

Anatomy and Physiology: The Musculoskeletal System

CHAPTER 1

The musculoskeletal system (also known as the locomotor system) encompasses all the bones, cartilage, muscles, joints, tendons and ligaments within the body. It serves as the structural foundation, with bones providing shape, support and protection. The musculoskeletal system is required to sustain life through contraction of the diaphragm and heart muscle; to convey communication through facial expressions and body language and to protect internal structures such as the heart and lungs (Henstock 2021). Muscles, composed of fibres, facilitate both voluntary movements of body parts and involuntary actions within internal organs. The muscles are the active part of the apparatus of locomotion. In some cases, the musculoskeletal system is seen as two body systems in one or two systems that work very closely with each other, with one being the muscular system and the other the skeletal system. Without the skeleton to pull against, contracting muscle fibres cannot enable us to sit, stand, walk or run (Manfred 2022).

A fully functioning musculoskeletal system is fundamental to optimal health and well-being. Injury or disease involving this system can have a profound effect on an individual's mobility and, therefore, their ability to perform activities of daily living and can result in temporary or permanent disability (Santy-Tomlinson and Lucas 2019).

Kinesiology, also known as body mechanics, focuses on analysing the movement of various body parts. Enabled by the musculoskeletal system, in tandem with the nervous system, bodily motion occurs. Employing appropriate body mechanics is paramount to ensuring the safety of both patients and healthcare providers (Peate 2019).

This chapter discusses the anatomy and physiology of the musculoskeletal system.

MUSCLES

While the skeletal system serves as the fundamental architectural framework of the human body, providing structural support and leverage, it is the muscular system that is chiefly responsible for executing movement by pulling on bones. Muscular contraction and relaxation are the primary mechanisms by which movement is achieved, with muscles functioning as the active agents in this process. It is important to recognise that muscles possess the capability to contract, thereby initiating movement, but they lack the inherent capacity to push; conversely, bones are inert structures and necessitate muscular action to prompt motion.

In addition to facilitating external locomotion, muscles fulfil essential roles in internal physiological processes. They are integral to the movement and maintenance of internal organs, including the heart, lungs and gastrointestinal system. Notably, cardiac muscle, characterised by its involuntary and rhythmic contractions, is indispensable for sustaining the cardiac cycle and ensuring effective circulation.

Muscles serve as the primary engine that drives bodily movement, converting energy into locomotion. Whether undertaking deliberate physical activities or engaging in automatic physiological functions, such as respiration and ocular movement, all actions are brought

together by the coordinated activity of muscles. Even subtle, delicate expressions of emotion, such as smiling, kissing or frowning, involve intricate muscular coordination.

Muscle, also tissue, exhibits a thermogenic effect, this means that when muscles contract, they generate heat as a byproduct of their metabolic activity. This heat production helps to regulate body temperature and is instrumental in maintaining homeostasis and optimal physiological function.

Muscles in the human body often work in pairs known as agonist and antagonist muscles. These pairs are associated with joints and bones, enabling movement through the application of force. The agonist muscle is responsible for initiating and carrying out a specific movement, such as bending the arm at the elbow. Its counterpart, the antagonist muscle, performs the opposite action, working to relax and lengthen as the agonist contracts. This coordinated interaction allows for smooth, controlled movements and prevents excessive strain on joints and ligaments.

Body mechanics refers to the efficient use of the musculoskeletal system to perform tasks while minimising the risk of injury or strain. It involves proper alignment, posture and movement patterns to enhance biomechanical efficiency and reduce stress on the body's structures.

Maintaining balance involves the coordination of muscles and sensory input from the vestibular system (inner ear) and proprioceptors (sensory receptors in muscles and joints). Muscles throughout the body, especially those in the legs and core, work together to adjust body position and counteract external forces, such as gravity or changes in terrain, to prevent falls and maintain stability.

Posture refers to the alignment of the body's musculoskeletal structures, including the spine, pelvis and limbs, while sitting, standing or moving. Proper posture distributes the body's weight evenly, reducing strain on muscles, ligaments and joints. Muscles of the trunk, neck and back play a crucial role in supporting the spine and maintaining an upright posture, especially during prolonged sitting or standing activities.

Body alignment involves positioning the body segments in optimal alignment to minimise stress and strain on the musculoskeletal system. This includes maintaining a neutral spine, aligning the head, shoulders and hips and distributing body weight evenly between the feet. Proper body alignment ensures efficient movement patterns and reduces the risk of overuse injuries or musculoskeletal imbalances.

MUSCLE TISSUES

There are three types of muscle tissue, and they have distinct structures and functions, but they all play essential roles in movement, support and physiological processes within the body:

1. Skeletal
2. Cardiac
3. Smooth

See Figure 1.1.

Table 1.1 discusses the different types of muscle tissue.

SKELETAL MUSCLE

The skeletal muscles make up the muscular system of the body (made up of over 600 muscles), accounting for 40–50% of the body weight in an adult. Skeletal muscle consists of elongated, single-striated fibres ranging in length from a few centimetres to 40 cm, each containing multiple nuclei. Unlike other muscle types, skeletal muscle is under voluntary control,

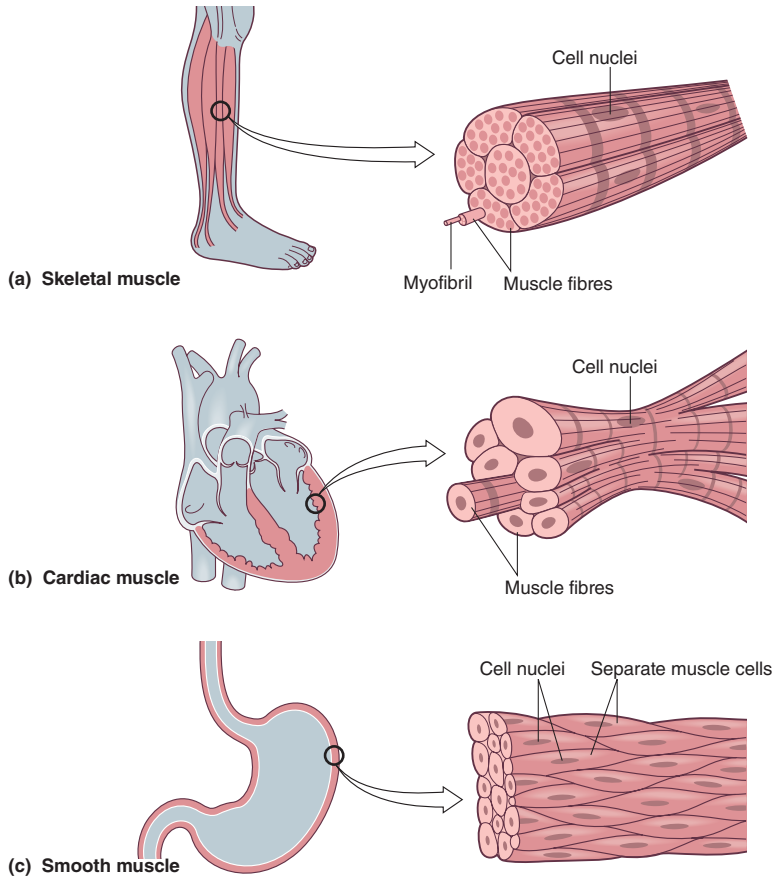


FIGURE 1.1 Muscle tissue

Table 1.1 Different types of muscle tissue

Skeletal muscle	Smooth muscle	Cardiac muscle
Attached to bones or the skin (facial muscles only)	Found in the walls of hollow visceral organs and blood vessels	Located in the walls of the heart
Single, long cylindrical cells	Single, narrow, rod-shaped cells	Branching chains of cells
Striated, multinucleated cells	Non-striated, uninucleated cells	Striated, uninucleated cells
Under voluntary control	Involuntary control	Involuntary control

meaning it can be consciously relaxed or contracted through intentional effort; it is the only voluntary muscle of the body. Skeletal muscle is also known as striped or striated muscle because of the banded patterns of the cells seen under the microscope.

The sarcolemma, which is the muscle cell membrane, encloses the sarcoplasm, the cytoplasm of the muscle cell. Tubules originating from the sarcolemma extend into the sarcoplasm, facilitating rapid distribution of contraction signals throughout the muscle fibre. Within the muscle fibre, myofibrils are responsible for contraction and are composed of

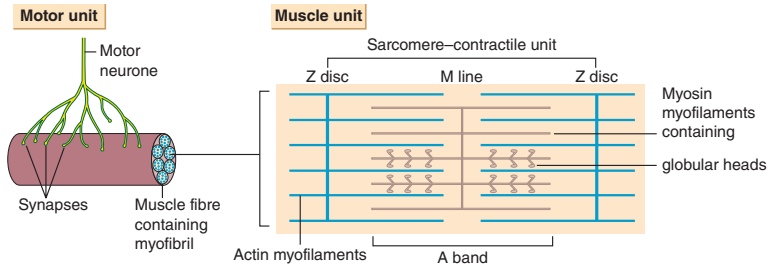


FIGURE 1.2 The motor and muscle units

bundles of filaments consisting of actin and myosin. These filaments are organised into functional units known as sarcomeres, with actin filaments positioned centrally within the sarcomere and myosin filaments located at either end. The Z line demarcates the boundaries of the sarcomere, while the M line is situated at its midpoint. Actin and myosin filaments are interconnected by cross bridges, which repeatedly engage and disengage during contraction, leading to the shortening of the sarcomere. The release of calcium from various structures triggers muscle contraction. Each muscle fibre is enveloped by a layer of endomysium, which bundles together to form fascicles, each of which is further encased in perimysium. Figure 1.2 shows the motor and muscle units.

The site where the nerve impulse initiates muscle contraction is known as the neuromuscular junction (NMJ). Each muscle fibre possesses a single NMJ where the neurone's axon connects to the fibre. Near the motor endplate, at the terminal end of the axon, there exists a synaptic cleft that separates the nerve from the motor endplate, although they are not in direct contact. Muscle activation occurs through chemical transmission, with acetylcholine, contained within the axon, binding to receptors on the motor endplate.

The binding of acetylcholine at the NMJ triggers a series of events that result in the generation of an action potential, the spread of the action potential across the sarcolemma and into the interior of the muscle fibre and ultimately the release of calcium ions and the muscle contractions.

CARDIAC MUSCLE

The fibres are striated and branched, typically containing a single nucleus centrally located. At each end, they connect through specialised thickenings of the plasma membrane, which contain desmosomes and gap junctions. Desmosomes provide structural support and cohesion during strong contractions, while gap junctions facilitate swift transmission of electrical signals, particularly crucial for heart function. Unlike skeletal muscle, this type of muscle operates involuntarily, beyond conscious control. Exclusive to the heart's walls, cardiac muscle functions to propel blood throughout the body.

SMOOTH MUSCLE

This muscle type consists of non-striated, involuntary fibres, each housing a single nucleus positioned centrally. Numerous gap junctions interconnect individual fibres, enabling coordinated, forceful contractions across multiple fibres. This mechanism is evident in various anatomical structures, such as the iris, hollow organ walls, blood vessels, stomach, intestines, urinary bladder and uterus. Unlike skeletal muscle, smooth muscle fibres contract independently.

Smooth muscle tissue plays a crucial role in facilitating peristaltic movements, which are essential for various physiological processes. Peristalsis refers to the coordinated, wave-like contractions and relaxations of smooth muscle fibres that propel substances through hollow organs, such as the digestive tract, stomach and urinary bladder.

In the digestive tract, smooth muscle contractions aid in the movement of food along the gastrointestinal system, starting from the oesophagus and continuing through the stomach and intestines. These rhythmic contractions push food forward, mix it with digestive enzymes, and ultimately facilitate absorption of nutrients.

Within the stomach, smooth muscle contractions help churn food and mix it with gastric juices, aiding in digestion and the breakdown of food particles into smaller, more digestible components. This process is essential for the subsequent absorption of nutrients in the intestines.

In the urinary bladder, smooth muscle contractions play a key role in the storage and elimination of urine. When the bladder fills with urine, its smooth muscle layer, known as the detrusor muscle, stretches. As the bladder reaches its capacity, coordinated contractions of the detrusor muscle occur, leading to the sensation of urgency and the eventual expulsion of urine through the urethra.

PROPERTIES OF MUSCLE TISSUE

Muscle tissue possesses four distinct properties:

1. **Excitability (irritability):** The capacity to detect and react to stimuli by generating electrical impulses, leading to muscle cell contraction.
2. **Contractility:** The capability to undergo shortening.
3. **Extensibility:** The ability to stretch or lengthen.
4. **Elasticity:** The capacity of muscle fibres to rebound and return to their original resting length after being stretched.

Table 1.2 provides a further exploration of the properties of muscles.

The combination of excitability, contractility, extensibility and elasticity allows muscle tissue to respond to stimuli, generate force, adapt to changes in length and maintain optimal function throughout a wide range of activities and movements.

Table 1.2 Properties of muscles

Property	Discussion
Excitability (irritability)	Excitability, also known as irritability, is the fundamental property that allows muscle cells to detect and respond to various stimuli. When stimulated by signals from the nervous system or by chemical signals such as hormones, muscle cells generate electrical impulses known as action potentials. These action potentials travel along the length of the muscle cell membrane, triggering the release of calcium ions from internal stores. The presence of calcium ions inside the muscle cell initiates a series of biochemical reactions that ultimately lead to muscle contraction. Without excitability, muscles would not be able to respond to signals from the nervous system or coordinate movement.

(Continued)

Table 1.2 (Continued)

Property	Discussion
Contractility	Contractility is the ability of muscle tissue to shorten forcibly when stimulated by an action potential. This property allows muscles to generate tension and produce movement by pulling on bones or other tissues to which they are attached. During contraction, the overlapping protein filaments within muscle cells slide past each other, causing the muscle to shorten. Contractility is essential for tasks ranging from simple movements such as blinking or smiling to complex activities such as running or lifting heavy objects.
Extensibility	Extensibility is the ability of muscle tissue to be stretched or lengthened beyond its resting length without damage. Muscles must be able to stretch to accommodate changes in joint angles and body positions during movement. For example, when stretching, muscles elongate to allow for increased flexibility and range of motion. Extensibility also plays a crucial role in activities such as jumping or lifting weights, where muscles are stretched before contracting forcefully.
Elasticity	Elasticity is the ability of muscle tissue to return to its original shape and length after being stretched or contracted. Once the stretching force is removed, elastic elements within the muscle fibres, such as the protein titin (a large protein found in muscle tissue), contribute to the recoil of the muscle back to its resting state. This property ensures that muscles maintain their structural integrity and efficiency during repetitive movements. Without elasticity, muscles would remain stretched or contracted after each movement, leading to decreased mobility and impaired function.

Source: Adapted from Henstock (2021); Migliozi (2020).

BONE

There are 206 bones in the adult human, of various shapes and sizes; babies are born with 300 bones, but as humans age, several bones fuse to become bigger bones. A baby's bones are primarily composed of cartilage, and over time most of this cartilage turns into bone through a process called ossification. Half of the bones in the adult are in the feet and hands.

The presence of joints in the limbs, the elbow and knee joints, allows movement; if there were no joints, then there could be no movement and the skeleton would be rigid. Cartilage, a type of firm but flexible connective tissue, provides protection for those joints that are exposed to the force that is generated during movement. Ligaments attaching bone to bone help to provide joint strength and are either incorporated into a joint capsule or they may be independent of it. Movement at the joint is achieved through the contraction of muscles that pass across it.

THE SKELETON

The skeleton provides the body with shape and physical support for the systems contained within it. The skeleton forms part of the musculoskeletal system which enables us to move. For classification purposes, the skeleton is segregated into two main parts: the axial skeleton and the appendicular skeleton. Figure 1.3 represents the appendicular and axial skeleton.

Table 1.3 outlines the bones of the axial skeleton and Table 1.4 the appendicular skeleton.

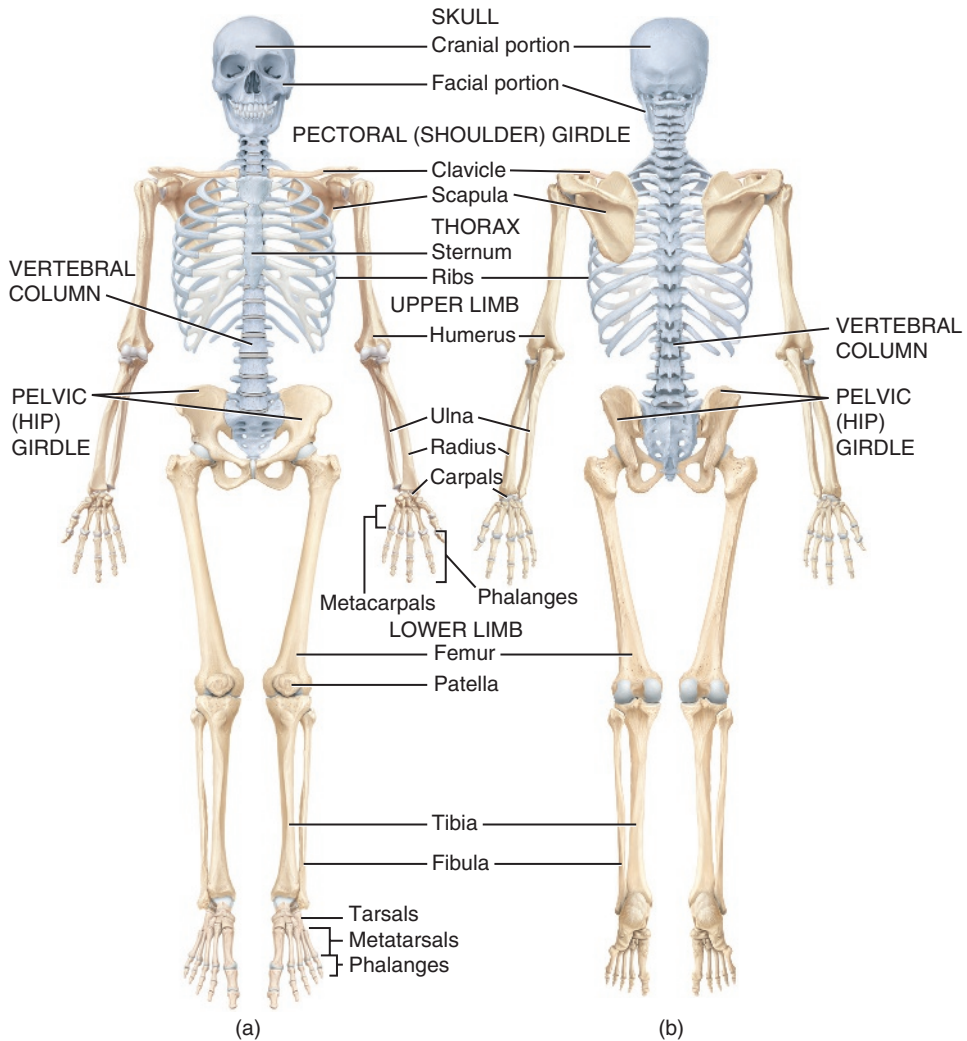


FIGURE 1.3 The human skeleton (a) anterior view and (b) posterior view. Axial skeleton blue and appendicular skeleton white. *Source:* Reproduced with permission from Tortora and Derrickson (2009). John Wiley & Sons.

BONE COMPOSITION

Although bones possess the strength to shield underlying tissues and organs and bear the body's weight, they are not entirely solid. Only the outer edges of bones consist of dense, solid bone, referred to as compact bone. Meanwhile, the interior of bones comprises lighter bone that forms a meshwork rather than a solid mass; this is known as spongy or trabecular bone. While not as robust as compact bone, spongy bone is considerably lighter due to its numerous spaces, preventing excessive skeletal weight. Nonetheless, spongy bone contributes to the internal strength of bones, with its columns serving as 'struts' that fortify and stabilise the bone structure from within. Within the centre of bones lies a cavity called the medullary cavity, which accommodates the blood vessels supplying the bone and houses the bone

Table 1.3 The bones of the axial skeleton

Structure	Number of bones
Skull	
Cranium	8
Face	14
Hyoid	1
Auditory ossicles	6
Vertebral column	26
This number counts the sacrum and coccyx as single vertebrae. They are actually formed from fused vertebrae (five sacral and four coccygeal). Some sources give the number of vertebrae as 33 for this reason.	
Thorax	
Sternum	1
Ribs	24
Total number of bones in the axial skeleton	80

Table 1.4 The bones of the appendicular skeleton

Structure	Number of bones
Pectoral girdle	
Clavicle	2
Scapula	2
Upper limbs	
Humerus	2
Ulna	2
Radius	2
Carpals	16
Metacarpals	10
Phalanges	28
Pelvic girdle	
Pelvic bone	2
Lower limbs	
Femur	2
Patella	2
Fibula	2
Tibia	2
Tarsals	14
Metatarsals	10
Phalanges	28
Total number of bones in the appendicular skeleton	126
Total number of bones in the adult human skeleton	206

marrow which is responsible for the production of blood cells. See Figure 1.4 for compact and spongy bone with their blood supply.

In addition to these functions, bone serves as an extensive reservoir for minerals such as calcium and phosphate, playing a crucial role in maintaining the homeostatic balance of these minerals in the bloodstream. The physiological roles that bones perform include:

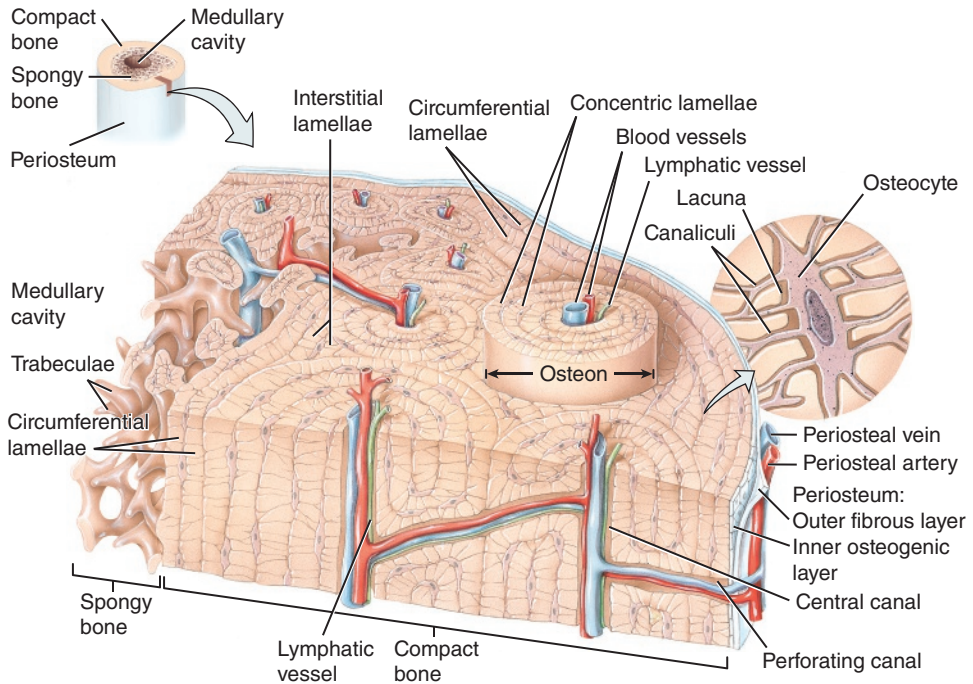


FIGURE 1.4 Compact and spongy bone and blood supply

- **Support and protection:** Bones play a crucial role in providing structural support and shape to the soft tissues of the body. As bone is an essentially non-compressible tissue, the skeleton defines the overall body contour, with soft tissues adhering to and enveloping the bones.

Moreover, bone serves as an exceptional shield for delicate organs; for instance, the skull envelops and safeguards the fragile brain, while the sternum and ribs shield the lungs and heart. Additionally, the vertebrae shield the spinal cord and the pelvis safeguards the abdominal and female reproductive organs in the lower body.

As bones must also facilitate movement, however, certain compromises are necessary in the bony protection surrounding our organs. For instance, the organs within the chest are sheltered by a ‘cage’ formed by ribs, allowing the chest cavity to expand and contract during breathing. Similarly, the vertebral column, instead of being a rigid bony tube, comprises 26 vertebrae with mobile joints between them, enabling bending and stretching while still ensuring protection of the spinal cord.

- **Enabling efficient movement:** The bones enable purposeful movement, either of the whole body or just parts of it. The bones of the limbs act as rigid levers which the muscles pull on to move. Without bones to anchor them, the movements produced by muscles would not be able to move the body very far. Other bones form the basis of supportive platforms which, when pulled on by the muscles, maintain body position and posture. Our tendency to walk on two legs instead of four creates a great deal of additional stress for the bones and muscles of the back that keep us in that upright position. The movements that are possible, from tiny, precise finger movements to whole body movements, are enabled by the moving

articulations between bones that are known as joints and the pulling action of the skeletal muscles on the bones that form the joints.

- Haematopoiesis: Bones also serve as the site for the production of blood cells – a process that is known as haematopoiesis. This process occurs exclusively in red bone marrow, also referred to as myeloid tissue, which occupies the internal cavities of vertebrae, pelvis, ribs, skull and the ends of long bones in adults. Consequently, these bones serve as the origin of both red and white blood cells throughout adult life.
- Red bone marrow harbours multipotent stem cells, which are undifferentiated cells that are capable of developing into various types of blood cells. These stem cells give rise to a diverse array of white blood cells crucial for immune function, as well as red blood cells essential for oxygen transport to tissues. As blood cells have a finite lifespan in circulation, they must be regularly replenished. Insufficient production of blood cells by the bone marrow can lead to immune deficiency and heightened susceptibility to infections in the case of white cell deficiency or severe anaemia if red cell production is inadequate.

Not all bones in adults contain red marrow. There are some bones, such as the shafts of long bones that are filled with yellow marrow; this is primarily composed of fat.

- Calcium homeostasis: Bone serves as a vast reservoir for essential minerals such as calcium and phosphate, possessing the capacity to release stored minerals in response to the body's needs. For instance, when blood calcium levels decline, bones can release calcium into the bloodstream. This release forms a component of the homeostatic mechanism that governs plasma calcium levels. Parathyroid hormone plays a pivotal role as the regulator of this system. Calcium ions play vital roles in various physiological processes throughout the body, including muscle contraction, nerve transmission, blood clotting and bone health. Therefore, it is crucial to regulate plasma calcium levels to ensure these physiological functions can occur effectively.

A healthy skeleton is essential for maintaining overall health and vitality, as it provides structural support, protects vital organs, enables movement and mobility, regulates mineral metabolism and contributes to blood cell production. Therefore, maintaining bone health through proper nutrition, regular exercise and lifestyle habits is crucial for ensuring optimal physical function and well-being throughout life.

BONE AS CONNECTIVE TISSUE

Bone, a type of connective tissue, shares common characteristics with other connective tissues, comprising specialised cells embedded within an extracellular matrix. Within bone, three types of specialised cells – osteoblasts, osteoclasts and osteocytes – carry out distinct functions. The extracellular matrix of bone is composed of an organic framework primarily consisting of collagen protein, onto which layers of inorganic calcium salts are deposited, resembling a cement. This composite structure renders bone simultaneously hard, rigid and strong due to the presence of calcium salts, while also maintaining flexibility owing to collagen. These properties provide bone with excellent tensile strength, compressive strength and flexibility. Healthy bone typically exhibits the appropriate proportions of collagen and calcium salts, demonstrating these characteristics.

Disorders affecting collagen production in bone can result in bones lacking normal flexibility, making them more prone to fractures under significant forces, as seen in brittle bone disease (osteogenesis imperfecta). Conversely, insufficient calcium salts in bone can lead to bones that are softer than usual, prone to bending under substantial forces, as observed in childhood rickets due to inadequate vitamin D. The most prevalent disorder is osteoporosis, where the balance of collagen to calcium salts is normal, but bone density is decreased. In osteoporosis, bones are less compact and dense than they should be, increasing the risk of fractures despite the bone composition being otherwise normal.

Moreover, bone is not merely a resilient and flexible material; it is also a dynamic and adaptive tissue constantly undergoing breakdown and renewal.

The continuous renewal of bone is mostly due to its piezoelectric nature. The bone shows piezoelectric effects, meaning it produces an electrical charge when under pressure from mechanical stress. Consequently, when bones are subjected to mechanical stress, such as weight-bearing exercise, they generate charge along the lines of greatest stress, stimulating the deposition of more bone tissue along those lines. Thus, regular weight-bearing exercise is crucial for maintaining bone health, as it stimulates bone strengthening in response to applied loads. Conversely, a lack of weight-bearing exercise, such as prolonged bed rest, can lead to rapid reductions in bone density. The functions of bone are carried out by the three bone cell types:

OSTEOBLASTS

Osteoblasts produce the organic matrix of bone, primarily composed of collagen and regulate the deposition of calcium salts onto this collagen matrix, resulting in the formation and mineralisation of solid bone. As such, these cells play a key role in both bone formation and the healing of fractures.

OSTEOCLASTS

Osteoclasts are large cells that attach themselves to a section of bone and secrete enzymes and acid onto it, causing it to dissolve. This process removes bone and releases minerals into the bloodstream. It also initiates the first stage of bone renewal and repair: osteoclasts remove the surface of the bone to be repaired, allowing osteoblasts to follow and create new bone on the freshly exposed surface.

The density of bone depends on the equilibrium between osteoblast and osteoclast activity. If osteoclasts are more active, bone density decreases, whereas if osteoblasts are more active, bone density increases. Numerous factors influence the activity of these cells.

OSTEOCYTES

Initially, these cells originate as osteoblasts, they undergo a transformation during the formation of compact bone. They develop elongated, finger-like projections and become embedded within the newly formed bone matrix (see Figure 1.4). As bone deposition progresses, their cellular extensions extend through minute channels in the bone and establish

connections with neighbouring osteocytes. Positioned within the concentric layers of compact bone, osteocytes form a dynamic network capable of detecting and transmitting changes within the bone structure. While the precise functions of osteocytes remain incompletely understood, they are believed to play a key role in converting mechanical stress on the bone into electrical signals. Enclosed within the bone matrix, osteocytes are strategically situated to perceive the magnitude and direction of forces acting on the bone, thus serving as the origin of bone's piezoelectric properties.

CARTILAGE

Cartilage is a connective tissue found in certain body structures, such as the outer ear and the tip of the nose. It serves as a crucial protective layer and cushion between bones at different joints. As ageing occurs, wear and tear can lead to the roughening and erosion of cartilage, marking the initial stages of joint inflammation and degeneration associated with osteoarthritis.

There are three types of cartilage:

- 1. Hyaline cartilage:**
This type of cartilage is adapted to protect bones from the impacts of friction when they interact with each other or other structures. Hyaline cartilage has a smooth, glassy surface, significantly minimising friction during movement by enabling easy sliding of the cartilage-covered surfaces. It is located on the ends of bones within movable joints, at the tips of the ribs, the nasal tip and constitutes the majority of the fetal skeleton.
- 2. Elastic cartilage:**
This type of cartilage is similar to hyaline cartilage in appearance; microscopic examination reveals the presence of elastin fibres within the extracellular matrix. These elastin fibres provide the cartilage with the ability to return to its original shape when stretched or pulled out of shape. This cartilage is crucial for maintaining the shape of structures regularly subjected to bending or stretching as part of their function, such as the epiglottis – a cartilaginous flap located above the larynx that folds down to cover the airway during swallowing, preventing food from entering and obstructing airflow. Elastic cartilage also comprises the outer ear, preserving the ear's shape.
- 3. Fibrocartilage:**
This type of cartilage serves as a transitional structure between cartilage and ligament. It contains a high concentration of collagen, which, although present in many connective tissues, is notably abundant in fibrocartilage in two forms: types I and II. This composition means that fibrocartilage is strong, moderately elastic and resistant to compression. It is commonly found forming the outer edge of the intervertebral discs and the menisci within the knee joint. In these locations, fibrocartilage acts as a spongy pad, providing cushioning for joints subjected to significant weight-bearing. Additionally, fibrocartilage comprises the pubic symphysis – the anterior joint between the pelvic bones.

LIGAMENTS

These are strong connectors (straps) that link bones together, visible as bands spanning across the joint formed by the connected bones. The quantity and tension (tightness) of ligaments at a movable joint determine its stability and the extent of its movement. A joint with

increased stability will feature numerous ligaments securing the bones but may exhibit restricted mobility for this reason. Individuals with particularly flexible, stretchable ligaments may possess the capacity to 'hyper-extend' their joints, often described as being double-jointed.

TENDONS

The tendons are robust connective tissue formations that are responsible for attaching muscles to bones, facilitating muscle contraction to produce bone movement and joint flexion or extension. Tendons have a degree of elasticity, which reduces the risk of tendon or bone damage during abrupt muscle contractions. However, they are also resilient enough to withstand the challenging forces generated by muscles, effectively transmitting these forces to induce bone movement.

THE FORMATION OF BONE

The template for bone formation begins in utero, where 'models' of bones made of hyaline cartilage are established. By the end of the third month of pregnancy, the skeletal framework is fully formed, predominantly composed of hyaline cartilage. This cartilage gradually undergoes replacement by bone through a process called ossification. Initially, calcification of the cartilage occurs, followed by the invasion of osteoblasts and the formation of bone to supplant the cartilage. Known as endochondral ossification (see Figure 1.5), this process takes place within the cartilage template and is the primary method by which most of our bones develop. As ossification progresses, blood vessels penetrate the bone cavity from the centre outward. In the case of long bones, such as those depicted in Figure 1.6, cartilage remains only at the two ends of the bone and in a narrow strip between the end and the bone shaft. The cartilage covering the bone ends transforms into articular cartilage, which reduces friction and shields the bone end at the joint. The strip of cartilage separating the bone end from the shaft serves as a growth point, enabling bone elongation as the individual grows. This strip is known as the growth plate or the epiphyseal plate.

As the ossification of the entire skeleton is not complete by birth, infants are born with large amounts of cartilage. The bones of babies and children are softer and more porous than an adult's, but they become harder and denser with age, reaching their peak density at age 20–30 years.

BONE GROWTH

As a person's stature increases, the bones of the limbs lengthen; this longitudinal growth is accompanied by a thickening of bones to maintain body proportions as individuals mature. Bone lengthening primarily occurs in the cartilage of the epiphyseal plate. During early puberty, chondrocytes within the cartilage divide continuously, generating new cartilage on the side of the epiphyseal plate closest to the bone's end. Simultaneously, osteoblasts infiltrate the cartilage from the shaft side of the plate, turning it into bone tissue. This process propels the cartilage plate towards the bone end, facilitating bone growth as the trailing edge of the epiphyseal plate solidifies (see Figure 1.6).

The growth of long bones stops as the division of chondrocytes in the leading edge of the growth plate slows down and eventually ceases, typically towards the end of puberty. Despite this, the ossification process of the epiphyseal growth plate persists, ultimately resulting in full ossification once the cartilage front ceases to advance. Both the growth spurt experienced

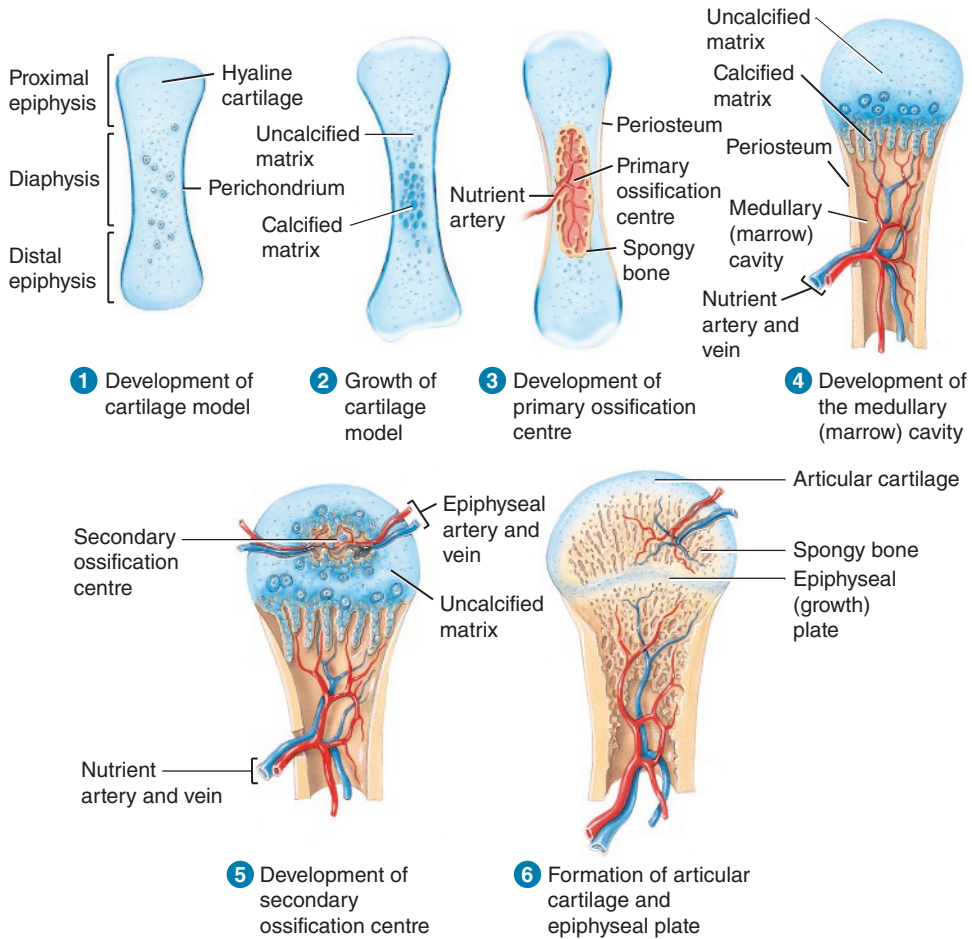


FIGURE 1.5 Endochondral ossification of the tibia

during puberty and the closure of the epiphyseal plate at its conclusion are brought about by sex hormones: oestrogen in females and testosterone in males.

Conversely, circumferential bone growth takes place on the outer surface of the bone. Osteoblasts deposit new bone in concentric layers, similar to those observed in compact bone. Concurrently, osteoclast activity within the bone cavity removes bone from the inner surface, leading to an increase in the cavity size proportionate to the overall bone circumference (see Figure 1.7).

BONE REMODELLING

The process of removing and renewing bone, known as remodelling, persists throughout adulthood (see Figure 1.8). Whether this remodelling leads to bone loss or maintenance and strengthening depends on various factors. Lifestyle decisions play a crucial role in promoting a healthy skeleton as we age.

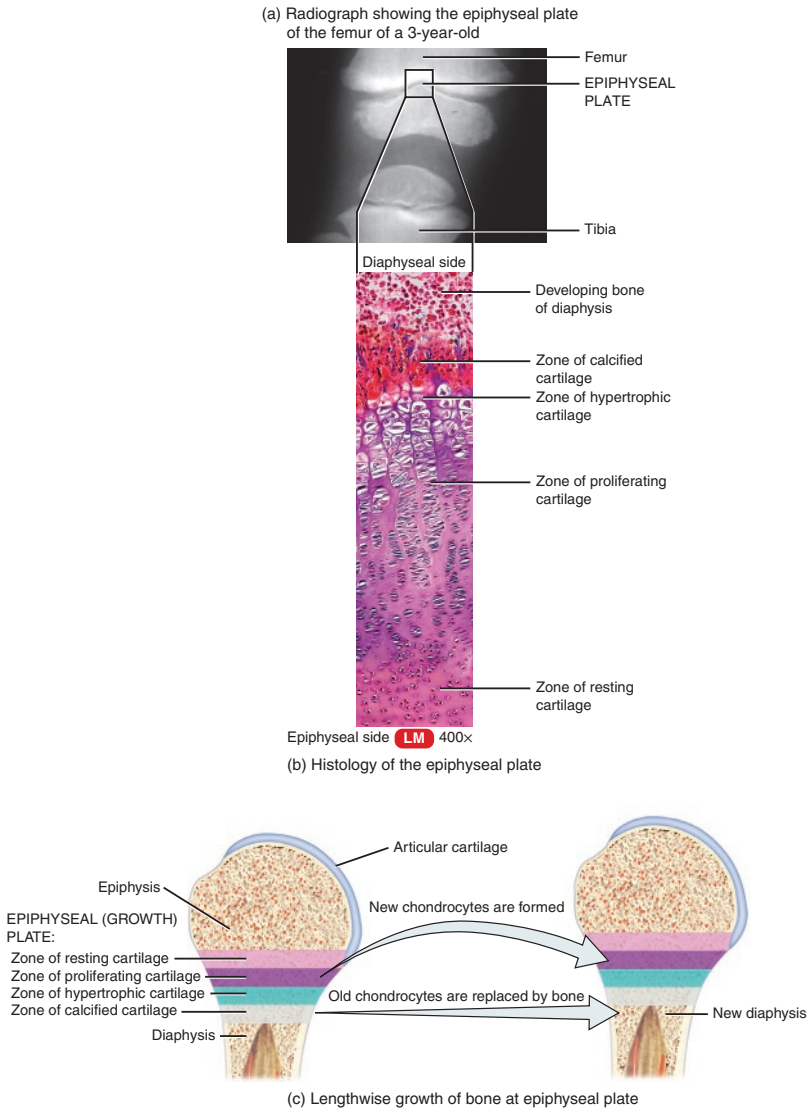


FIGURE 1.6 Long bones grow in length from the cartilaginous epiphyseal plates.
 Source: Reproduced with permission from Tortora and Derrickson (2014). John Wiley & Sons.

BONE FRACTURES

Bone possesses a unique ability among tissues to undergo complete healing, substituting damaged tissue with fresh, fully functional bone rather than scar tissue. This natural capacity enables bone to regenerate itself following a fracture, similar to its initial formation during development. The abundant blood supply to bone plays a crucial role in fracture healing, facilitating the arrival of phagocytic white blood cells to clear away bone fragments and necrotic cells, while also safeguarding against infection. Additionally, the restoration of any damaged blood vessels is imperative for achieving comprehensive healing (Marsell and Einhorn 2011). The steps of the healing process after a fracture of the bone are shown in Figure 1.9.

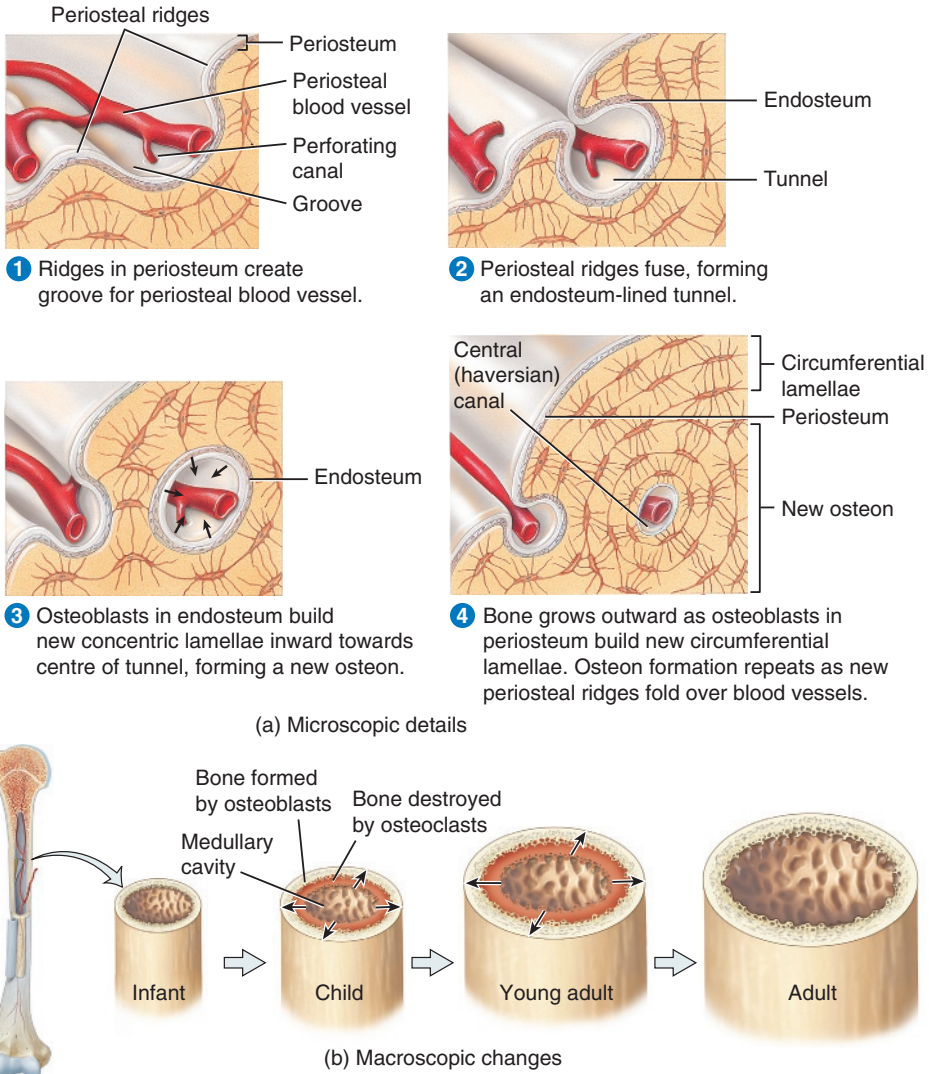


FIGURE 1.7 Bones increase in width but maintain the same proportion of compact bone to medullary cavity

The fractured bone ends experience initial stabilisation through the formation of a cartilaginous callus, followed by full stabilisation with the formation of a robust bony callus. At this stage, the bone becomes capable of bearing weight once again. The gradual transformation of the disorganised bone in the hard callus into the well-ordered lamellar structure of typical compact bone, with spongy bone in the interior, occurs over time. This process is provoked by the loading of the bone during weight-bearing activities. A completely healed fracture may show no visible signs of injury externally, but internal healing typically leaves a remodelled area of bone that can sometimes be detected through imaging, though it lacks the type of scar tissue seen in soft tissue healing. However, the same cannot be said for injuries to ligaments, cartilage or tendons, as these tissues lack regenerative ability.

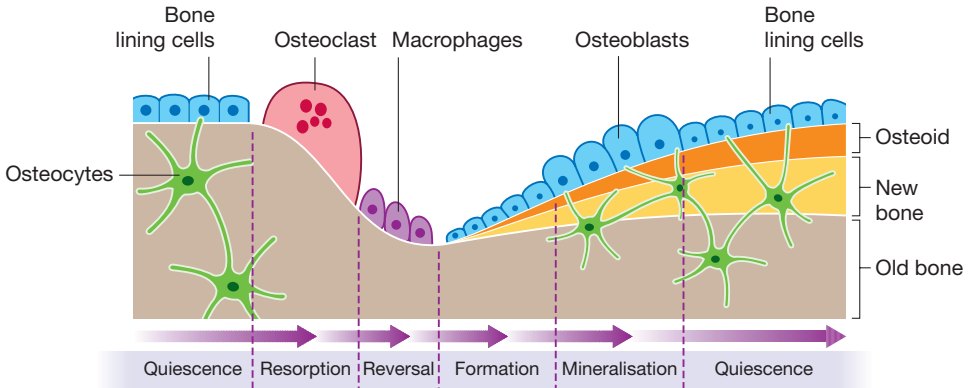


FIGURE 1.8 Bone remodelling

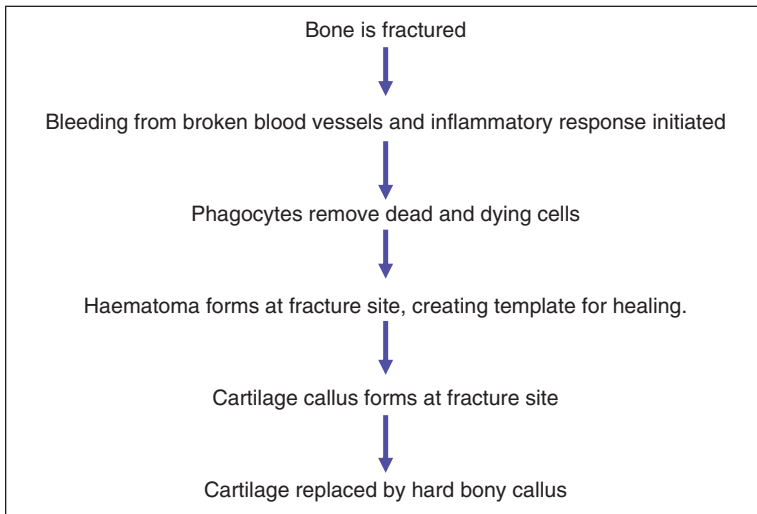


FIGURE 1.9 The stages of fracture healing in bone

BONE SHAPES

Observing a skeleton, it is apparent that bones exhibit a range of shapes dictated by their positioning and role. Various bone shapes are identified and commonly categorised based on their distinct forms.

LONG BONES

These bones are longer than they are wide and include the humerus, femur, radius, ulna, tibia and fibula. The clavicles, metacarpals, metatarsals and phalanges are also long bones despite their shortness. These bones permit limb movement.

Long bones consist of a shaft (diaphysis) composed primarily of compact bone and ends (epiphyses) composed mainly of cancellous or spongy bone. Located between the two is an intermediate region that is known as the metaphysis, also containing spongy bone.

The compact bone in the shafts forms supportive pillars of bone; these are thickest at the point where the forces applied to the bone are greatest (see Figure 1.10).

SHORT BONES

Typically, these bones are approximately as wide as they are long. They are typically located in limb areas where movement is restricted, such as the wrists and ankles. Examples include the carpals of the wrist and the tarsals of the foot (see Figure 1.11). These bones feature a thin compact bone layer covering mostly spongy or cancellous bone.

FLAT BONES

Flat bones are thin bones, found encasing and protecting delicate tissue (such as the skull) or where there is a need for a broad surface for extensive muscle attachment (such as the scapula or shoulder blade). Other examples are the sternum, ribs and some bones of the pelvis (see Figure 1.12).

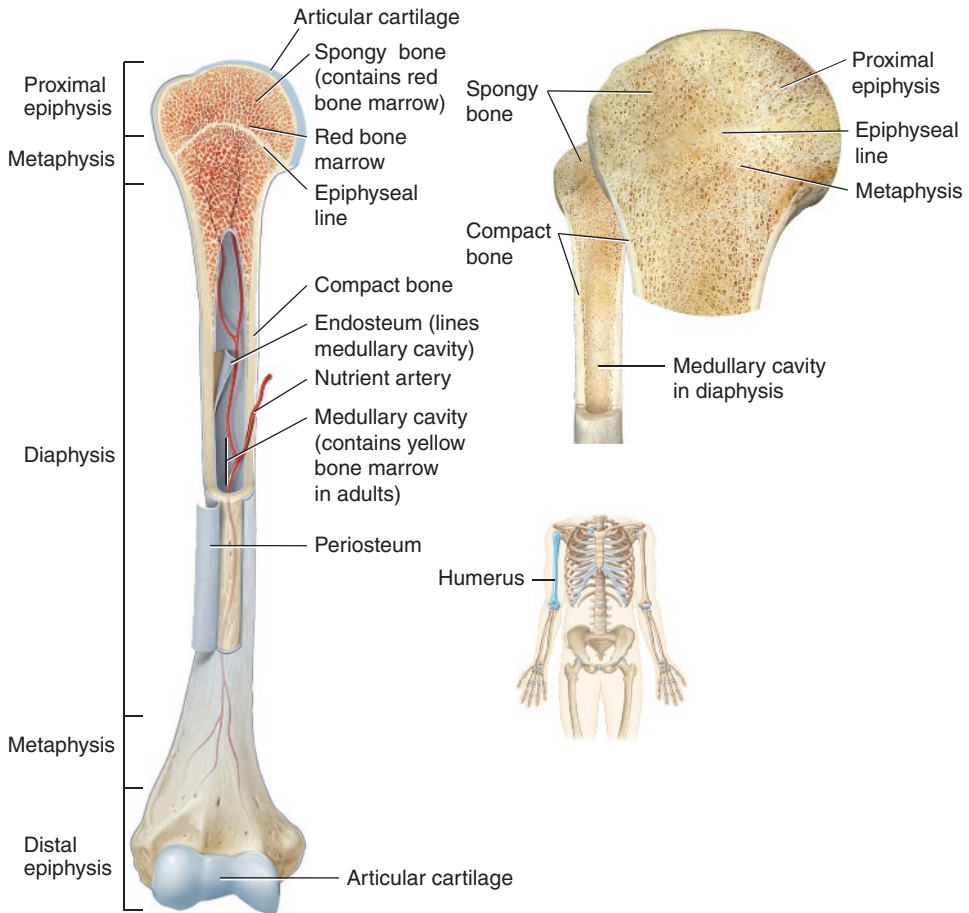


FIGURE 1.10 Parts of a long bone

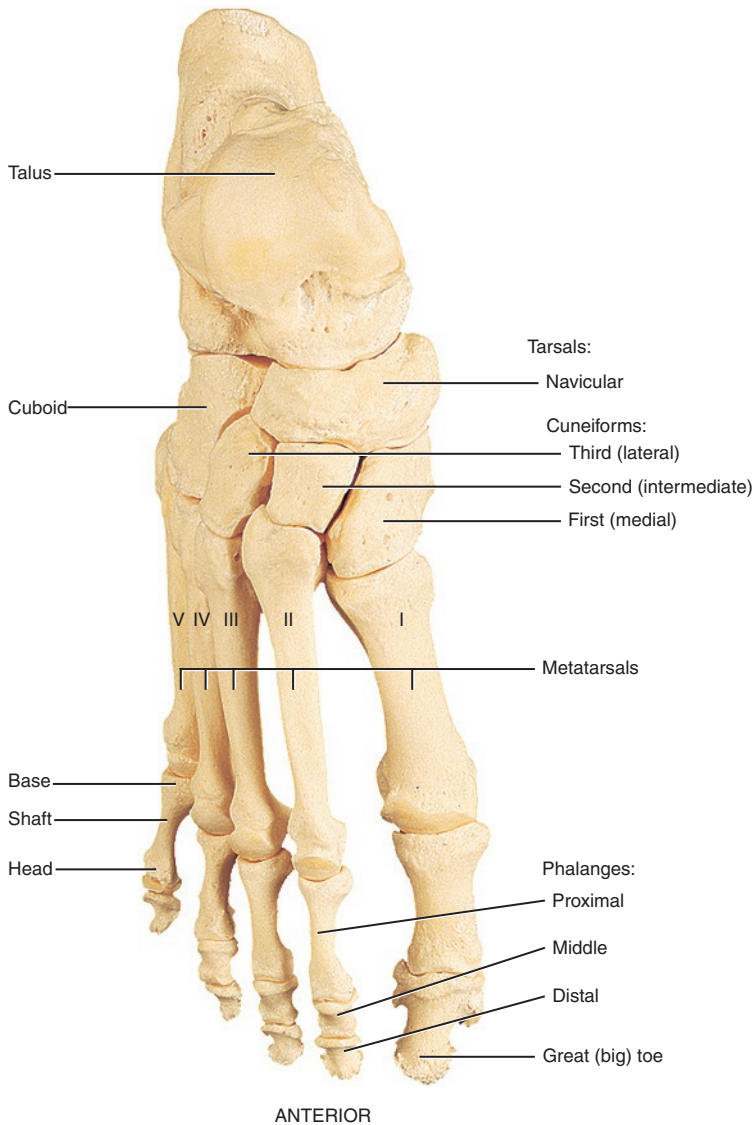


FIGURE 1.11 The tarsal bones – short bones. *Source:* Reproduced with permission from Tortora (2008). John Wiley & Sons.

IRREGULAR BONES

These bones, because of their irregular shapes, do not fit into any of the categories already described. They also consist of spongy bone that is enclosed by thin layers of compact bone. They include the vertebrae (see Figure 1.13), the sphenoid and zygomatic bones of the skull and the ossicles of the ear.

SESAMOID BONES

Sesamoid bones emerge within tendons at locations where a tendon intersects near a joint, serving to shield the tendon from friction and abrasion at that juncture. These bones are

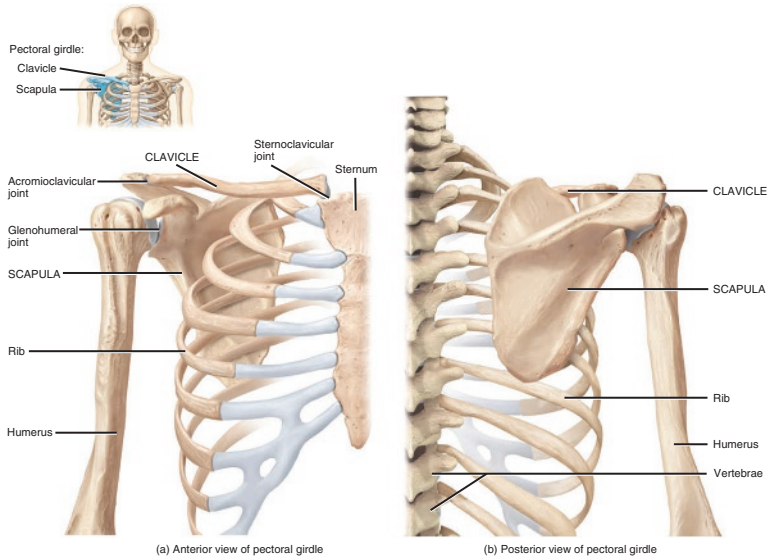


FIGURE 1.12 Examples of flat bones: (a) the sternum and (b) the scapula and ribs

typically small and circular, earning their name from early anatomists who likened their appearance to sesame seeds. The primary example of such a bone is the patella (see Figure 1.14).

JOINTS

Joints occur when two bones come together. With the exception of the hyoid bone in the neck, every bone connects with another bone at a joint. These structures not only unite bones but are also referred to as articulations.

MOVEMENTS

The bones serve as levers, facilitating the transmission of muscular forces. Through leverage, contraction and pulling, multiple bones can alter the magnitude and direction of forces generated by skeletal muscles, aided by tendons and ligaments. These movements can vary from intricate tasks, for example, writing or threading a needle (fine coordination) to broader actions such as changing body position (gross movement). The interplay between the skeleton and muscles is crucial for functions such as breathing.

Tendons, fibrous connective tissues, attach muscles to bones and can also link muscles to structures such as the eyeball, assisting in bone or structure movement. Ligaments, on the other hand, attach bone to bone, providing stability by holding structures together.

Different joints offer various types of movement; for instance, the shoulder joint exhibits more versatility than the knee. These are the primary categories of movement:

- Flexion: reducing the angle at the joint, bending the knee or elbow.
- Extension: increasing the angle at the joint, for example, straightening the knee or elbow.
- Adduction: moving the body part towards the centre of the body, for example, bringing one leg in towards the other.

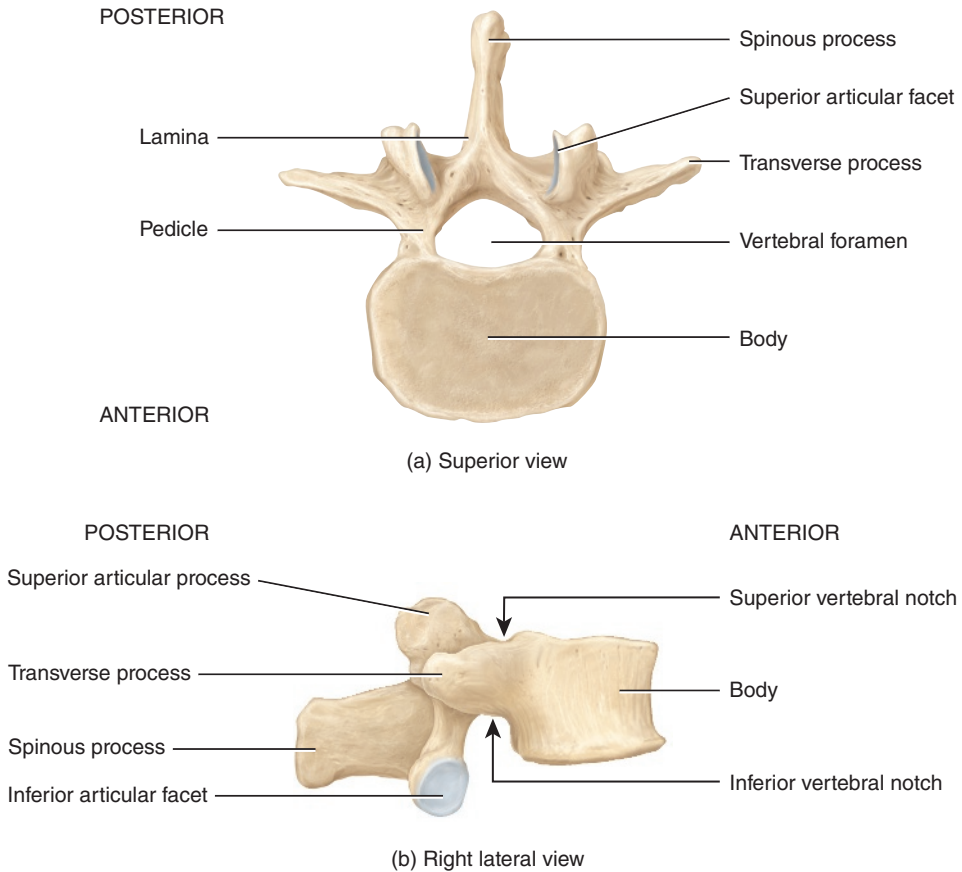


FIGURE 1.13 (a, b) The vertebrae – irregular bones

- Abduction: moving the body part away from the centre of the body, for example, taking one leg away from the other.
- Rotation: turning or twisting a body part, either clockwise (external or lateral) or anticlockwise (internal or medial), for example, turning the leg to point the toes outwards.

FIBROUS JOINTS

These joints are also known as synarthrodial joints. They are connected solely by a ligament. Ligaments consist of dense irregular tissue composed of rich collagen fibres. Unlike other joint types, there is no synovial cavity present in this particular joint configuration.

CARTILAGINOUS JOINTS

Cartilaginous joints, also termed synchondroses (singular synchondrosis) and symphyses (singular symphysis), form where the connection between articulating bones comprises cartilage without a synovial cavity. An example includes the joints between vertebrae in the spine.

Symphysis joints represent permanent cartilaginous joints featuring an intervening pad of fibrocartilage. One example is the symphysis pubis.

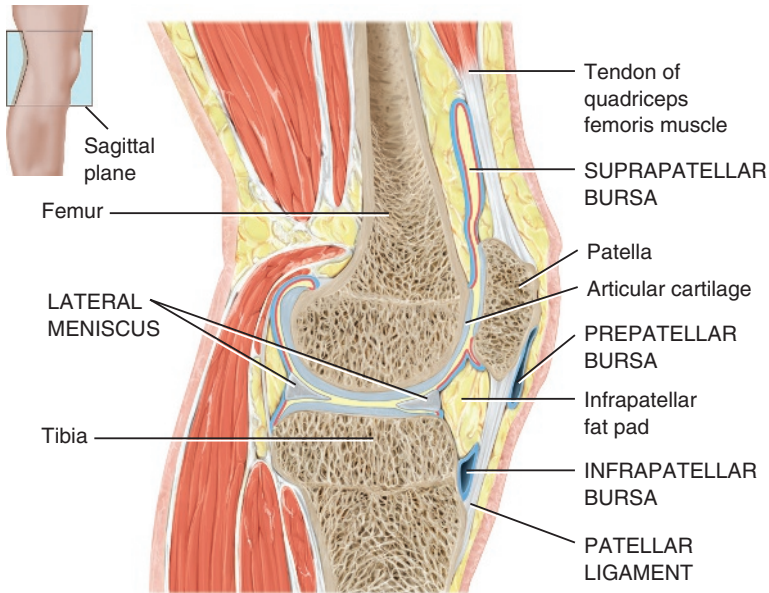


FIGURE 1.14 A sesamoid bone, the patella – shown in lateral view, in the tendon of the quadriceps muscle, positioned to protect the tendon from friction when the knee joint bends

SYNOVIAL JOINTS

Also termed diarthrosis joints, this classification represents the most common type of joint. These joints are highly mobile, encompassed by an articular capsule that encloses the entire joint. Within this capsule, a synovial membrane, serving as the inner layer, produces synovial fluid. Additionally, hyaline cartilage cushions the ends of the articulating bones.

Synovial fluid, typically clear or yellowish and possessing a thin, viscous consistency, plays a vital role in preventing friction by lubricating the joint, while also supplying nutrients and eliminating waste products.

There are six types of freely movable or synovial, joints (Figure 1.15).

Most joints are synovial joints, which allow for much more movement than cartilaginous joints. Synovial joints are primarily located in the limbs where mobility is essential. Ligaments help provide their stability and the muscles contract to produce movement.

HINGE

A convex portion of one bone fits into a concave portion of another bone. Movement reflects the hinge and bracket movement of a household hinge and bracket; movement is limited to flexion and extension. The joint produces an open and closing motion. These joints are uniaxial.

PIVOT

A rounded part of one bone fits into the groove of another bone. These joints will only allow movement of one bone around another and are classified as uniaxial movement.

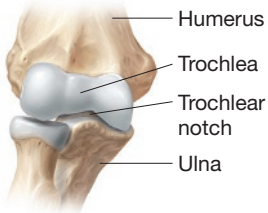
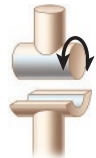
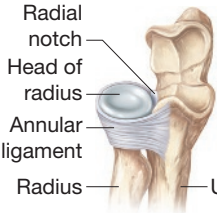

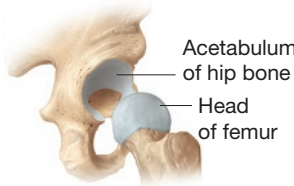

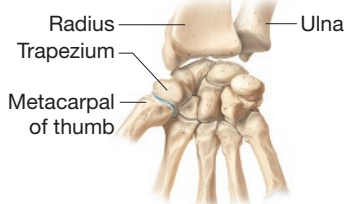
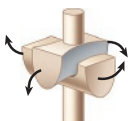
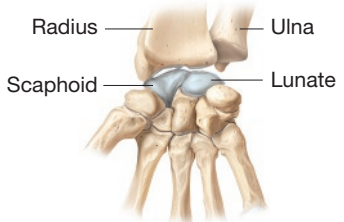

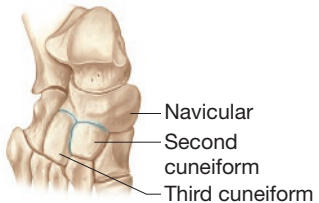

Type of joint	Examples	Structure
Hinge	Elbow, knee 	
Pivot	Radius and ulna, the atlas and axis 	
Ball and socket	Hip, shoulder 	
Saddle	The carpometacarpal joints of the thumb 	
Condyloid	The radiocarpal and metacarpophalangeal joints of the hand 	
Gliding	Intertarsal and intercarpal joints of the hands and feet 	

FIGURE 1.15 Joint types

BALL AND SOCKET

The spherical end of one bone fits into a concave socket of another bone. Movement occurs through flexion, extension and adduction. This is a triaxial joint.

CONDYLOID

Where an oval surface of one bone fits into a concavity of another bone and where condyloid joints are located. Permits flexion, extension and adduction. This is a biaxial joint.

SADDLE

Similar to condyloid joints, however, these joints allow greater movement. Permitting flexion, extension and adduction. The joint is classed as triaxial.

GLIDING

These joints have a flat or slightly curved surface enabling gliding movements. The joints are bound by ligaments and movement in all directions is restricted. The joint moves back and forth and from side to side.

FIXED JOINTS

There are some joints, for example, those in the skull, that are fixed and do not permit any movement to occur. The bones in the skull are held together with fibrous tissue, as are the joints in the pelvis.

CONCLUSION

The human skeleton is a dynamic, living framework constantly adapting to improve its performance. It offers support and protection for the body, possessing remarkable strength, flexibility and the capacity to regenerate itself after injury. Furthermore, the skeleton functions as a system of levers operated by muscles to generate movements, ranging from precise fingertip gestures to the explosive force propelling a sprinter from the starting blocks at the sound of the starting gun.

However, the skeleton's role extends beyond mere movement facilitation. The red marrow within certain bones serves as the origin of all blood cells, crucial for immunity and oxygen transportation to body tissues. Moreover, due to its substantial calcium reserves, the skeleton plays a key role in maintaining plasma calcium levels within a homeostatic range. It acts as a calcium source to replenish plasma levels when necessary, ensuring the uninterrupted function of calcium-dependent processes throughout the body.

GLOSSARY OF TERMS

Agonist: The primary muscle responsible for producing a specific movement.

Antagonist: A muscle that opposes the action of another muscle, controlling the speed and range of movement.

Articular capsule: A structure surrounding a joint, composed of connective tissue that stabilises the joint and restricts its movement.

Bone marrow: Soft tissue within bone cavities, responsible for producing blood cells (haematopoiesis) and storing fat.

Compact bone: Dense, hard bone tissue that forms the outer layer of bones and provides strength and support.

Diaphysis: The shaft or main portion of a long bone, composed of compact bone and containing the medullary cavity.

Epiphysis: The rounded end of a long bone, composed largely of spongy bone and covered by articular cartilage.

Joint: The point of connection between two or more bones, allowing movement and providing structural support.

Ligament: Fibrous connective tissue that connects bone to bone, providing stability and reinforcement to joints.

Muscle: Tissue composed of cells capable of contracting and relaxing to produce movement, heat and maintain posture.

Muscle fibre: The individual cell of a muscle, capable of contracting in response to electrical or chemical signals.

Myofibril: Thread-like structures within muscle fibres, containing contractile proteins (actin and myosin) responsible for muscle contraction.

Ossification: The process of bone formation, in which osteoblasts deposit mineral salts and collagen fibres to create new bone tissue.

Osteoblast: Cells responsible for the formation of new bone tissue through the process of ossification.

Osteoclast: Cells responsible for breaking down and resorbing bone tissue, essential for bone remodelling and repair.

Osteocyte: Mature bone cell embedded within the bone matrix, maintaining bone structure and facilitating communication between bone cells.

Periosteum: Fibrous membrane covering the surface of bones, containing blood vessels, nerves and osteogenic cells involved in bone repair and growth.

Sarcomere: The functional unit of a muscle fibre, consisting of overlapping actin and myosin filaments responsible for muscle contraction.

Skeletal system: The framework of bones and associated tissues in the body, providing support, protection, movement and mineral storage.

Synovial joint: A highly mobile joint characterised by the presence of a synovial cavity, articular cartilage, synovial membrane and synovial fluid.

Tendon: Skeletal system: The framework of bones and associated tissues in the body, providing support, protection, movement and mineral storage.

Z line: Also known as the Z disc or Z band, is a structural component found within muscle fibres, specifically in striated muscle tissue such as skeletal and cardiac muscles.

MULTIPLE CHOICE QUESTIONS

1. Which type of muscle is voluntary and responsible for conscious movements?
 - a) Smooth muscle
 - b) Cardiac muscle
 - c) Skeletal muscle
 - d) Visceral muscle
2. What is the main function of ligaments in the musculoskeletal system?
 - a) Transmit nerve signals
 - b) Store energy
 - c) Connect muscle to bone
 - d) Connect bone to bone
3. Which bone cell type is responsible for bone resorption and remodelling?
 - a) Osteoblast
 - b) Osteocyte
 - c) Osteoclast
 - d) Chondrocyte
4. The shaft of a long bone is called:
 - a) Diaphysis
 - b) Epiphysis
 - c) Metaphysis
 - d) Periosteum
5. Which structure serves as the boundary between adjacent sarcomeres in skeletal muscle?
 - a) Z line
 - b) M line
 - c) I band
 - d) H zone
6. What is the functional unit of muscle contraction?
 - a) Myofibril
 - b) Sarcomere
 - c) Myosin filament
 - d) Actin filament
7. What is the primary function of red marrow in bones?
 - a) Store minerals
 - b) Produce blood cells
 - c) Provide cushioning
 - d) Facilitate movement
8. Which type of joint allows the least amount of movement?
 - a) Synovial joint
 - b) Cartilaginous joint
 - c) Fibrous joint
 - d) Diarthrosis joint

9. The outer layer of bone tissue is composed mainly of:
- a) Spongy bone
 - b) Cortical bone
 - c) Trabecular bone
 - d) Compact bone
10. Which bone cell type is responsible for bone formation?
- a) Osteoclast
 - b) Osteocyte
 - c) Osteoblast
 - d) Chondrocyte

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