Interacting Systems

Muscular and Skeletal Systems

Endocrine system
- The skeleton protects the endocrine organs especially in the pelvis, chest, and brain.
- Bone takes up and releases calcium in response to hormones.
- Androgens and growth hormone promote muscle strength and increase in mass.

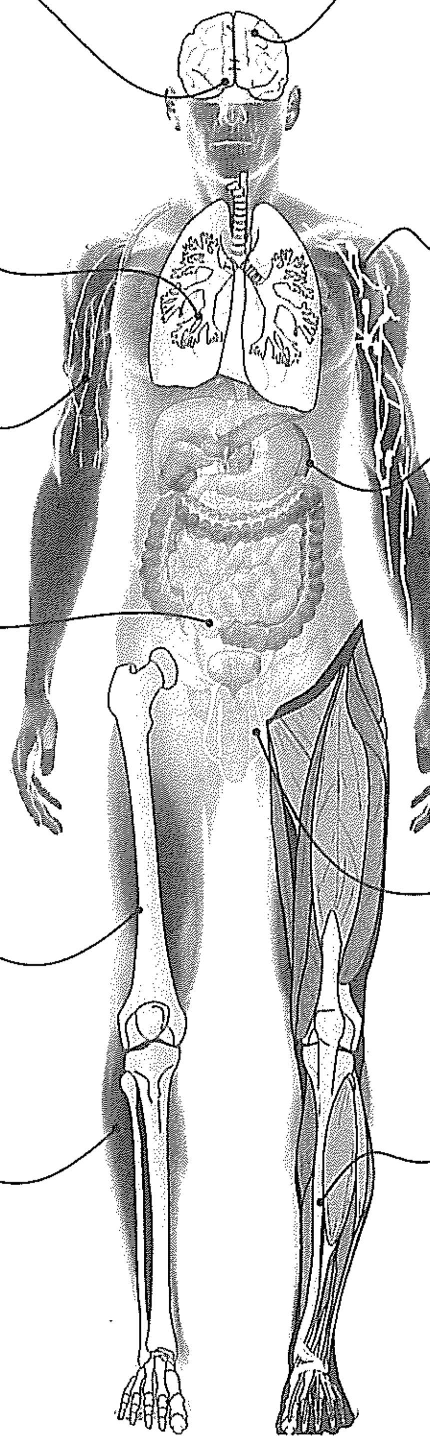
Respiratory system
- Skeleton encloses and protects lungs
- Flexible ribcage enables ventilation of the lungs for exchange of gases (O_2/CO_2).
- Diaphragm and intercostals produce volume changes in breathing.

Cardiovascular system
- Heart and blood vessels transport O_2, nutrients, and waste products to all the body.
- Bone marrow produces red blood cells
- Bone matrix stores calcium, which is required for contraction of muscle in the heart and blood vessels.

Digestive system
- Skeleton provides some protection and support for the abdominal organs.
- Digestive system provides nutrients for growth, repair, and maintenance of muscle and connective tissues.

Skeletal system
- Muscular activity maintains bone strength and helps determine bone shape.
- Muscles pull on bones to create movement.

Integumentary system
- Skin absorbs and produces precursor of vitamin D, which is involved in calcium and phosphorus metabolism.
- Skin covers and protects the muscle tissue.



Nervous system
- The skeleton protects the CNS.
- Bone acts as a store of calcium ions required for nerve function.
- Innervation of bone and joint capsules provides sensation and positional awareness.
- Muscular activity is dependent on innervation.

Lymphatic system and immunity
- Stem cells in the bone marrow give rise to the lymphocytes involved in the immune response.

Urinary system
- The skeleton protects the pelvic organs.
- Final activation of vitamin D, which is involved in calcium and phosphorus metabolism, occurs in the kidneys.
- Urination controlled by a voluntary sphincter in the urethra.

Reproductive system
- The skeleton protects the reproductive organs.
- Reproductive (sex) hormones influence skeletal development.

Muscular system
- Skeleton acts as a system of levers for muscular activity.
- Bone provides a store of calcium for muscle contraction.

General Functions and Effects on all Systems

The skeletal system provides bony protection for the internal organs, especially the brain and spinal cord, and the lungs, heart, and pelvic organs. The muscular system acts with the skeletal system to generate voluntary movements. Smooth and cardiac muscle provide motility for involuntary activity.

Disease

Symptoms of disease
- Pain (moderate to severe)
- Inflammation
- Limitations in function

Disorders of the bones and joints
- Growth disorders
- Trauma (fractures and sprains)
- Infection
- Tumors
- Degenerative diseases

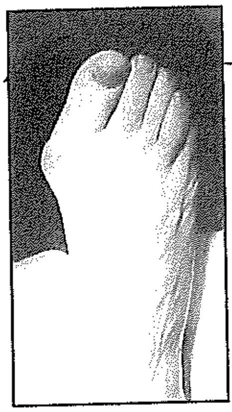
Diseases of the skeletal muscles
- Inherited diseases
- Fibrosis (scarring)
- Strains, tears, and cramps
- Denervation and atrophy

Medicine & Technology

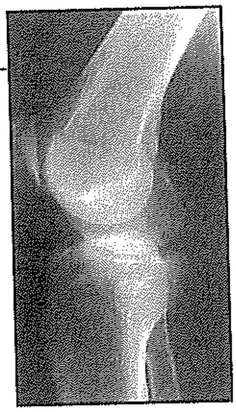
Diagnosis of disorders
- Blood tests
- Bone scans
- Medical imaging techniques
- Athroscopy

Treatment of injury
- Surgery
- Physical and drug therapies
- Prosthetics and orthotics

Treatment of inherited disorders
- Surgery
- Radiotherapy (for cancers)
- Physical and drug therapies
- Prosthetics and orthotics
- Gene therapy



- Osteomalacia
- Osteoarthritis
- Osteoporosis
- Sarcomas
- Muscular dystrophy



- Joint replacement
- Grafts
- Genetic counselling
- X-rays
- MRI

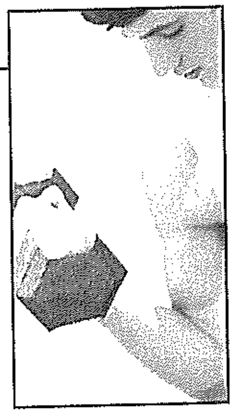
Support & Movement

The Musculoskeletal System

The musculoskeletal system can be affected by disease and undergoes changes associated with aging.

Medical technologies and exercise can be used to diagnose, treat, and delay the onset of musculoskeletal disorders.

- Osteoarthritis
- Osteoporosis
- Muscular atrophy



- Muscle fatigue
- Fast vs slow twitch
- Aerobic training
- Anaerobic training

Aging and the bones, joints, and muscles
- Bone loss
- Loss of muscle mass
- Accumulated trauma
- Increased incidence of cancers

The Effects of Aging

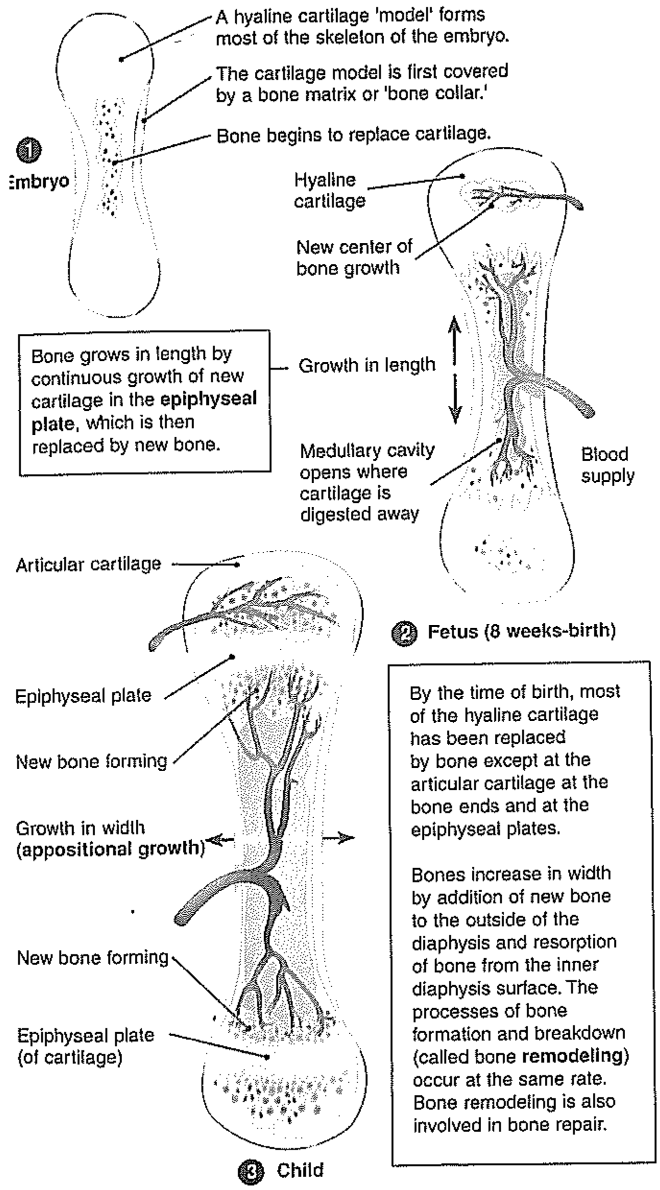
Effects of exercise on bones, joints, and muscles
- Increased bone density
- Increased lean muscle mass
- Changes in flexibility & joint mobility
- Changes in fiber type & recruitment
- Changes in oxidative capacity

Exercise

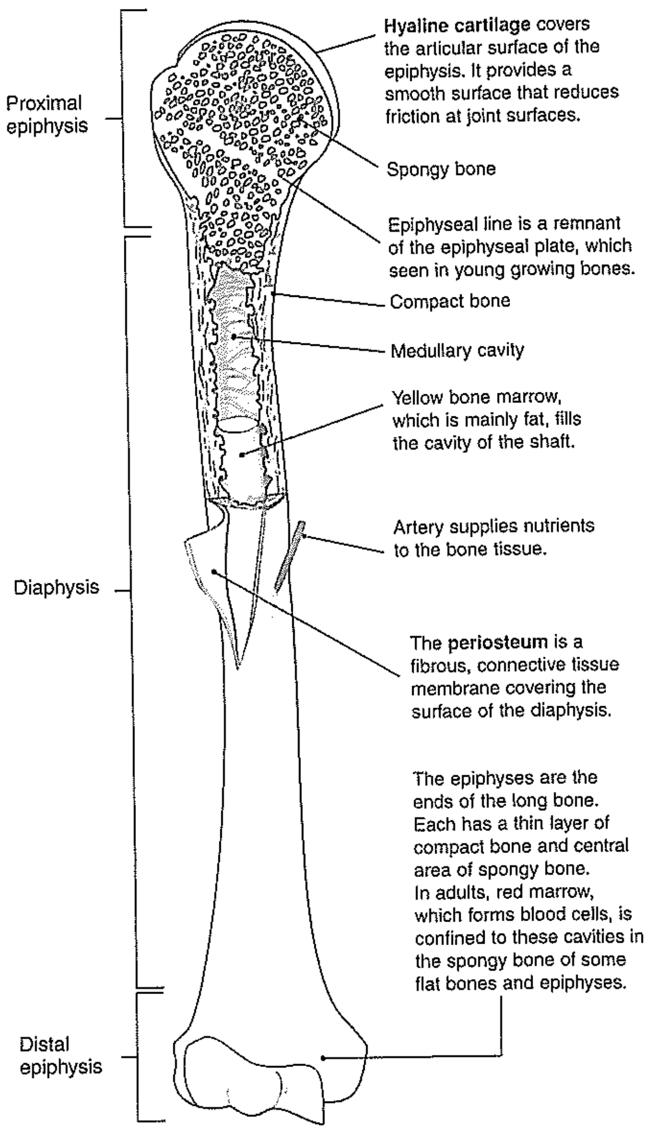
Bone

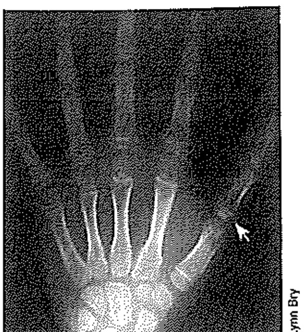
e skeleton is formed from two hard connective tissues: **bone** d **cartilage**. It has five basic functions: it provides **support** and otection for soft tissues and organs, it allows for **movement**, d it is involved in **storing minerals** (calcium and phosphorus) d **blood cell formation**. Bones also have a role in the nduction of sound in the middle ear. Although bone is a hard sue, it is dynamic and is continually **remodeled** and repaired cording to needs and in response to blood calcium levels and the pull of gravity and muscles. Hormones are also involved: the maturation of bones is influenced by thyroid hormones, adrenal androgens, and gonadal sex steroids. Bones have a simple gross structure, typified by the long bone such as the humerus, but a complex internal structure of **lamellae**. Most bones of the skeleton are formed from hyaline cartilage by a process of **ossification** (bone formation) and they grow by **bone remodeling**. Bone remodeling is also important in bone repair.

Ossification and Bone Growth

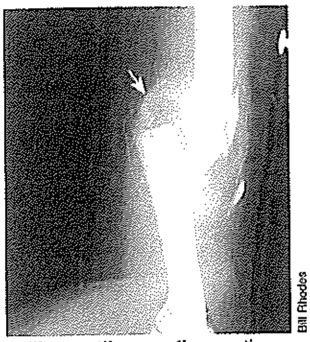


Mature Long Bone



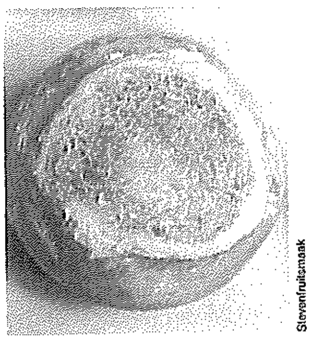


This x-ray shows the epiphyseal plates of a child's hand, seen as separate from the longer bones.



A **fibrocartilage callus** or tissue mass (indicated) begins the repair process on a fractured humerus.

Red bone marrow is stored in the cavities of spongy bone. Here it is being extracted for transplant.



A section of a femur head shows outer compact bone surrounding inner spongy bone and marrow.

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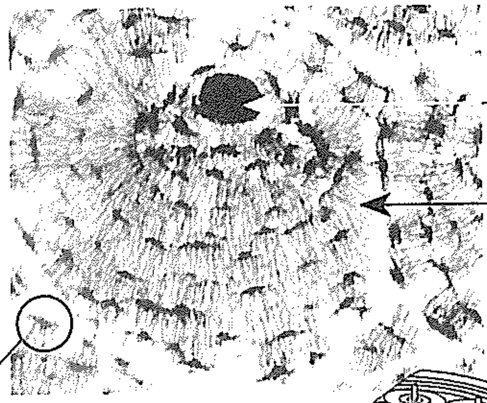
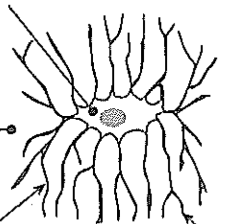
Related activities: Hematopoiesis, Growth
Web links: Skeleton and Joints

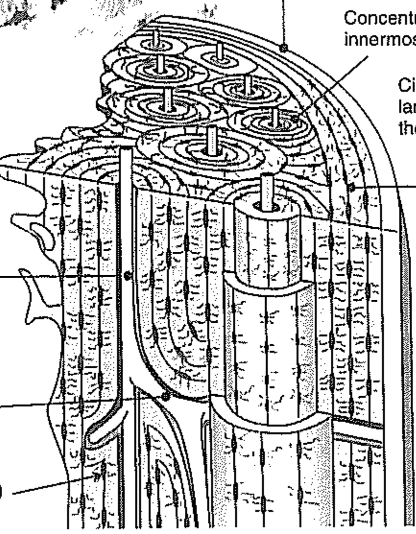
The Ultrastructure of Bone

The cells that produce the bone are called **osteoblasts.** They secrete the matrix of calcium phosphate and collagen fibers that forms the rigid bone. Once mature and embedded within the matrix, the bone cells are called **osteocytes.** Dense bone has a very regular structure, composed of repeating units called **Haversian systems.** Each Haversian system has concentric rings of hard material enclosing the bone cells. Haversian canals running through the bone contain blood vessels and nerves so that the bone cells can be supplied with oxygen and nutrients, and wastes can be removed.





Osteocyte (bone cell) embedded in a lacuna within the matrix (mainly calcium phosphate and collagen). The osteocytes maintain the bone tissue.



1. Describe the way in which bones grow in length and distinguish this from appositional growth:

2. Describe how the skeleton fulfills each of the following functional roles:

   (a) Support:

   (b) Protection:

   (c) Movement:

   (d) Blood cell production:

   (e) Mineral storage:

3. Identify the feature described by each of the following definitions:

   (a) A feature of bones that are still increasing in length:

   (b) The long shaft of a mature bone:

   (c) Fibrous, connective tissue membrane covering the surface of the bone shaft:

   (d) The end of a long bone, covered in articular hyaline cartilage:

4. Distinguish between osteoblasts and osteocytes and describe the role of each:

5. Explain the function of the Haversian canal system in hard bone tissue:

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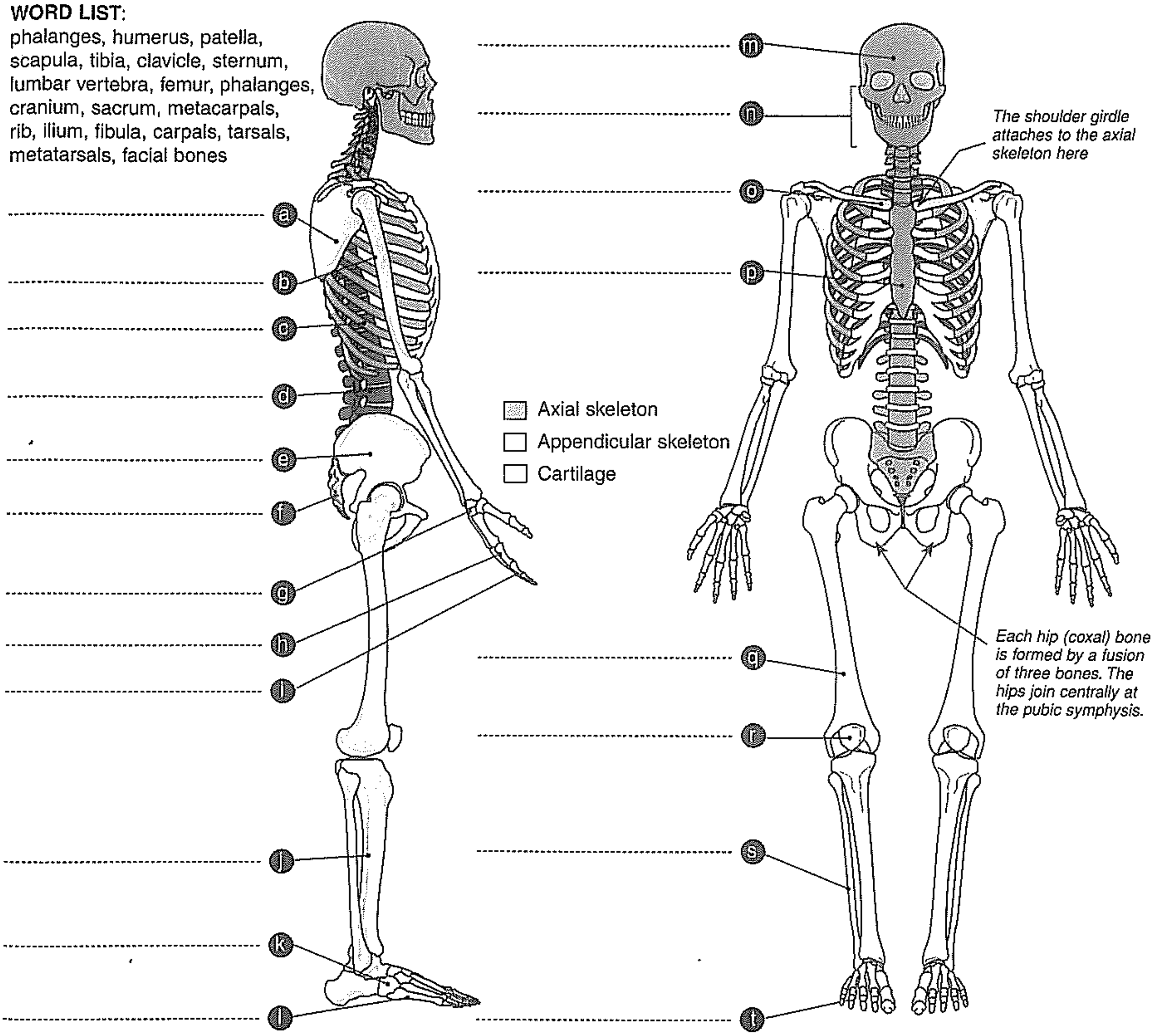
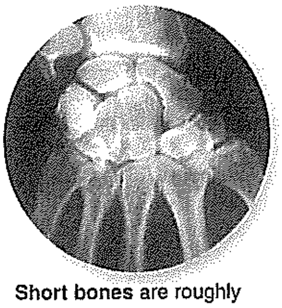
The Human Skeleton

The human skeleton consists of two main divisions: the **axial skeleton**, comprising the **skull**, **rib cage**, and **spine**, and the **appendicular skeleton**, made up of the limbs and the pectoral and pelvic girdles. As well as being identified by their location, bones are also described by their shape (e.g. irregular, flat, long, or short), which is related to their functional position in the skeleton. Most of the bones of the upper and lower limbs, for example, are long bones. Bones also have features such as processes, holes (foramina, *sing.* **foramen**), and depressions (**fossae**), associated with nerves, blood vessels, ligaments, and muscles. Understanding the basic organization of the skeleton, the particular features associated with its component bones, and the nature of skeletal articulations (**joints**) is essential to understanding how the movement of body parts is achieved.

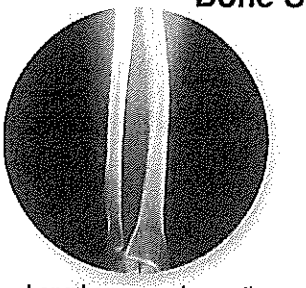
WORD LIST:
phalanges, humerus, patella, scapula, tibia, clavicle, sternum, lumbar vertebra, femur, phalanges, cranium, sacrum, metacarpals, rib, ilium, fibula, carpals, tarsals, metatarsals, facial bones



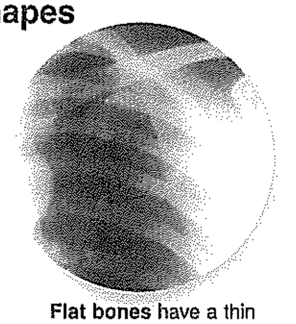
Bone Shapes



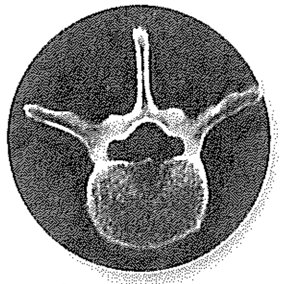
Short bones are roughly cube shaped and contain mostly spongy bone:
- carpals (above)
- tarsals
- patella



Long bones are longer than they are wide:
- most bones of the upper limbs. e.g. ulna, radius
- most bones of the lower limbs, e.g. femur, tibia



Flat bones have a thin flattened shape:
- ribs (above)
- sternum
- scapulae
- some skull bones



Irregular bones have an irregular shape and do not fit into the other groups:
- vertebrae (above)
- hip bones
- facial bones

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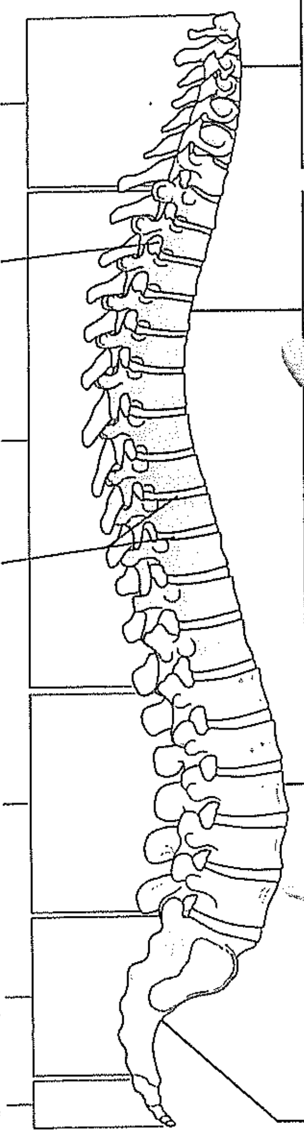
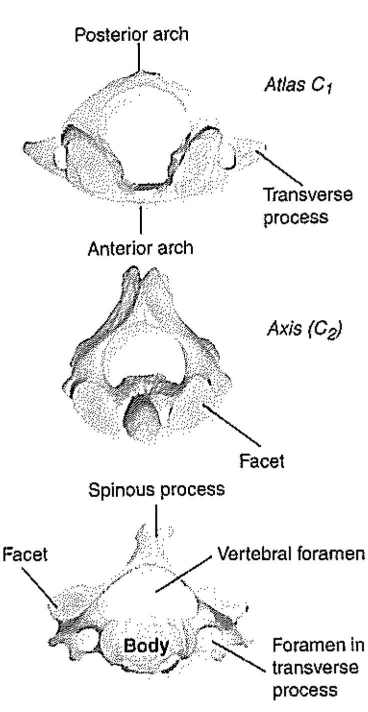
Related activities: Joints, Aging and the Skeleton **Web links:** The Vertebral Column, The Axial Skeleton, The Appendicular Skeleton

The Bones of the Spine



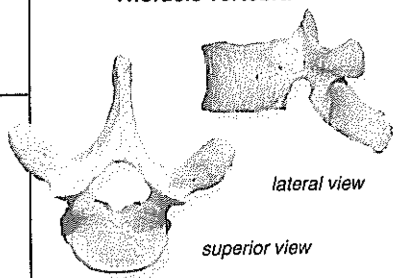
Features: Cervical vertebrae are the smallest and lightest of the vertebrae. They always have openings (foramina) through which the vertebral arteries pass. The atlas (C1) has no body and articulates with the skull, while C2 (the axis) acts as a pivot for rotation of the atlas.

Cervical vertebrae



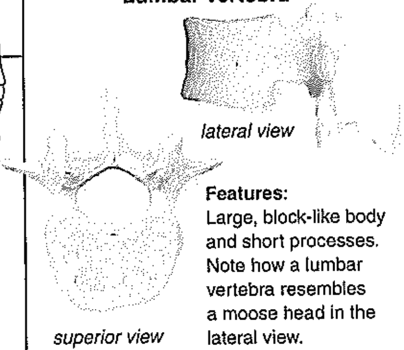
Vertebral features as illustrated in a ***typical cervical vertebra***

Thoracic vertebra



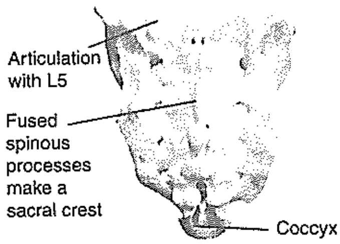
Features: Larger than the cervical vertebrae, with a slightly heart-shaped body. The transverse processes articulate with the ribs. The spinous process is long and points sharply downward.

Lumbar vertebra



Features:
Large, block-like body and short processes. Note how a lumbar vertebra resembles a moose head in the lateral view.

Sacrum and Coccyx



Features: Fused vertebrae. The sacrum articulates with L_5 and the coccyx.

Photos courtesy Prof. John Bath

1. Use the word list provided on the previous page to label the bones (a)-(t) of the skeleton in the diagram.

2. Identify the vertebrae associated with each of the following features:

   (a) Functional role in bearing much of the spinal load: ______

   (b) Articulate with the ribs. Vertebral body is heart shaped (highlight this on the diagram): ______

   (c) Articulates with the skull and lacks a vertebral body: ______

   (d) Typically has a small body and foramina (openings) in the transverse processes: ______

   (e) Forms the posterior wall of the bony pelvis: ______

3. (a) Describe the function of the shoulder (pectoral) girdle and name its components: ______

   (b) Identify the single point of attachment of shoulder girdle to the axial skeleton: ______

4. Explain how and why the male and female pelves (*sing.* pelvis) differ: ______

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Joints

Bones are too rigid to bend without damage. To allow movement, the skeletal system consists of many bones held together at **joints** by flexible connective tissues called **ligaments**. All movements of the skeleton occur at joints: points of contact between bones, or between cartilage and bones. Joints may be classified structurally as fibrous, cartilaginous, or synovial based on whether fibrous tissue, cartilage, or a joint cavity separates the bones of the joint. Each of these joint types allows a certain degree of movement. **Fibrous joints**, such as the sutures of the skull, generally allow little or no movement. **Cartilaginous joints** (e.g the pubic **symphysis**) generally allow slight movement, while **synovial joints** enable free movement in one or more planes (see table overleaf). Bones are made to move about a joint by the force of muscles acting upon them.

Cartilaginous Joints

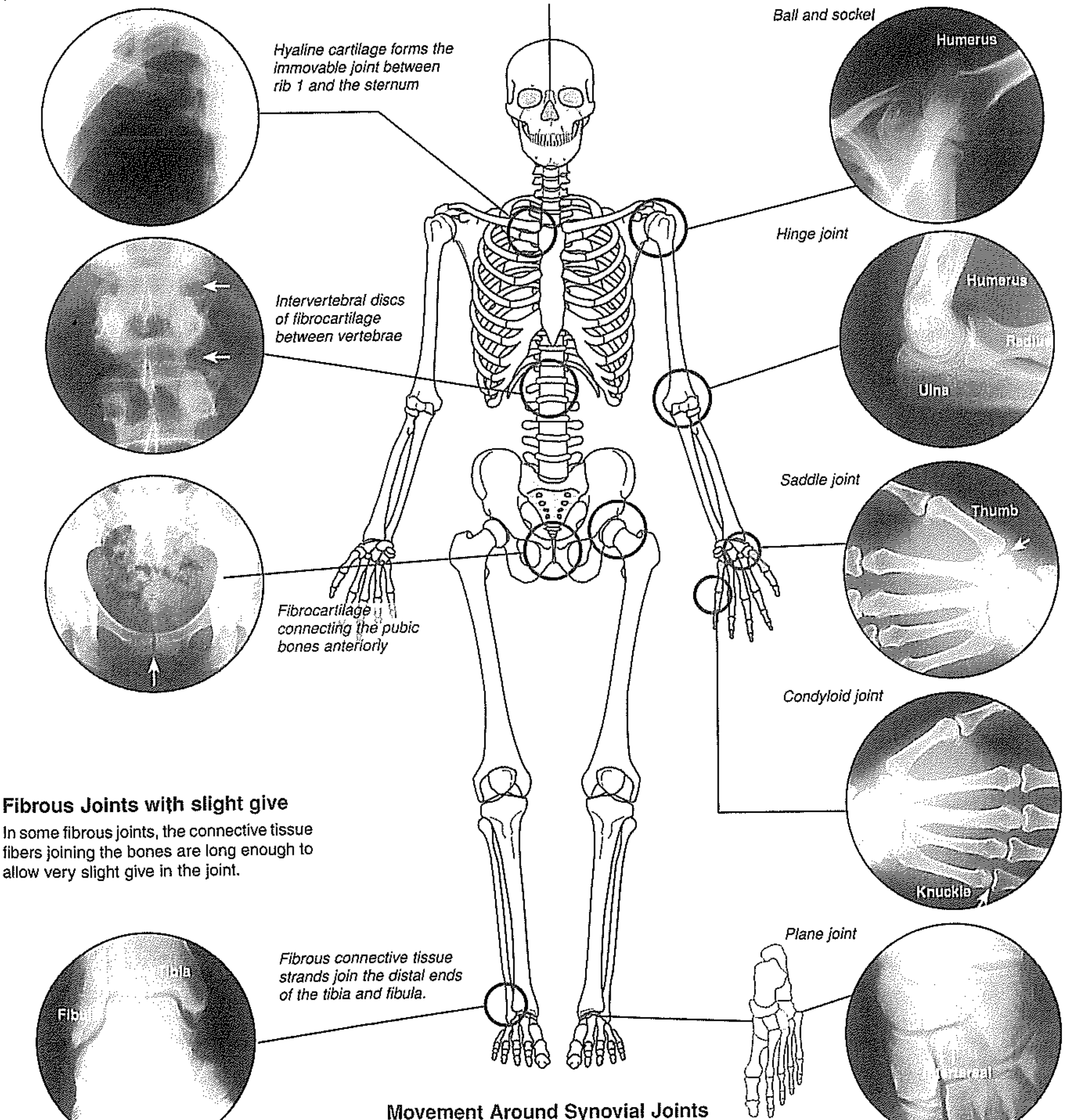
Here, the bone ends are connected by cartilage. Most allow limited movement although some (e.g. between the first ribs and the sternum) are immovable.

Immovable Fibrous Joints

The bones are connected by fibrous tissue. In some (e.g. sutures of the skull), the bones are tightly bound by connective tissue fibers and there is no movement.

Synovial Joints

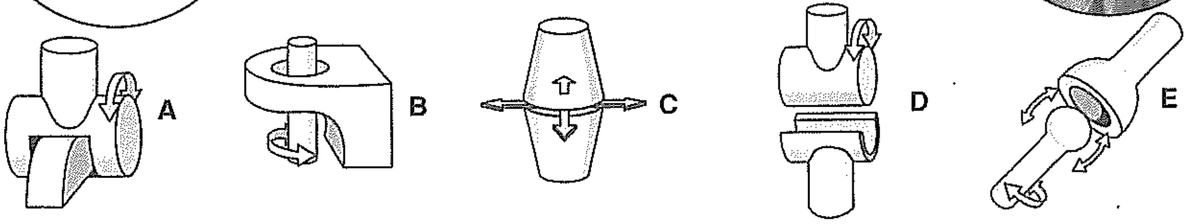
These allow free movement in one or more planes. The articulating bone ends are separated by a joint cavity containing lubricating synovial fluid (see overleaf).



Fibrous Joints with slight give

In some fibrous joints, the connective tissue fibers joining the bones are long enough to allow very slight give in the joint.

Movement Around Synovial Joints



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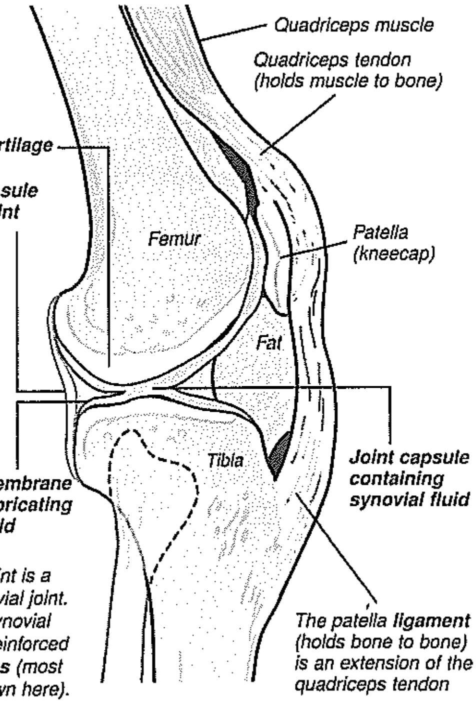
Related activities: Body Membranes and Cavities, The Mechanics of Locomotion, Autoimmune Diseases **Web links:** Skeleton and Joints

Classification of Synovial Joints

Joint	Structure	Movement	Examples
Plane (gliding)	Flat articular surfaces	Short gliding movements	- intercarpal joints - intertarsal joints
Hinge	Cylindrical end of one bone fits into a trough-like surface on the other bone	Angular movement in one plane	- elbow (humerus-ulna) - ankle joint - joints between the phalanges
Pivot	Round end of one bone fits into a sleeve or ring of bone	Rotation around the long axis	- joint between radius and ulna - joint between atlas and axis
Condyloid	Two oval articular surfaces	Free movement in two planes (side to side and back and forth)	- knuckles of the hands
Saddle	One convex and one concave articular surface	Free movement in two planes	- joint between carpals and metacarpals in the thumb
Ball and socket	Spherical head of one bone fits into a round socket on the other	Free movement in all axes	- shoulder joint - hip joint (hip/femur)

Synovial joints allow free movement of body parts in varying directions (one, two or three planes). Some examples of typical synovial joints and the movements they allow are described above.

Structure of a Synovial Joint



*The knee joint is a typical synovial joint. Like most synovial joints, it is reinforced by **ligaments** (most are not shown here).*

1. Classify each of the synovial joint models (**A-E**) at the bottom of the previous page, according to the descriptors below:

   (a) Pivot: ________ (b) Hinge: ________ (c) Ball-and-socket: ________ (d) Saddle: ________ (e) Gliding: ________

2. Describe the basic function of joints: ______________________

   ____

3. The skull bones of babies at birth and early in infancy are not fused and some areas (the **fontanelles**) have still to be converted to bone. Describe two reasons why the skull bones are not fused into sutures until around 2 years of age:

   (a) ______________________

   (b) ______________________

4. Describe the major difference between a fibrous and a cartilaginous joint: ______________________

   ____

5. (a) Describe the features common to most synovial joints: ______________________

   ____

   ____

   (b) Explain the role that synovial fluid and cartilage play in the structure and function of a synovial joint:

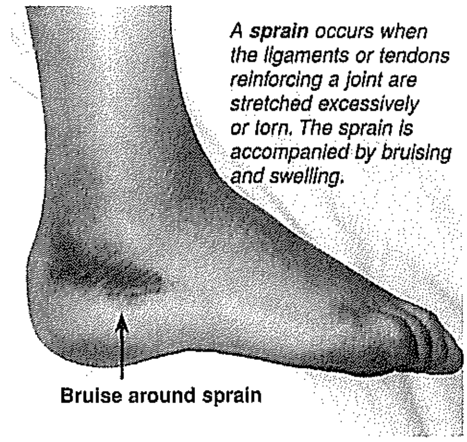
   ____

   ____

   ____

   ____

   ____



*A **sprain** occurs when the ligaments or tendons reinforcing a joint are stretched excessively or torn. The sprain is accompanied by bruising and swelling.*

6. Sprains (right) are extremely painful. Explain why they are also slow to heal:

   ____

   ____

   ____

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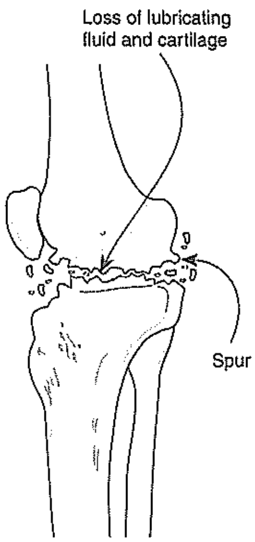
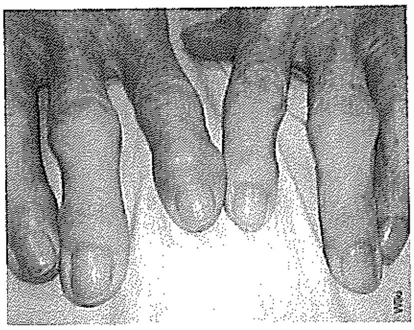
Aging and the Skeleton

After reaching physical maturity the body undergoes **degenerative changes** known as **senescence** or **aging**. The process is characterized by increasing homeostatic imbalance, and increasing susceptibility to stress and disease. Aging occurs as a result of cells dying and renewal rates slowing or stopping. This applies to bone as well as other tissues; the rate of bone remodelling slows and bone resorption rates begin to exceed rates of deposition. Consequently, there is a loss on skeletal strength and an increased tendency for bones to fracture. Note that the degenerative diseases of the skeleton described below (**osteoporosis** and **osteoarthritis**) are related to but not caused by aging. There are many people well into old age who have no signs of skeletal disease.

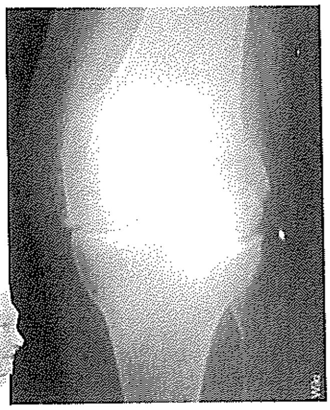
Osteoarthritis

Osteoarthritis (OA) a chronic degenerative disease aggravated by mechanical stress on bone joints. It is characterized by the degeneration of cartilage and the formation of bony outgrowths (**bone spurs** or osteophytes) around the edges of the eroded cartilage. This leads to pain, stiffness, inflammation, and full or partial loss of joint function. OA occurs in almost all people over the age of 60 and affects three times as many women as men. Weight bearing joints such as those in the knee, foot, hips, and spine are the most commonly affected. Although there is no cure, the symptoms can be greatly relieved by painkillers, anti-inflammatory drugs, and exercises to maintain joint mobility.





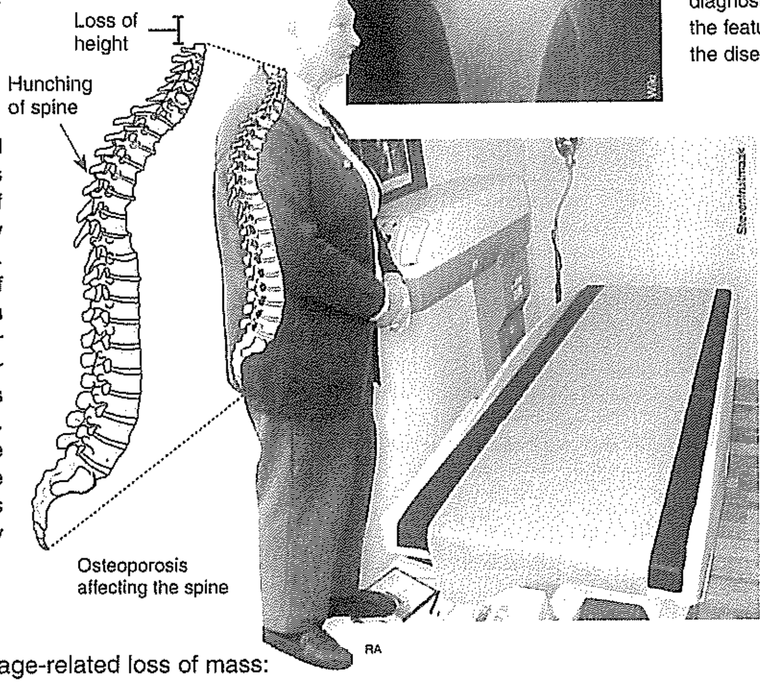
The loss of cartilage, the wearing of bone, and the growth of spurs all combine to change the shape of joints affected by OA. This forces the bones out of their normal positions and causes deformity, as seen in the fingers of this elderly patient.



In severe osteoarthritis, the cartilage can become so thin that it no longer covers the thickened bone ends. The bone ends touch, rub against each other, and start to wear away, as shown in this X-ray of an osteoarthritic knee (left). X rays are the commonly used diagnostic method for OA as the features associated with the disease show up clearly.

Osteoporosis

Osteoporosis is an age-related disorder where bone mass decreases, and there is a loss of height and an increased tendency for bones to break (**fracture**). Women are at greater risk of developing the disease than men because their skeletons are lighter and their estrogen levels fall after menopause (estrogen provides some protection against bone loss). Younger women with low hormone levels and/or low body weight are also affected. Osteoporosis affects the whole skeleton, but especially the spine, hips, and legs.



The diagnosis of osteoporosis is made by measuring the **bone mineral density** (BMD). The most widely-used method is **dual energy X-ray absorptiometry** or DXA (left). Two X-ray beams with differing energy levels are aimed at the patient's bones. The BMD is determined from the absorption of each beam by bone.

1. Describe the main reason for age-related loss of mass:

2. Describe how the structural changes in an osteoathritic joint relate to loss of function:

3. Explain why loss of bone mineral density is associated with increased risk of bone fracture:

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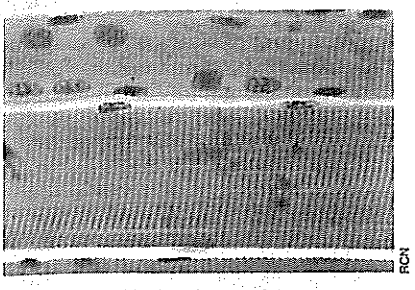
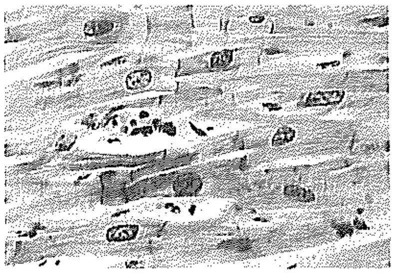
Muscle Structure and Function

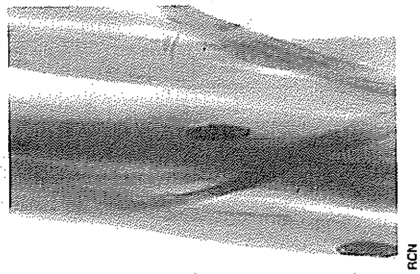
There are three kinds of muscle tissue: **skeletal, cardiac**, and **smooth** muscle, each with a distinct structure. The muscles used for posture and locomotion are skeletal (voluntary) muscles and are largely under conscious control. Their distinct appearance is the result of the regular arrangement of contractile elements within the muscle cells. Muscle fibers are innervated by the branches of motor neurons, each of which terminates in a specialized cholinergic synapse called the **neuromuscular junction** (or motor end plate). A motor neuron and all the fibers it innervates (which may be a few or several hundred) are called a **motor unit**.



Skeletal muscle
Also called striated or striped muscle. It has a banded appearance under high power microscopy. Sometimes called voluntary muscle because it is under conscious control. The cells are large with many nuclei at the edge of each cell.



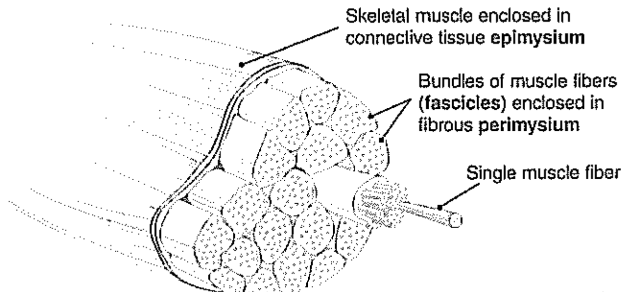
Cardiac muscle
Specialized striated muscle that does not fatigue. Cells branch and connect with each other to assist the passage of nerve impulses through the muscle. Cardiac muscle is not under conscious control (it is involuntary).



Smooth muscle
Also called involuntary muscle because it is not under conscious control. Contractile filaments are irregularly arranged so the contraction is not in one direction as in skeletal muscle. Cells are spindle shaped with one central nucleus.

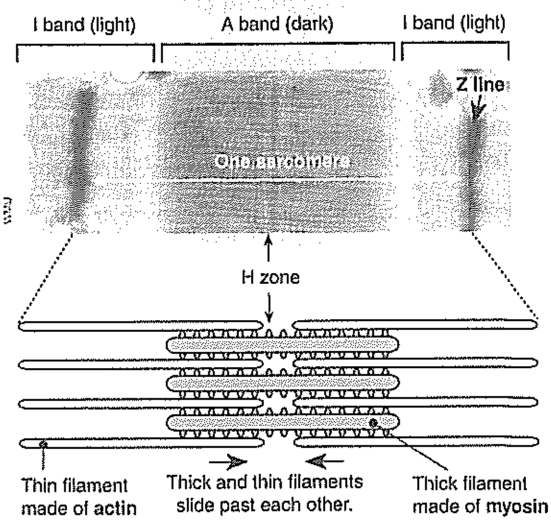
Structure of Skeletal Muscle

Skeletal muscle is organized into bundles of muscle cells or **fibers**. Each fiber is a single cell with many nuclei and each fiber is itself a bundle of smaller **myofibrils** arranged lengthwise. Each myofibril is in turn composed of two kinds of **myofilaments** (thick and thin), which overlap to form light and dark bands. It is the alternation of these light and dark bands which gives skeletal muscle its striated or striped appearance. The **sarcomere**, bounded by the dark Z lines, forms one complete contractile unit.

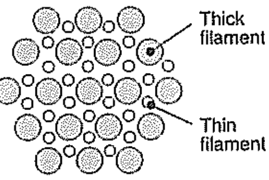


The relationship between muscle, fascicles, and muscle fibers (cells)

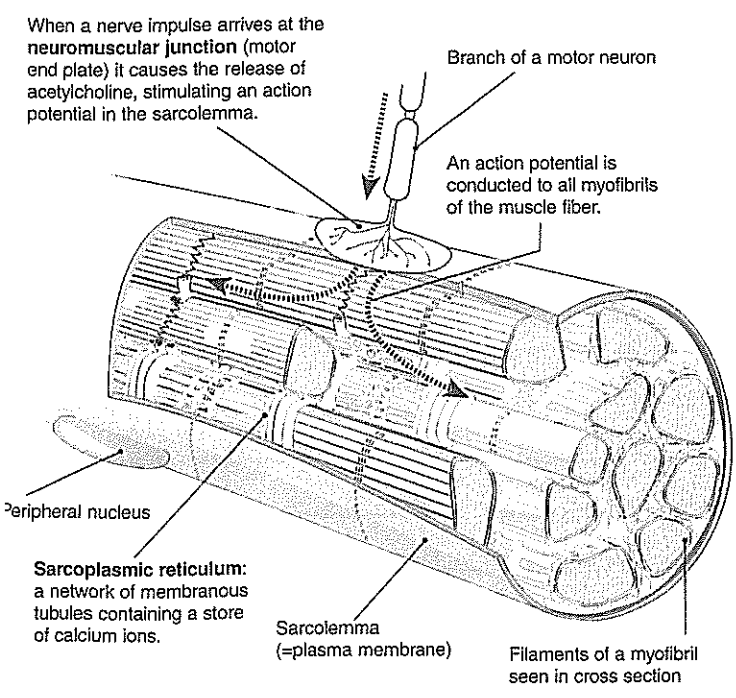
Longitudinal section of a sarcomere

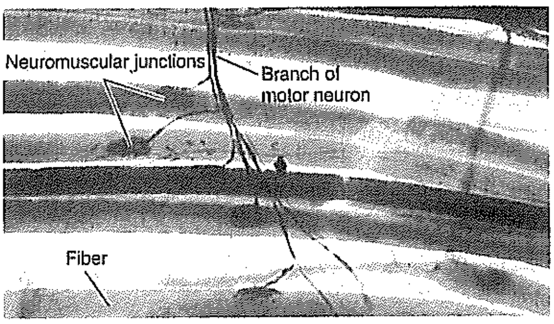


Cross section through a region of overlap between thick and thin filaments.



The photograph of a sarcomere (above) shows the banding pattern arising as a result of the arrangement of thin and thick filaments. It is represented schematically in longitudinal section and cross section.





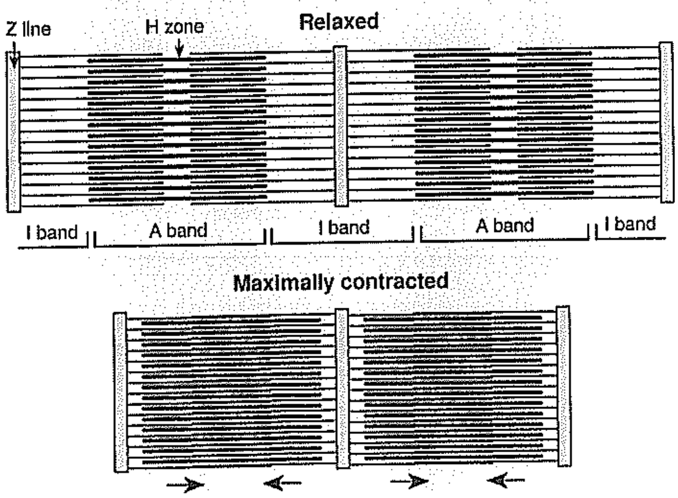
Above: Axon terminals of a motor neuron supplying a muscle. The branches of the axon terminate on the sarcolemma of a fiber at regions called the neuromuscular junction. Each fiber receives a branch of an axon, but one axon may supply many muscle fibers.

ISBN: 978-1-877462-26-9

Related activities: The Sliding Filament Theory, Chemical Synapses,

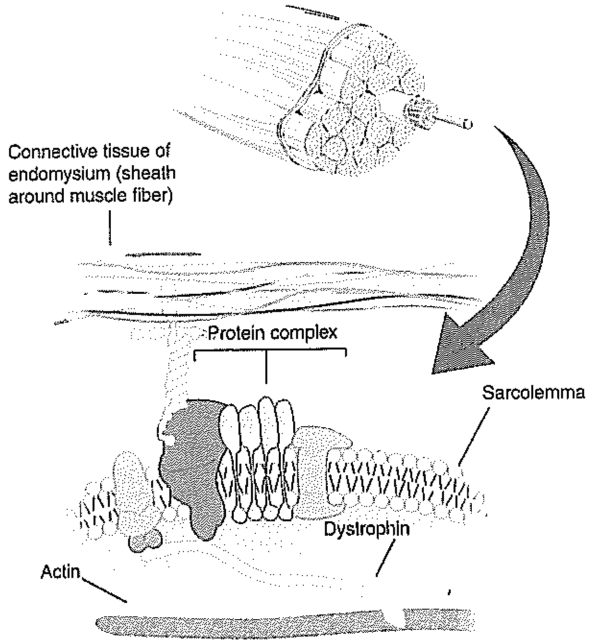
The Banding Pattern of Myofibrils

Within a myofibril, the thin filaments, held together by the **Z lines**, project in both directions. The arrival of an action potential sets in motion a series of events that cause the thick and thin filaments to slide past each other. This is called **contraction** and it results in shortening of the muscle fiber and is accompanied by a visible change in the appearance of the myofibril: the I band and the sarcomere shorten and H zone shortens or disappears (below).



The response of a single muscle fiber to stimulation is to contract maximally or not at all; its response is referred to as the **all-or-none law** of muscle contraction. If the stimulus is not strong enough to produce an action potential, the muscle fiber will not respond. However skeletal muscles as a whole are able to produce varying levels of contractile force. These are called **graded responses.**

When Things Go Wrong



Duchenne's muscular dystrophy is an X-linked disorder caused by a mutation in the gene DMD, which codes for the protein **dystrophin.** The disease causes a rapid deterioration of muscle, eventually leading to loss of function and death. It is the most prevalent type of muscular dystrophy and affects only males. Dystrophin is an important structural component within muscle tissue and it connects muscles fibers to the extracellular matrix through a protein complex on the sarcolemma. The absence of dystrophin allows excess calcium to penetrate the sarcolemma (the fiber's plasma membrane). This damages the sarcolemma, and eventually results in the death of the cell. Muscle fibers die and are replaced with adipose and connective tissue.

1. Distinguish between **smooth muscle**, **striated muscle**, and **cardiac muscle**, summarizing the features of each type:

____

____

____

2. (a) Explain the cause of the banding pattern visible in striated muscle: _______________

____

____

(b) Explain the change in appearance of a myofibril during contraction with reference to the following:

The I band: _______________

The H zone: _______________

The sarcomere: _______________

3. Describe the purpose of the connective tissue sheaths surrounding the muscle and its fascicles: _______________

____

4. Explain what is meant by the all-or-none response of a muscle fiber: _______________

____

5. Explain why the inability to produce **dystrophin** leads to a loss of muscle function: _______________

____

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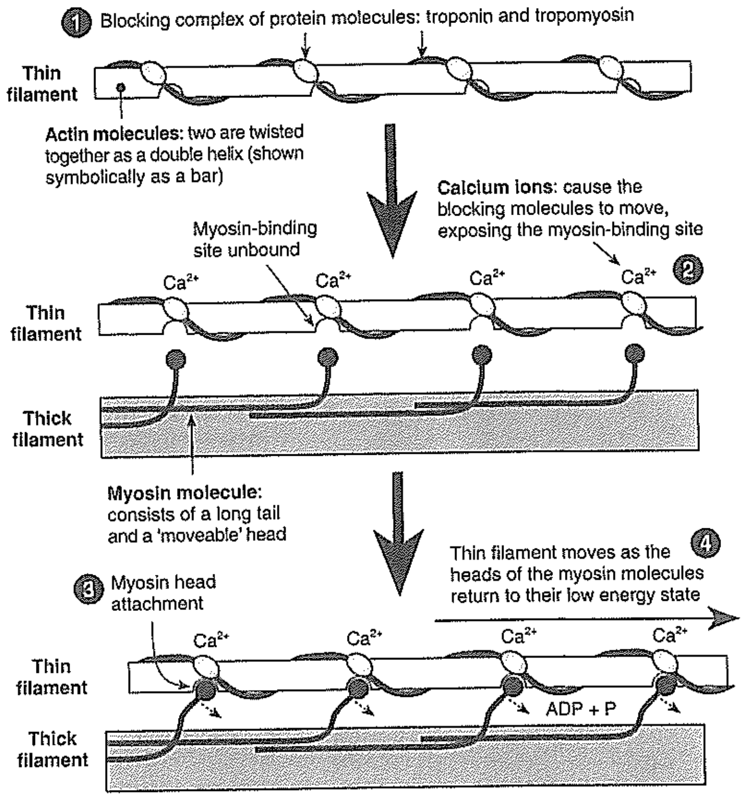
The Sliding Filament Theory

The previous activity described how muscle contraction is achieved by the thick and thin muscle filaments sliding past one another. This sliding is possible because of the structure and arrangement of the thick and thin filaments. The ends of the thick myosin filaments are studded with heads or **cross bridges** that can link to the thin filaments next to them. The thin filaments contain the protein actin, but also a regulatory protein complex. When the cross bridges of the thick filaments connect to the thin filaments, a shape change moves one filament past the other. Two things are necessary for cross bridge formation: calcium ions, which are released from the **sarcoplasmic reticulum** when the muscle receives an action potential, and ATP, which is hydrolyzed by ATPase enzymes on the myosin. When cross bridges attach and detach in sarcomeres throughout the muscle cell, the cell shortens. Although a muscle fiber responds to an action potential by contracting maximally, skeletal muscles as a whole can produce varying levels of contractile force. These **graded responses** are achieved by changing the frequency of stimulation (**frequency summation**) and by changing the number and size of motor units recruited (**multiple fiber summation**). Maximal contractions of a muscle are achieved when nerve impulses arrive at the muscle at a rapid rate and a large number of motor units are active at once.

The Sliding Filament Theory

Muscle contraction requires calcium ions (Ca^{2+}) and energy (in the form of ATP) in order for the thick and thin filaments to slide past each other. The steps are:

1. The binding sites on the **actin** molecule (to which myosin 'heads' will locate) are blocked by a complex of two protein molecules: tropomyosin and troponin.
2. Prior to muscle contraction, ATP binds to the heads of the myosin molecules, priming them in an erect high energy state. Arrival of an action potential causes a release of Ca^{2+} from the sarcoplasmic reticulum. The Ca^{2+} binds to the troponin and causes the blocking complex to move so that the myosin binding sites on the actin filament become exposed.
3. The heads of the cross-bridging myosin molecules attach to the binding sites on the actin filament. Release of energy from the hydrolysis of ATP accompanies the cross bridge formation.
4. The energy released from ATP hydrolysis causes a change in shape of the myosin **cross bridge**, resulting in a bending action (*the power stroke*). This causes the actin filaments to slide past the myosin filaments towards the centre of the sarcomere.
5. (Not illustrated). Fresh ATP attaches to the myosin molecules, releasing them from the binding sites and repriming them for a repeat movement. They become attached further along the actin chain as long as ATP and Ca^{2+} are available.



1. Match the following chemicals with their functional role in muscle movement (draw a line between matching pairs):

(a) Myosin	• Bind to the actin molecule in a way that prevents myosin head from forming a cross bridge
(b) Actin	• Supplies energy for the flexing of the myosin 'head' (power stroke)
(c) Calcium ions	• Has a moveable head that provides a power stroke when activated
(d) Troponin-tropomyosin	• Two protein molecules twisted in a helix shape that form the thin filament of a myofibril
(e) ATP	• Bind to the blocking molecules, causing them to move and expose the myosin binding site

2. Describe the two ways in which a muscle as a whole can produce contractions of varying force:

(a) ______________________________

____

(b) ______________________________

____

3. (a) Identify the two things necessary for cross bridge formation: ______________________________

(b) Explain where each of these comes from: ______________________________

____

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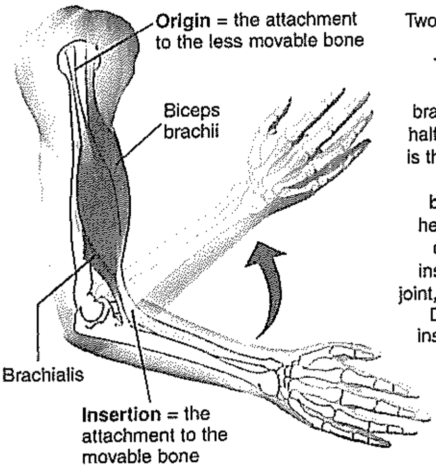
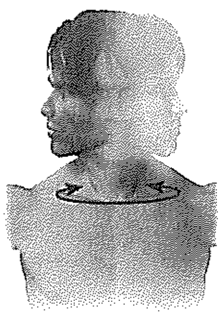
Related activities: Muscle Structure and Function
Web links: Muscle Cell Contraction

The Mechanics of Movement

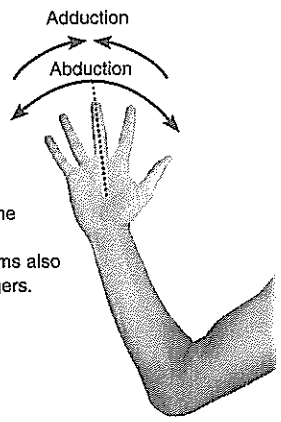
We are familiar with the many different bodily movements achievable through the action of muscles. Contractions in which the length of the muscle shortens in the usual way are called **isotonic contractions**: the muscle shortens and movement occurs. When a muscle contracts against something immovable and does not shorten the contraction is called **isometric.** Skeletal muscles are attached to bones by tough connective tissue structures called **tendons.** They always have at least two attachments: the **origin** and the **insertion.** They create movement of body parts when they contract across **joints.** The type and degree of movement achieved depends on how much movement the joint allows and where the muscle is located in relation to the joint. Some common types of body movements are described below (left panel). Because muscles can only pull and not push, most body movements are achieved through the action of opposing sets of muscles (below, right panel).



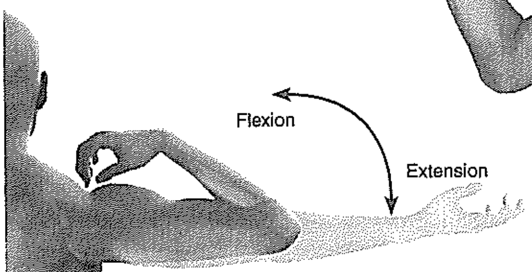
Two muscles are involved in flexing the forearm. The **brachialis**, which underlies the biceps brachii and has an origin half way up the humerus, is the **primer mover.** The more obvious **biceps brachii**, which is a two headed muscle with two origins and a common insertion near the elbow joint, acts as the synergist. During contraction, the insertion moves towards the origin.



Rotation is movement of a bone around its longitudinal axis. It is a common movement of ball and socket joints and the movement of the atlas around the axis.



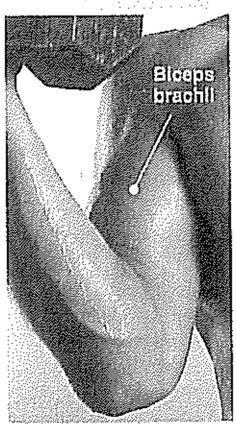
Abduction is a movement away from the midline, whereas **adduction** describes movement towards the midline. The terms also apply to opening and closing of the fingers.



Flexion decreases the angle of the joint and brings two bones closer together. **Extension** is its opposite. Extension more than 180° is called **hyperextension.**

The Action of Antagonistic Muscles

The skeleton works as a system of levers. The joint acts as a **fulcrum**, the muscles exert the **force**, and the weight of the bone being moved represents the **load**. The flexion (bending) and extension (unbending) of limbs is caused by the action of **antagonistic muscles**; muscles that work in pairs and whose actions oppose each other. Every coordinated movement in the body requires the application of muscle force. This is accomplished by the action of agonists, antagonists, and synergists. The opposing action of agonists and antagonists also produces muscle tone. Note that either muscle in an antagonistic pair can act as the **prime mover**, depending on the movement (e.g. flexion or extension).

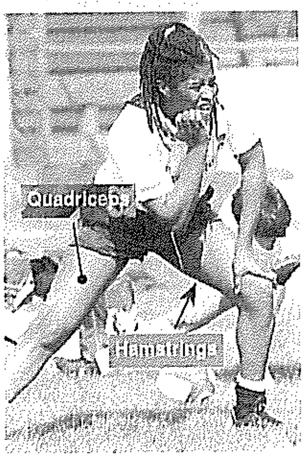


Agonists or prime movers: muscles that are primarily responsible for the movement and produce most of the force required.

Antagonists: muscles that oppose the prime mover. They may also play a protective role by preventing over-stretching of the prime mover.

Synergists: muscles that assist the prime movers and may be involved in fine-tuning the direction of the movement.

During flexion of the forearm (left) the **brachialis** muscle acts as the prime mover and the **biceps brachii** is the synergist. The antagonist, the **triceps brachii** at the back of the arm, is relaxed. During extension, their roles are reversed.



Movement of the leg is achieved through the action of several large groups of muscles, collectively called the **quadriceps** and the **hamstrings.**

The hamstrings are actually a collection of three muscles, which act together to flex the leg. The quadriceps at the front of the thigh (a collection of four large muscles) opposes the motion of the hamstrings and extends the leg. When the prime mover contracts forcefully, the antagonist also contracts very slightly. This stops overstretching and allows greater control over thigh movement.

1. Using appropriate terminology, explain how antagonistic muscles act together to raise and lower a limb:

____

____

2. (a) Identify the insertion for the biceps brachii during flexion of the forearm: ____________________

(b) Identify the insertion of the brachialis muscle during flexion of the forearm: ____________________

(c) Given its insertion, describe the forearm movement during which the biceps brachialis is the prime mover:

____

Related activities: Joints
Web links: Muscles in Action

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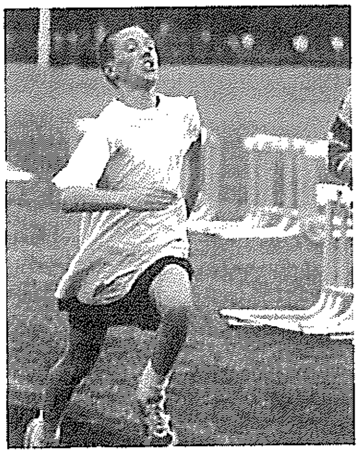
Energy for Muscle Contraction

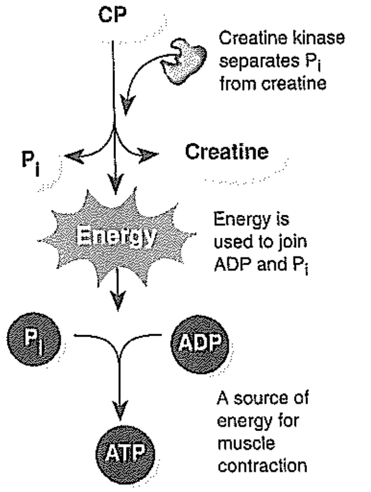
Exercise places an immediate demand on the body's energy supply systems. During exercise, the metabolic rate of the muscles increases by up to 20 times and the body's systems must respond appropriately to maintain homeostasis. The ability to exercise for any given length of time depends on maintaining adequate supplies of ATP to the muscles. There are three energy systems to do this: the **ATP-CP system**, the **glycolytic system**, and the **oxidative system**. The ultimate sources of energy for ATP generation in muscle via these systems are glucose, and stores of glycogen and triglycerides. Prolonged intense exercise utilizes the oxidative system, and relies on a constant supply of oxygen to the tissues. The **VO2** is the amount of oxygen (expressed as a volume) used by muscles during a specified interval for cell metabolism and energy production. **VO2max** is the maximum volume of oxygen that can be delivered and used per minute and therefore represents an individual's upper limit of aerobic metabolism. VO2max is used as a measure of fitness, and is high in trained athletes. At some percentage of VO2max (the **anaerobic threshold**) the body is unable to meet its energy demands aerobically and an **oxygen debt** is incurred.

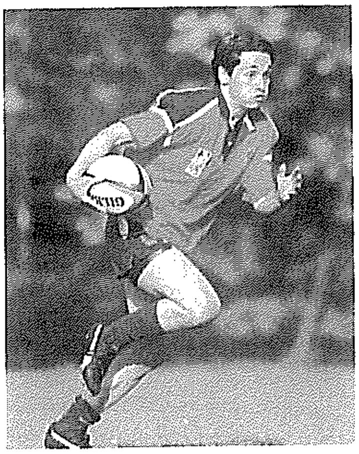


CP provides enough energy to fuel about 10 s of maximum effort (e.g. a 100 m race).

The ATP-CP System

The simplest of the energy systems is the **ATP-CP system**. CP or **creatine phosphate** is a high energy compound that stores energy sufficient for brief periods of muscular effort. Energy released from the breakdown of CP is not used directly to accomplish cellular work. Instead it rebuilds ATP to maintain a relatively constant supply. This process is anaerobic, occurs very rapidly, and is accomplished without any special structures in the cell. CP levels decline steadily as it is used to replenish depleted ATP levels. The ability of the ATP-CP system to maintain energy levels is limited to 3-15 seconds during an all out sprint. Beyond this, the muscle must rely on other processes for ATP generation.

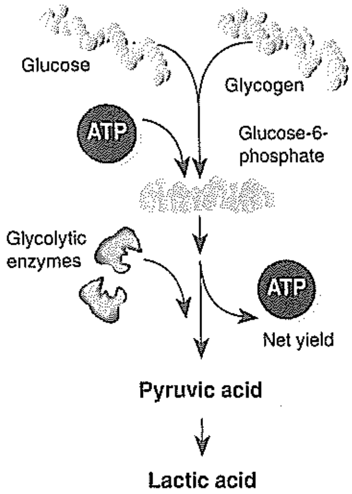




Rugby and other field sports demand brief intense efforts with recovery in-between.

The Glycolytic System

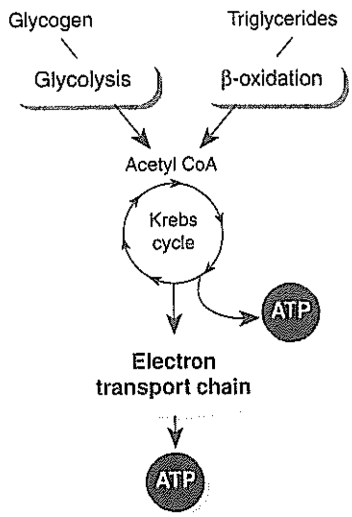
ATP can also be provided by glycolysis: the first phase of cellular respiration. The ATP yield from glycolysis is low (only net 2ATP per molecule of glucose), but it produces ATP rapidly and does not require oxygen. The fuel for the glycolytic system is glucose in the blood, or glycogen, which is stored in the muscle or liver and broken down to glucose-6-phosphate. Glycolysis provides ATP for exercise for just a few minutes. Its main limitation is that it causes lactic acid ($C_3H_6O_8$) to accumulate in the tissues. Indirectly, it is the accumulation of lactic acid that gives the feeling of muscle fatigue. The lactic acid must transported to the liver and respired aerobically. The extra oxygen needed for this is the **oxygen debt**.



Prolonged aerobic effort (e.g. distance running) requires a sustained ATP supply.

The Oxidative System

In the oxidative system, glucose is completely broken down to yield (about) 36 molecules of ATP. This process uses oxygen and takes place within the mitochondria. Aerobic metabolism has a high energy yield and is the primary method of energy production during sustained high activity. It is reliant on a continued supply of oxygen and therefore on the body's ability to deliver oxygen to the muscles. The fuels for aerobic respiration are glucose, stored glycogen, or stored **triglycerides**. Triglycerides provide free fatty acids, which are oxidized in the mitochondria by the successive removal of two-carbon fragments (a process called β-oxidation). These two carbon units enter the Krebs cycle as acetyl coenzyme A (acetyl CoA).



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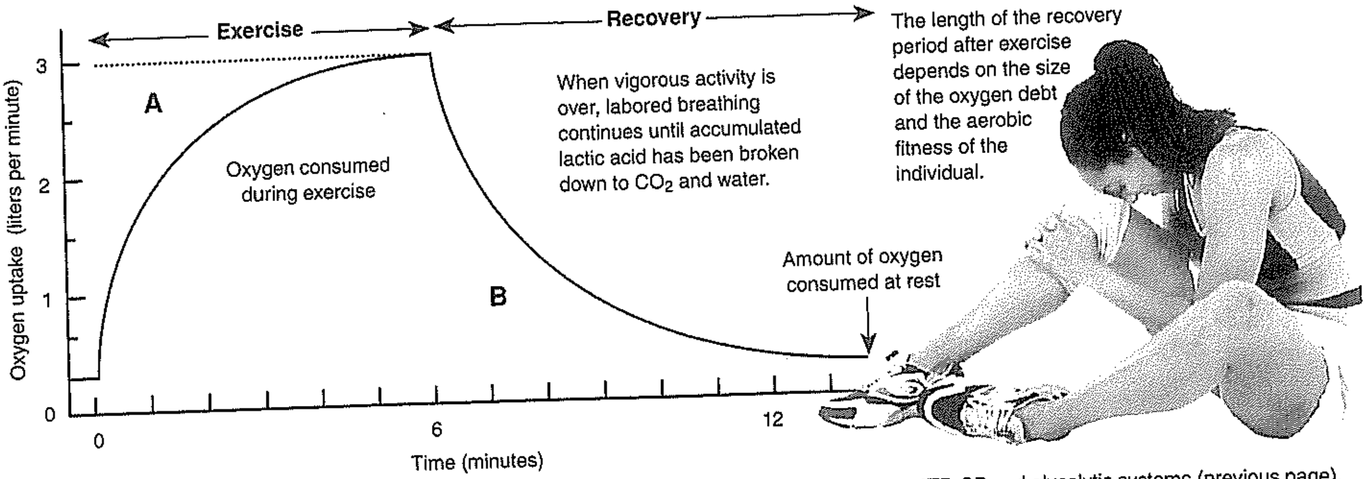
Related activities: Muscle Physiology and Performance, Muscle Fatigue

Oxygen Uptake During Exercise and Recovery



The graph above illustrates the principle of oxygen debt. In the graph, the energy demands of aerobic exercise require 3 liters of oxygen per minute. The rate of oxygen uptake increases immediately exercise starts, but the full requirement is not met until six minutes later. The **oxygen deficit** is the amount of oxygen needed (for aerobic energy supply) but not supplied by breathing. During the first six minutes, the energy is supplied largely from anaerobic pathways: the ATP-CP and glycolytic systems (previous page). After exercise, the oxygen uptake per minute does not drop immediately to its resting level. Extra oxygen is taken in despite the drop in energy demand (the **oxygen debt**). The oxygen debt is used to replace oxygen reserves in the body, restore creatine phosphate, and break down the lactic acid (through various intermediates) to CO_2 and water.

1. Explain why the supply of energy through the glycolytic system is limited:

2. Summarize the features of the three energy systems in the table below:

	ATP-CP system	Glycolytic system	Oxidative system
ATP supplied by:			
Duration of ATP supply:			

3. Study the graph and explanatory paragraph above, then identify and describe what is represented by:

   (a) The shaded region **A**:

   (b) The shaded region **B**:

4. With respect to the graph above, explain why the rate of oxygen uptake does not immediately return to its resting level after exercise stops:

5. The rate of oxygen uptake increases immediately exercise starts. Explain how the oxygen supply from outside the body to the cells is increased during exercise:

6. Lactic acid levels in the blood continue to rise for a time after exercise has stopped. Explain why this occurs:

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Muscle Tone and Posture

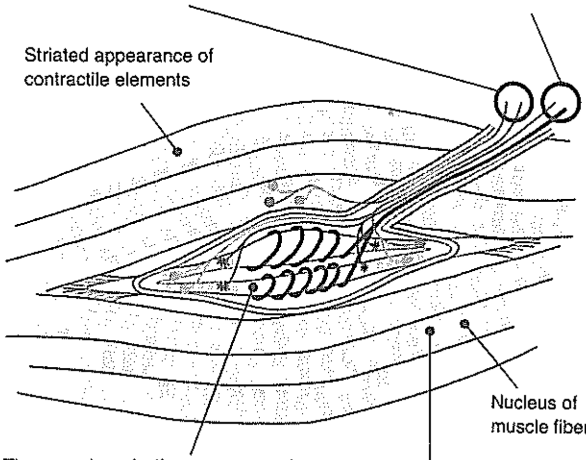
Even when we consciously relax a muscle, a few of its fibers at any one time will be involuntarily active. This continuous and passive partial contraction of the muscles is responsible for **muscle tone** and is important in maintaining **posture**. The contractions are not visible but they are responsible for the healthy, firm appearance of muscle. The amount of muscle contraction is monitored by sensory receptors in the muscle called **muscle spindle organs**. These provide the sensory information necessary to adjust movement as required. Abnormally low muscle tone (**hypotonia**) can arise as a result of traumatic or degenerative nerve damage, so that the muscle no longer receives the innervation it needs to contract. The principal treatment for these disorders is physical therapy to help the person compensate for the neuromuscular disability.

We are usually not aware of the skeletal muscles that maintain posture, although they work almost continuously making fine adjustments to maintain body position. Both posture and functional movements of the body are highly dependent on the strength of the body's core (the muscles in the pelvic floor, belly, and mid and lower back). The core muscles stabilize the thorax and the pelvis and lack of core strength is a major contributor to postural problems and muscle imbalances.

Physical therapy is a branch of health care concerned with maintaining or restoring functional movement throughout life. Loss of muscle tone and strength can develop as a result of aging, disease, or trauma. As a result of not being used, muscles will **atrophy**, losing both mass and strength. Although the type of physical therapy depends on the problem, it usually includes therapeutic exercise to help restore mobility and strength, and prevent or slow down the loss of muscle tissue.

The Role of the Muscle Spindle

Changes in length of a muscle are monitored by the **muscle spindle organ**, a stretch receptor located within skeletal muscle, parallel to the muscle fibers themselves. The muscle spindle is stimulated in response to sustained or sudden stretch on the central region of its specialized intrafusal fibers. Sensory information from the muscle spindle is relayed to the spinal cord. The motor response brings about adjustments to the degree of stretch in the muscle. These adjustments help in the coordination and efficiency of muscle contraction. Muscle spindles are important in the maintenance of muscle tone, postural reflexes, and movement control, and are concentrated in muscles that exert fine control over movement.



1. (a) Explain what is meant by muscle tone: __________

   (b) Explain how this is achieved: __________

2. (a) Explain the role of the muscle spindle organ: __________

   (b) With reference to the following, describe how the structure of the muscle spindle organ is related to its function:

   Intrafusal fibers lie parallel to the extrafusal fibers: __________

   Sensory neurons are located in the non-contractile region of the organ: __________

   Motor neurons synapse in the extrafusal fibers and the contractile region of the intrafusal fibers: __________

The Muscular System

ISBN: 978-1-877462-26-9

Related activities: Detecting Changing States, The Basis of Sensory Perception

Muscle Fatigue

Muscle fatigue refers to the decline in a muscle's ability to maintain force in a prolonged or repeated contraction. It is a normal result of vigorous exercise but the reasons for it are complex. During strenuous activity, the oxygen demand of the working muscle exceeds supply and the muscle metabolizes anaerobically. This leads to the metabolic changes (including lactic acid accumulation) that result in fatigue. The lactic acid (lactate) produced during muscle contraction diffuses into the bloodstream and is carried to the liver where it is reconverted to glucose via the **Cori cycle**. This requires energy from aerobic respiration and accounts for the **oxygen debt** which causes the continued heavy breathing after exercise has stopped. During moderate intensity exercise, the rate at which lactate enters the blood from the muscles is equal to its rate of removal by the liver. This steady-state situation is suitable for endurance training, because the lactic acid doesn't accumulate in the muscle tissue.

At Rest

- Muscles produce a surplus of ATP
- This extra energy is stored in CP (creatine phosphate) and glycogen

During Moderate Activity

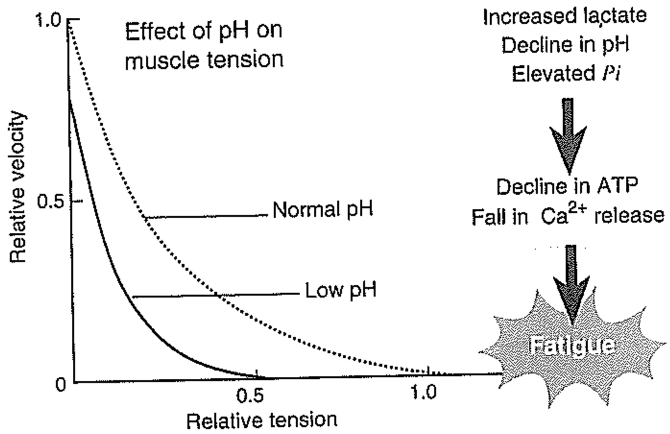
- ATP requirements are met by the aerobic metabolism of glycogen and lipids

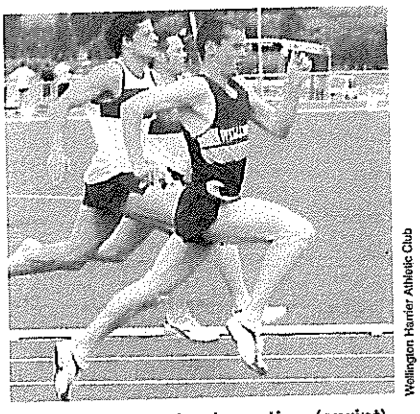
During Peak Activity

- Effort is limited by ATP. ATP production is ultimately limited by availability of oxygen.
- During short-term, intense activity, ATP is increased through anaerobic metabolism of glycogen (glycolysis).
- A by-product of this is lactic acid, which lowers tissue pH and affects cellular activity.
- When **fatigued**, the muscle can no longer contract fully.

Lactic Acid and Muscle Fatigue

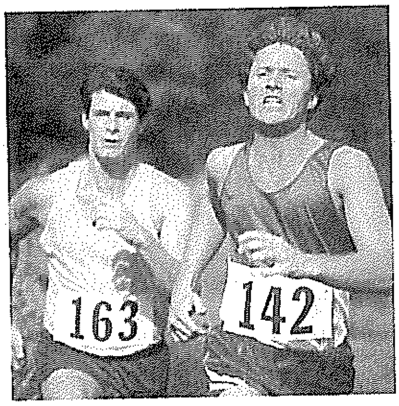
Lactic acid is a by-product of ATP production through anaerobic metabolism when oxygen demand exceeds supply. Lactic acid accumulation in the muscle causes a fall in tissue pH and inhibits the activity of the key enzymes involved in ATP production. This decline in ATP supply limits muscular performance during peak activity (see graph below). Together with the effects of ATP and creatine phosphate breakdown (accumulating phosphate (Pi) for example), lactic acid buildup also acts to slow the release of calcium into the T tubules and affects the ion pumps which move calcium ions back into the sarcoplasmic reticulum. This contributes to fatigue because calcium is a key component in muscle contraction.



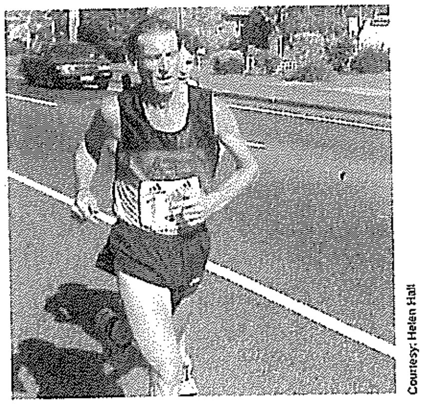


Wellington Harrier Athletic Club

Short term maximal exertion (sprint)
- Lactic acid build-up lowers pH
- Depletion of creatine phosphate
- Buildup of phosphate (P_i) affects the sensitivity of the muscle to Ca^{2+}



Mixed aerobic and anaerobic (5 km race)
- Lactate accumulation in the muscle
- Build-up of ADP and P_i
- Decline in Ca^{2+}release affects the ability of the muscle to contract



Courtesy: Helen Hall

Extended sub-maximal effort (marathon)
- Depletion of all energy stores (glycogen, lipids, amino acids) leads to a failure of Ca^{2+}release
- Repetitive overuse damages muscle fibers.

1. Explain the mechanism by which lactic acid accumulation leads to muscle fatigue: ____________________

____

2. Identify the two physiological changes in the muscle that ultimately result in a decline in muscle performance:

   (a) ____________________ (b) ____________________

3. Suggest why the reasons for fatigue in a long distance race are different to those in a 100 m sprint: ____________________

____

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Related activities: Energy and Exercise, Muscle Physiology and Performance

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Muscle Physiology and Performance

The overall effect of **aerobic training** on muscle is improved oxidative function and better endurance. Regardless of the type of training, some of our ability to perform different types of activity depends on our genetic make-up. This is particularly true of aspects of muscle physiology, such as the relative proportions of different fiber types in the skeletal muscles. Muscle fibers are primarily of two types: **fast twitch** (FT) or **slow twitch** (ST). Fast twitch fibers predominate during anaerobic, explosive activity, whereas slow twitch fibers predominate during endurance activity. In the table below, note the difference in the degree to which the two fiber types show fatigue (a decrease in the capacity to do work). Training can increase fiber size and, to some extent, the makeup of the fiber, but not the proportion of ST to FT, which is genetically determined.

The Effects of Aerobic Training on Muscle Physiology

Improved oxidation of glycogen. Training increases the capacity of skeletal muscle to generate ATP aerobically.

An increased capacity of the muscle to oxidize fats. This allows muscle and liver glycogen to be used at a slower rate. The body also becomes more efficient at mobilizing free fatty acids from adipose tissue for use as fuel.

Increased myoglobin content. Myoglobin stores oxygen in the muscle cells and aids oxygen delivery to the mitochondria. Endurance training increases muscle myoglobin by 75%-80%.

Increase in lean muscle mass and decrease in body fat. Trained endurance athletes typically have body fat levels of 15-19% (women) or 6-18% (men), compared with 26% (women) and 15% (men) for non-athletes.

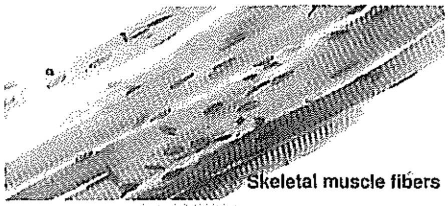
The size of **slow twitch fibers** increases. This change in size is associated with increased aerobic capacity.

An increase in the size and density of mitochondria in the skeletal muscles and an increase in the activity and concentration of Krebs cycle enzymes.

An increase in the number of capillaries surrounding each muscle fiber. Endurance trained men have 5%-10% more capillaries in their muscles than sedentary men.

Fast vs Slow Twitch Muscle

Feature	Fast twitch	Slow twitch
Color	White	Red
Diameter	Large	Small
Contraction rate	Fast	Slow
ATP production	Fast	Slow
Metabolism	Anaerobic	Aerobic
Rate of fatigue	Fast	Slow
Power	High	Low



There are two basic types of muscle fibers. Slow twitch (type I) muscle and fast twitch (type II) muscle fiber. Human muscles contain a genetically determined mixture of both slow and fast fiber types. On average, we have about 50% slow and 50% fast fibers in most of the muscles used for movement.

The slow twitch fibers contain more mitochondria and myoglobin than fast twitch fibers, which makes them more efficient at using oxygen to generate ATP without lactate acid build up. In this way, they can fuel repeated and extended muscle contractions such as those required for endurance events like a marathon.

Both fiber types generally produce the same force per contraction, but fast twitch fibers produce that force at a higher rate, so fast fibers are important when there is a limited time in which to generate maximal force (as in a sprint)

1. Explain three ways in which aerobic (endurance) training improves the oxidative function of muscle:

 (a) ____

 ____

 (b) ____

 ____

 (c) ____

 ____

2. Contrast the properties of fast and slow twitch skeletal muscle fibers, identifying how these properties contribute to their performance in different conditions:

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Related activities: Exercise and Blood Flow, Muscle Fatigue