasing. In each cycle, the myosin head is released from the cross bridge and newly bound ATP is hydrolyzed which promotes binding of myosin again to new actin molecule. This process occurs along the entire length of every myofibril in the muscle cell. Since in the earlier cycle the thin filament has moved towards the center of the sarcomere, a new binding site for the myosin head region is exposed in the thin filament. The entire process causes the thick and thin filaments in the muscle cell to slide past each other pulling the Z lines at each end of the sarcomere closer to one another shortening the sarcomere.

Many myosin heads can be found in one thick filament. Within one second, each of these heads can form cross bridges. Ca^{2+} and some other proteins also play a major role in muscle contraction. Myosin can only bind to actin when the binding sites on actin are exposed by the action of calcium ions.

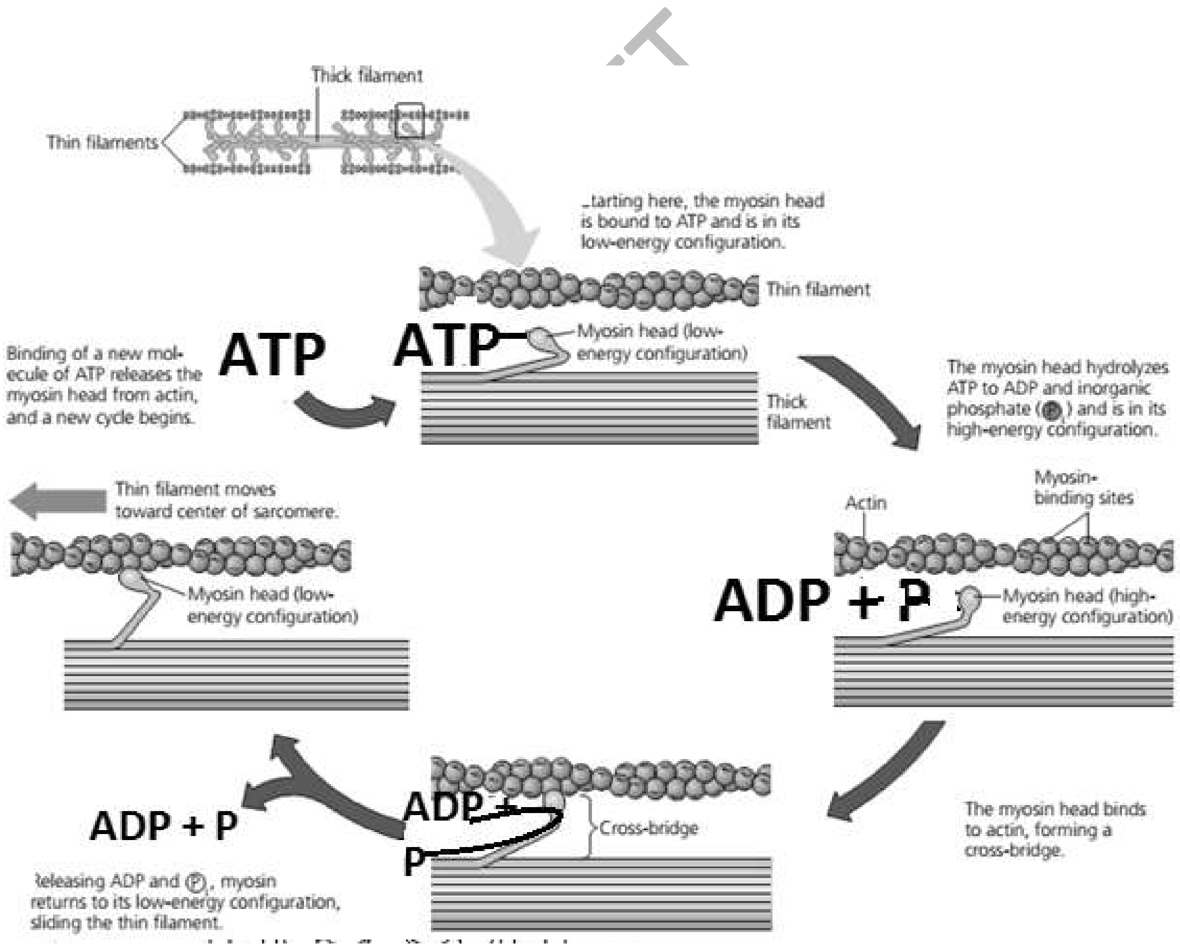


Figure: Interaction of actin and myosin in skeletal muscle cell contraction