Bones

Definition: organs of different morphology, of whitish or yellowish color, of solid consistency, endowed with great mechanical resistance.

The bones are connected by joints and give origin or insertion to the muscles. The adult skeleton is composed of approximately 206 bones. The shape of each bone is related to the static and dynamic mechanics of the locomotor system.

Classification of bones

- Long bones – one dimension prevails over the other two (length compared to width and thickness)
- Flat bones – two dimensions (length and width) prevail over the third (thickness)
- Short bones – all dimensions are equivalent.

Characteristics of long bones

- Diaphysis – elongated shaft (or body) of the long bone
- Epiphysis – more or less enlarged ends of the long bone.

Descriptive terminology of bone morphology

- Projections and reliefs
  - apophyses (processes) – well-defined projections
  - tuberosities – less well-defined projections
  - tubercles – defined reliefs
  - spines – pointed reliefs
- Depressions
  - sulci – thin depressions
  - fossae – rounded depressions
  - canals – elongated depressions.

Bones are made up of bone tissue:
- spongy – made up of more or less dense trabeculae, irregularly oriented, that surround the small cavities known as areolae
- compact – dense layer of bone tissue.

In addition to the areolae of the spongy bone tissue, there is another type of bone cavity represented by the medullary cavity of the long bones (within the diaphysis). The external surface of the bones is covered by the

Bone structure. The prevalence of length and width over thickness, or the relative equivalence of the dimensions allow bones to be classified as long (**A**), flat (**B**) and short (**C**).

periosteum, a fibrous membrane, and the internal cavities of the compact and spongy bone substance are covered by endosteum, also fibrous in nature.

The long bones are formed by compact bone tissue at the diaphysis (which delimits the medullary cavity) and of spongy bone at the epiphysis, surrounded by compact bone tissue.
The flat bones are formed by spongy bone tissue surrounded by two layers of compact bone tissue.
The short bones are formed by spongy bone tissue surrounded by compact bone tissue.

Bone tissue

It is formed by:
- cells – osteoblasts, osteocytes and osteoclasts
- intercellular matrix or substance – collagen fibers, amorphous substance (organic matrix) and mineral salts.

Osteoblasts

- Function – they synthesize intercellular substance
- Location – layer of cells adhering to the support (fibrous, cartilaginous or bone connective tissue) on which the intercellular substance is deposited.

Osteocytes

- Function – they are derived from osteoblasts and can transform back into osteoblasts
- Location – in the cavities of the bone matrix (called bone lacunae), each occupying a lacuna (bone canaliculi).

Osteoclasts

- Function – they reabsorbed intercellular substance
- Location – erosion cavities of intercellular substance (resorption lacunae).

Collagen fibers

- Bundles of tropocollagen filaments with a high elastic modulus and high breaking load.

Amorphous substance

- Hyaluronic acid and hexosamine polymers with little water and electrolytes.

Mineral salts

- Calcium (99% of the body’s calcium; 26% of the dry weight of the bone)
- Phosphorus (90% of the body’s phosphorus; 12% of the dry weight of the bone)
- Sodium (25% of the body’s sodium)
- Chloride
- Fluoride.

Structure of bone tissue

Both the trabeculae of the spongy tissue and the continuous layer of the compact bone tissue are formed of bone lamellae.

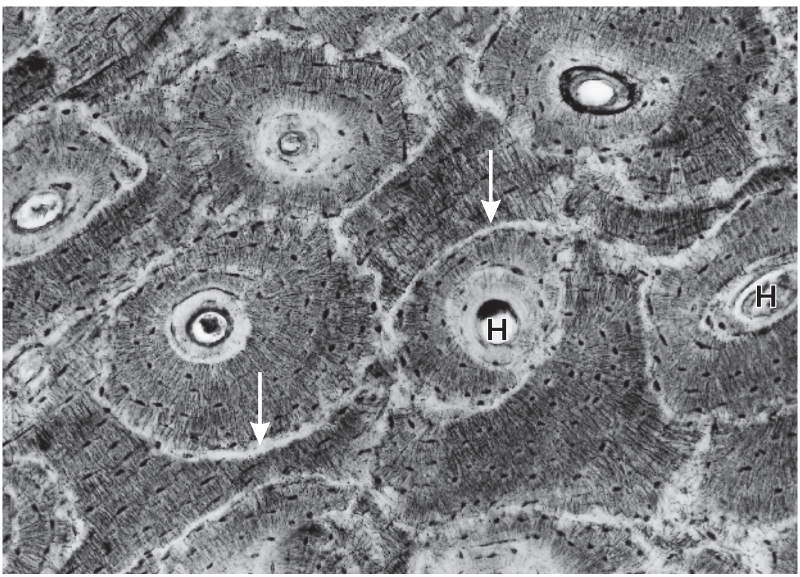
Definition of bone lamellae: thin layer (with a thickness of 5-10 µm) formed of collagen fibers, amorphous substance, mineral salts and a row of lacunae containing osteocytes.

Characteristics of bone lamellae

- In each bone lamella, the collagen fibers run parallel to each other, the orientation of the fibers differing from one lamella to the other
- In infancy, the lamellae of compact bone tissue are arranged concentrically
- Starting from puberty, the concentric organization of the lamellae of compact bone tissue is rearranged, creating a new arrangement known as interlocking fragments (lamellar bone tissue with osteons and breccia).

Definition of osteons (concentric haversian system): fragment of lamellar bone tissue with concentric arrangement of the lamellae within a central canaliculus (haversian canal).

Definition of breccia: fragment of lamellar bone tissue formed from non-concentric lamellae without a central canaliculus.



Section of a human compact bone (adult femoral diaphysis). Many osteons can be seen with a haversian canal (**H**) in a central position. Among the osteons there are fragments of bone breccia. The boundary between the osteons and the bone breccia is represented by the cementing lines indicated by **arrows**.

Levels of bone tissue organization

1st level structure → compact and spongy arrangement of the bone

2nd level structure → lamellar (concentric or with osteons and breccia) and non-lamellar composition

3rd level structure → different spatial orientation of collagen fibers

4th level structure → submicroscopic arrangement of the collagen fibers, mineral salts and amorphous substance

5th level structure → molecular arrangement of the bone constituents

There is a relationship between the 1st level structure and the mechanical engagement of a bone:

- in the diaphysis of the long bones there is a fixed relationship between the external diameter and internal diameter, which gives an optimal mechanical resistance
- in the spongy bone, the trabeculae follow the lines of greater mechanical engagement (load trajectories)

Mechanical resistance of the bone (dependent on the levels of bone tissue arrangement)	
Traction	10-20 kg/mm^2
Compression and flexion	15 kg/mm^2
Torsion	18 kg/mm^2

Joints

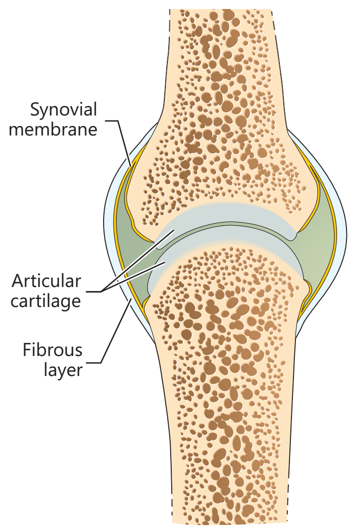
Definition: structures formed of two or more different or even similar contact surfaces whose shape and mode of contact depend on one or more possibilities of movement of the bone segments they are part of.

Joint appendages

- Articular cartilage
- Joint capsule
- Synovial membrane (or synovium)
- Synovial bursae
- Marginal labra
- Articular menisci (discs)
- Ligaments
- Connective tissue.

Articular cartilage

- Covers the articular surfaces of the bones
- It is a connective tissue
- It is of hyaline type
- It is formed of cell groups (which give it a state of tension and determine its elasticity) immersed in an amorphous substance called chondrin (or matrix), rich in three-dimensionally arranged collagen fibers and a ground substance composed of polysaccharides; it does not contain vessels and nerves, so the intake of nutritious substances and the elimination of waste products occurs through exchanges between the chondrin and the synovial fluid
- It is 0.2-6 mm thick (the increase in thickness is due to swelling of the ground substance):
  - dependent on pressure and extension stresses
  - greater at the periphery than at the center (due to the action of the ligaments)
- Improves the contact of the articular surfaces
- Reduces joint wear caused by stresses
- Undergoes:
  - thinning, if the motor stresses are reduced (articular ankylosis)
  - thickening (long-lasting), if the motor stresses are increased (for example, through training).



Articular cartilage, macroscopic aspect.

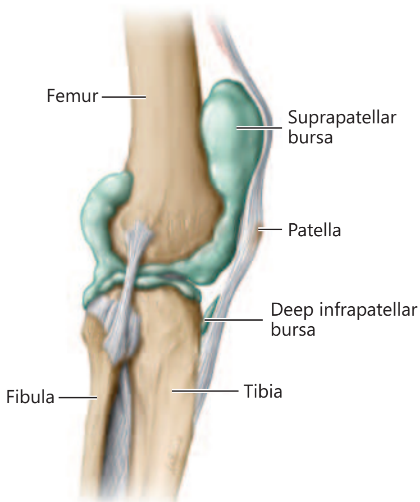
Joint capsule

- It is formed of a fibrous layer and a synovial membrane.

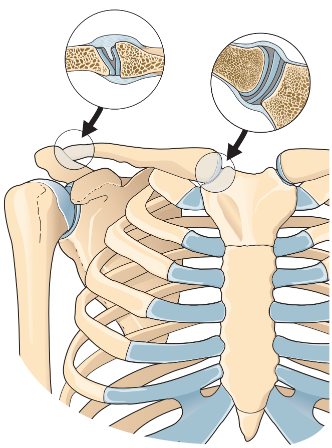
Synovial membrane

- It is rich in vessels and nerves

- Secretes a fluid (synovial fluid) containing albumin with the following functions:
  - nutrition of the articular cartilage
  - lubrication of the internal walls of the articular cavity
- Its inactivity causes it to thicken, reducing joint mobility.



Two important mucous bursae. Above, the suprapatellar bursa, the largest in the human body. Below on the right, the deep infrapatellar bursa.



Menisci of the scapulohumeral girdle.

Sinovial bursae

- Contain synovial fluid
- Allow the tendons and muscles to slide over the bones and connective tissue or other muscles
- Facilitate choice of direction of a muscle or group of muscles
- Make muscle action more efficient by increasing the corresponding lever arm.

Marginal labra

- Are formed of fibrous cartilage
- Lack vessels and nerves
- Increase concordance between the articular surfaces (examples of these are the marginal labra that extend the glenoid and acetabular cavities).

Articular menisci

- Are formed of fibrous cartilage
- Lack vessels and nerves
- Improve articular concordance
- Act as shock absorbers
- Increase the articular surface
- They can be complete or incomplete.

Ligaments

- Are formed of numerous collagen fibers and scarce elastic fibers
- Have few vessels and nerves
- Their elongation does not exceed 20% of their resting length
- Are very resistant to traction, but not to torsion
- Reinforce the joint capsule
- Maintain articular concordance
- Precede muscle action
- Reduce muscle fatigue.

Connective tissue

- Is interposed between muscles and joint capsule
- Is rich in sensory receptors.

Classification of joints

Synarthrosis (continuity joints)

Syndesmosis (fibrous synarthrosis)
- Joining the articular surfaces through collagen or elastic fibers
- Examples:
  - interosseous membrane (between the radius and ulna)
  - proximal and distal tibiofibular joints
  - gomphoses (joint between tooth and bone)
  - sutures
  - ligamenta flava.

Synchondrosis (cartilaginous synarthroses)
- Joining the articular surfaces through hyaline cartilage
- Examples:
  - sternocostal joints (first, sixth and seventh rib)
  - bone metaphysis.

Symphysis (fibrocartilaginous synarthrosis)
- Joining the articular surfaces through fibrous cartilage and connective tissue
- Examples:
  - joint between the pubic bones
  - joint between the vertebral bodies (disc plus anterior and posterior longitudinal ligaments).

Synostosis (bone synarthroses)
- Consequence of bone fusion at the end of growth
- Examples:
  - joints between the pelvic bones.

Diarthrosis (contiguity joints)

Hinge joint (trochlea)
- Concave surface congruent with the convex surface
- 1 degree of freedom (flexion-extension)
- Horizontal rotation axis
- Examples:
  - humeroulnar joint
  - interphalangeal joints
  - knee joint.

Pivot joint (trochoid joint)
- Concave surface congruent with the convex surface
- 1 degree of freedom (external and internal rotation)
- Vertical rotation axis
- Examples:
  - proximal and distal radioulnar joints
  - atlantoaxial joint.

Condylar joint (ellipsoid joint)
- Concave ellipsoidal surface congruent with the convex ellipsoidal surface
- 2 degrees of freedom (flexion-extension and abduction-abduction)
- 2 rotation axes (horizontal and sagittal)
- Examples:
  - metacarpophalangeal joint
  - radiocarpal joint.

Saddle joint
- Ellipsoidal surfaces each with two curvatures – concave and convex (saddle)
- 2 degrees of freedom
- 2 rotation axes
- Examples:
  - carpometacarpal joint of the thumb.

Ball and socket joint (spheroidal joint)
- Partially spherical surfaces, concave and convex
- 3 degrees of freedom (all movements)
- 3 rotation axes
- Examples:
  - glenohumeral joint
  - hip joint.

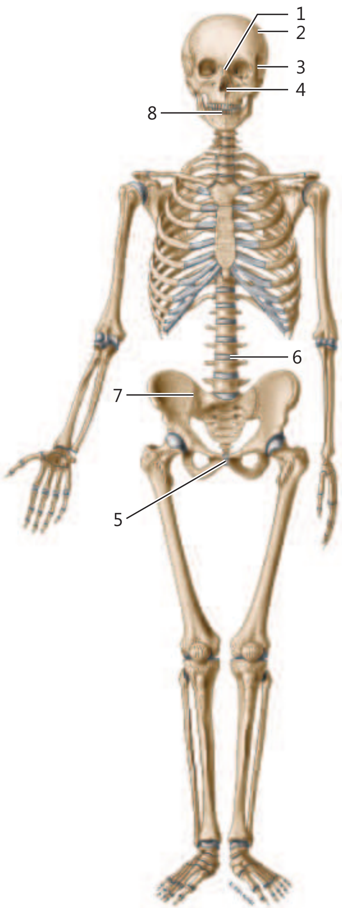
Plane joint
- Has no axes of movement
- The articular surfaces are mainly flat and irregular
- Allows limited sliding movements

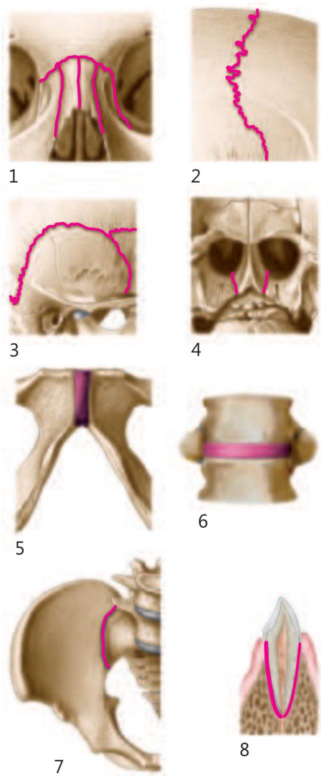
- Examples:
  - carpal joints
  - tarsal joints
  - sternocostal joints (second, third, fourth and fifth rib)
  - intervertebral joints.

Amphiarthrosis

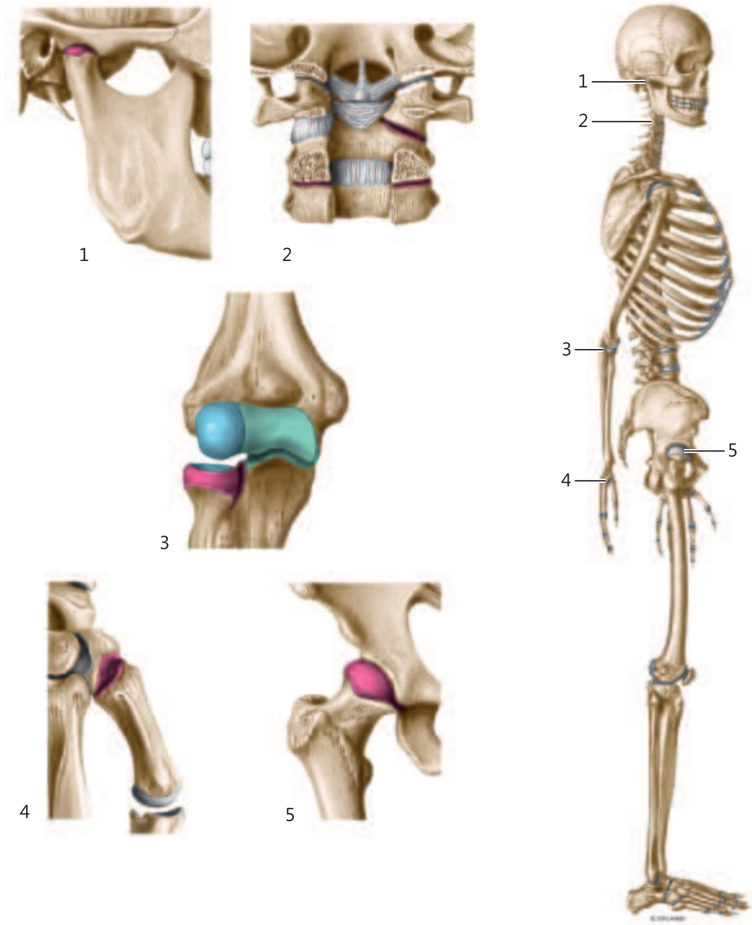
- Little mobility
- Very tense joint capsules and ligaments
- Poorly congruent articular surfaces
- Examples:
  - sacroiliac joint
  - proximal tibiofibular joint.

Main types of synarthrosis





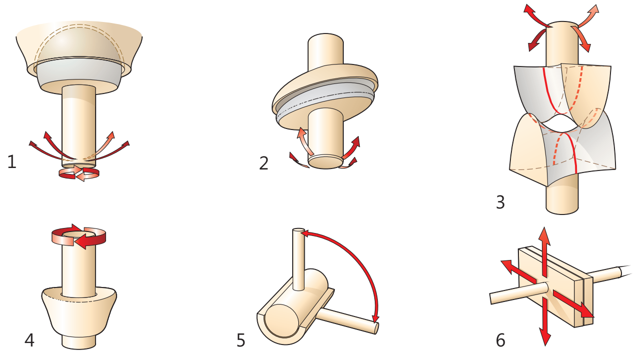
Main types of diarthrosis



Main types of *diarthrosis*: **1**, condylar joint; **2**, plane joint; **3**, pivot or trochoid joint (in *red*), hinge joint or trochlea (in *green*), condylar joint (in *blue*); **4**, saddle joint; **5**, ball and socket (or spheroidal) joint.

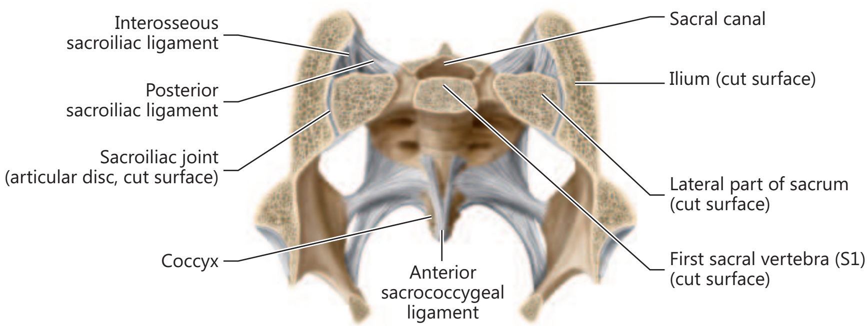
Main types of *synarthrosis*: **1**, plane suture; **2**, serrate suture; **3**, squamous suture; **4**, wedge-and-groove suture or schindylesis; **5-6**, symphysis; **7**, amphiarthrosis; **8**, gomphosis.

Articular surfaces of the diarthroses



Schematic drawing of the shape of the articular surfaces of the diarthroses: **1**, enarthrosis (semispherical shape); **2**, condylar joint (ellipsoidal shape); **3**, saddle joint (the two meeting surfaces are concave on one axis and convex on the axis orthogonal to it); **4**, pivot or trochoid joint (cylindrical shape); **5**, hinge joint (cylindrical shape); **6**, plane joint (flat surfaces).

Example of amphiarthrosis: sacroiliac joint



Transverse section passing through the first sacral segment showing the relations between sacrum and hip bones at the level of the sacroiliac joints.

Joint movements

See section "Reference system", page 47.

Kinematic chains

The arrangement of bones in series (typical of the limbs and vertebral column), in parallel (characteristic of the phalanges, metacarpal and metatarsal bones), in a group (such as the carpal, tarsal and pelvic bones), and the arrangement of the resulting joints, considered from a functional perspective, i.e., from the point of view of movements allowed, constitute a kinematic chain (the sequence of muscle actions constitutes a kinetic chain).

Characteristics of kinematic chains:

- degree of freedom (sum of the degrees of freedom of each joint in the chain)
- open kinematic chain (the distal joint is free in the space); examples include the limbs and vertebral column (an open kinematic chain appears closed when it is opposed by a force that acts against its movement, for example, the thrust of the ground against the load of the foot)
- closed kinematic chain (the chain is closed on itself; examples include the pelvis and the thoracic cage)

Kinematic chain of the upper limb

Joints*	Degrees of freedom
Glenohumeral or shoulder (ball and socket joint)	3
Sternoclavicular (double plane joint)	3
Acromioclavicular (double plane joint)	3
Scapulothoracic (pseudo joint)	1
Elbow (pivot or trochoid joint and hinge joint or trochlea)	2
Wrist (condylar joint)	2
Metacarpophalangeal (condylar joint)	2
Proximal interphalangeal (hinge joint or trochlea)	1
Distal interphalangeal (hinge joint or trochlea)	1
Total degrees of freedom of the upper limb	18

* Excluding the sternocostal and costovertebral joints.

Joints of the upper limb.

Kinematic chain of the lower limb

Joints*	Degrees of freedom
Hip (ball and socket joint)	3
Knee (hinge joint or trochlea)	2
Ankle (complex hinge joint)	2
Metatarsophalangeal (condylar joint)	2
Proximal interphalangeal (hinge joint or trochlea)	1
Distal interphalangeal (hinge joint or trochlea)	1
Total degrees of freedom of the lower limb	11

* Excluding the subtalar (talocalcaneal), transverse tarsal, tarsometatarsal and intermetatarsal joints.

Joints of the lower limb.

Both in the kinematic chain of the upper limb and in that of the lower limb, the number of degrees of freedom of each joint tends to decrease in the distal direction. As a result, gripping and manipulation are favored by the upper limb, also facilitated by the parallel arrangement of the phalanges and the metacarpals, whose joints can be moved individually. In the lower limb, however, the flexion-extension of the toes is total, favoring above all the transmission of the load to the ground.

Muscles

Definition: terminal elements responsible for the executive phase of movements.

Anatomical structure

Each muscle is formed of:
- connective tissue lining fascia (epimysium)
- muscle fibers, the number of which depends on:
  - size of the transverse diameter of the muscle
  - trophism of the muscle fibers
  - orientation of the muscle fibers
- supporting connective tissue layer (to the epimysium – the outermost connective tissue layer – are added the perimysium – which wraps groups of muscle fibers – and the endomysium – which covers each muscle fiber).

The muscle fasciae compact and protect the muscle fibers, giving them their elasticity, maintaining their trophism (through vessels and nerves that run along the fasciae) and preserving muscle tone.

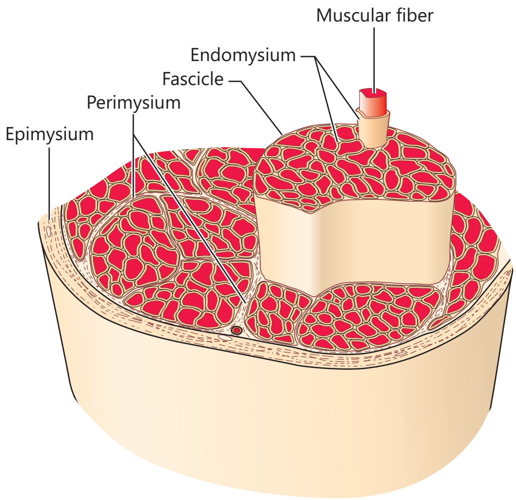


Diagram of the transverse section of skeletal muscle showing the connective tissue layer.

Each muscle fiber:
- has a diameter between 10 and 100 µm
- is coated in a connective tissue fascia (endomysium)
- is characterized by sarcoplasm (cytoplasm) and sarcolemma (plasma membrane)
- has a certain number of fibrils (myofibrils).

Each myofibril:
- has a diameter between 1 and 2 µm
- is formed of myofilaments (actin and myosin) that are contiguous to each other or in contact in relation to the functional state and aligned parallel to the axis of the muscle.

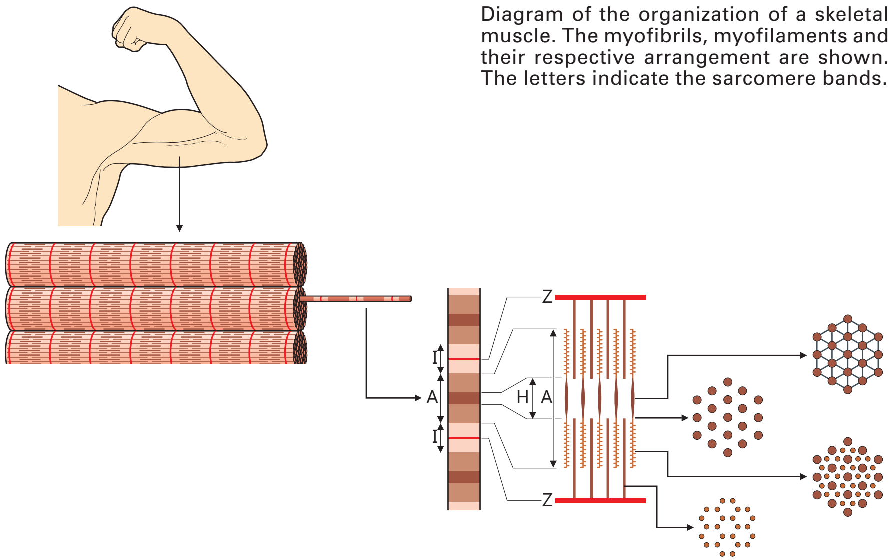


Diagram of the organization of a skeletal muscle. The myofibrils, myofilaments and their respective arrangement are shown. The letters indicate the sarcomere bands.

Ultrastructure of the myofibrils

The myosin filaments (formed of myosin molecules) are thicker and have pedunculated expansions (heads).
The actin filaments (formed of actin, tropomyosin and troponin molecules) are thinner.

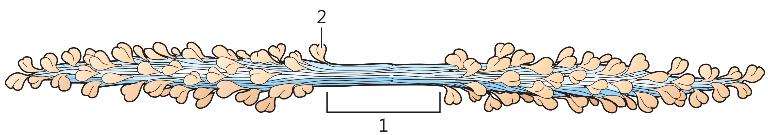


Diagram illustrating the arrangement of the myosin molecules within a filament (in this case a thick filament). **1**, Bare area; **2**, myosin heads (from VV.AA. *Citologia e istologia funzionale.* Milan, Edi.Ermes, 2005).

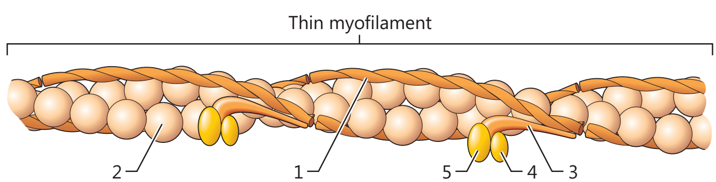


Diagram of a thin myofilament. **1**, Tropomyosin; **2**, actin; **3**, troponin A; **4**, troponin C; **5**, troponin T (modified from Colombo R, Olmo E. *Biologia della cellula.* Milan, Edi.Ermes, 2007).

Muscle contraction

During contraction, the heads of the myosin filaments bind to the actin filaments (with a cogwheel mechanism through which, when a head loses contact, this is achieved by the next one and so on until contraction ends).

Morphological and molecular events of muscle contraction

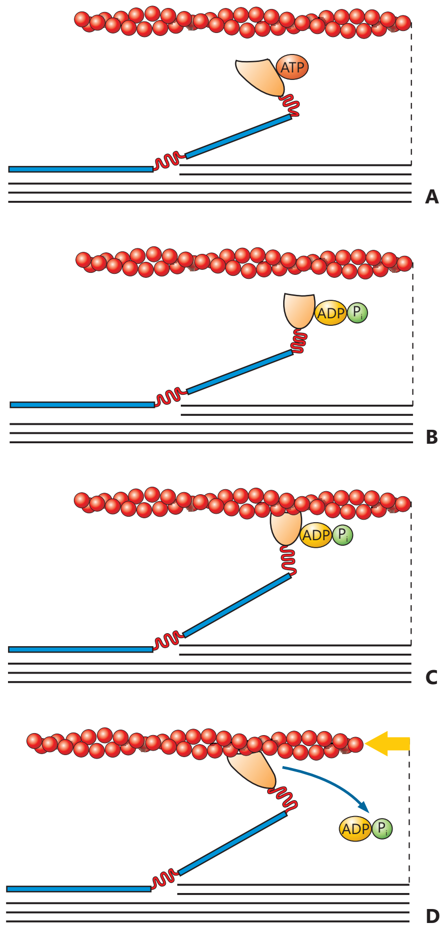
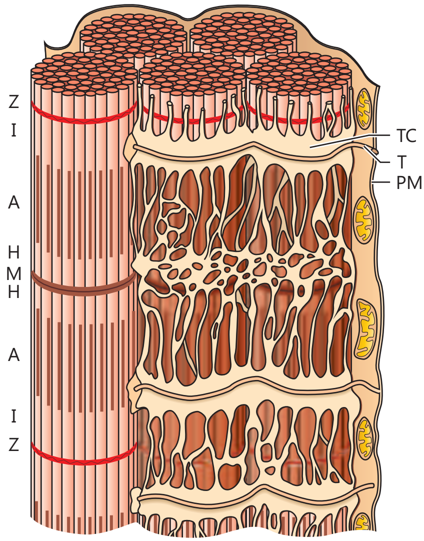


Diagram illustrating the relationship between "molecular events" and "morphological events" during muscle contraction. **A**, At rest, the myosin heads always bind to an ATP molecule; they are separated from the actin filament and form an angle of 45° with respect to the latter; **B**, with the arrival of calcium, the myosin heads hydrolyze ATP, exploiting the energy released to take on a 90° configuration with respect to the actin filament. The hydrolysis products, ADP and Pi, remain bound to the head; **C**, the myosin head (90°) binds to the actin filament; **D**, the actin/myosin bond favors the release of the ATP hydrolysis products from the myosin head. This allows the head to return to the 45° configuration. During the latter phenomenon, myosin pulls the actin filament towards the center of the sarcomere (modified from Rosati P, Colombo R. *Istologia.* 4th ed. Milan, Edi.Ermes, 2001).

The energy required for muscle contraction is derived from degradation of glycogen and from the oxidation reactions that lead to the formation of substances such as ATP and creatine phosphate.
During muscle contraction, chemical energy is transformed into mechanical energy.



Three-dimensional diagram of the arrangement of the sarcoplasmic reticulum in a skeletal striated muscle fiber. The letters on the left indicate the sarcomere bands. The plasma membrane (**PM**) forms tubular invaginations (**T**) in relation to which the terminal cisternae (**TC**) of the reticulum are associated. The association of two terminal cisternae and the interposed tubule **T** is called a "triad", and is always located between **A**-band and **I**-band.

Sarcomere

Observation of a muscle in longitudinal section shows transverse striations (hence the term striated muscle) known as bands or zones, produced by the particular alignment of the actin and myosin filaments.

The alternation of a light band (I-band), divided in half by a dark line (Z-line), and a dark band (A-band), divided in half by a light zone (H-zone), which in turn is divided in half by a dark line (M-line), can be observed.

The sarcomere (basic contractile unit or functional contractile unit) is bounded by two Z-lines, thus comprising an A-band and two I-semibands.

Activity of the muscle fibers

The transmission of the motor stimulus to the muscle, responsible for the excitation or inhibition of the muscle fiber activity, occurs through axons that originate from the motor neurons α and γ of the anterior horns of the spinal cord and from the cells of the somatic motor nuclei of the cranial nerves. Through the peripheral nerves, the axons reach the muscle fibers, with which they then come into contact through particular synaptic devices called neuromuscular junctions.

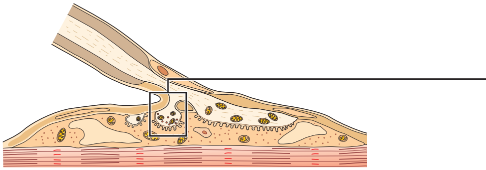
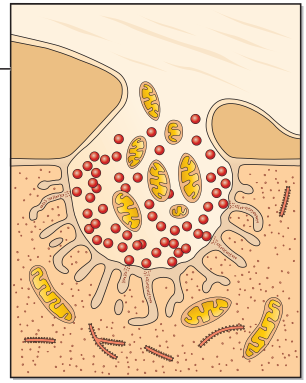
Neuromuscular junction

It is composed of:

- synaptic vesicles within the terminal part of the axon (synaptic bouton)
- presynaptic membrane
- synaptic space (cleft or gap)
- postsynaptic membrane.

When the synaptic terminal bouton is reached by a nerve impulse, the synaptic vesicles release acetylcholine into the synaptic space, which binds to the receptors of the postsynaptic membrane, causing a variation in their action potential (depolarization), which gives rise to the action potential that propagates to the system of sarcotubules and T-tubules. Sarcotubules are longitudinal canaliculi of the smooth endoplasmic reticulum of the sarcoplasm that give rise to the transverse cisternae called terminal cisternae, whereas the T-tubules are invaginations of the sarcolemma of the muscle fiber. This system of cisternae and canaliculi is in contact with the myofibrils.

Upon arrival of the depolarization wave, the transverse cisternae release calcium ions into the myofibrils, which activate the bond between actin and myosin. Acetylcholine, synthesized by choline acetyltransferase, is degraded by acetylcholinesterase immediately after

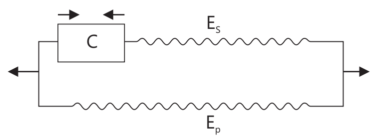
Schematic drawing of an expansion of the motor end plate showing its ultrastructural characteristics. Note that, unlike the synapse, the muscle fiber membrane (postsynaptic membrane) forms numerous invaginations. The synaptic space is also occupied by the basal lamina. The vesicles of the boutons on the motor end plate contain acetylcholine.

the arrival of the impulse, simultaneously with the reabsorption of calcium ions in the terminal cisternae through a calcium pump.

Mechanical muscle model

It expresses the relationship between muscle fiber and elastic structures, which are components of the connective tissue. The elastic structures are arranged:

- in series – tendons and their extensions inside the muscles
- in parallel – sarcolemma, connective fasciae and connective tissue interposed between muscle fibers.



Mechanical muscle model.

Function of the elastic structures:

- in series – to cushion the stresses produced by stretching and muscle contractions
- in parallel – to cushion the stresses produced by muscle stretching.

Representing the contractile elements with C, the elastic ones in series with Es and the elastic ones in parallel with E_p, if only C were present, after stretching, the entire process necessary for the contraction would be carried out only actively, thus requiring additional energy. The elastic contribution to muscle stretching allows a saving in contractile energy, due precisely to the elastic return of the muscle. In addition, E_s and E_p resist traction and muscle contraction by protecting the muscle internally.

Motor unit

It is the functional unit of the neuromuscular system, consisting of:

- motor neuron
- nerve fiber
- a variable number of muscle fibers innervated by the nerve fiber (from 5-6 to 1000-2000, almost always in the same muscle).

Muscle contraction is a process defined as the “all-or-none law”, in the sense that if the stimulus exceeds a certain threshold, the whole muscle will respond by contracting. This law is not always valid in the case of motor units; i.e., it may occur that not all the muscle fibers of a motor unit contract simultaneously. It is in fact possible that there is a difference in the threshold value between the muscle fibers (or the neuromuscular junctions) of a single motor unit.

The degree of precision of a muscle's movements depends on the ratio between muscle fibers to motor neurons of that muscle: the greater the number of motor neurons relative to the number of muscle fibers, the greater the degree of precision of the muscle (this is the case, for example, in the short muscles of the thumb and index finger).

In addition to the possible threshold difference within a single motor unit, there is a difference in the threshold between motor units, which are therefore distinguished into the following motor units:

- low threshold
  - with rapid rise in discharge rate (I)
  - with slow rise in discharge rate (II)
- high threshold
  - with rapid rise in discharge rate (III)
  - with slow rise in discharge rate (IV).

Muscular force (tension) depends on the number of motor units activated and their discharge rate. The threshold is the fundamental element for recruiting a greater or smaller number of motor units (and therefore muscle fibers) based on the amount of muscle effort required. In muscle activity, low-threshold motor nerve fibers are recruited first, followed by high-threshold fibers (the former have a greater discharge rate than the latter). The high-threshold fibers are recruited only when a high tension is required.

Motor neurons α (that innervate the extrafusal muscle fibers, i.e., the true muscle fibers, whereas motor neurons γ innervate the intrafusal muscle fibers, i.e., the fibers of the muscle spindle) of the anterior horn of the spinal cord are distinguished as:

- tonic α motor neurons (low threshold)
- phasic α motor neurons (high threshold)

It is the tonic α motor neurons that first activate the muscle fibers through the tonic α nerve fibers (being recruited before the phasic α one, due to the low threshold). However, the tonic α nerve fibers have a lower conduction velocity than the phasic α nerve fibers.

At birth, all the motor units are tonic (i.e., slow) and so are the corresponding muscle fibers, defined as red due to their histological staining. Over the course of development, in relation to the predominantly static or dynamic function of the muscle, they differentiate into phasic (or fast) motor units corresponding to white muscle fibers. Each muscle is therefore formed of red and white fibers, the numerical prevalence of which is related to the function it performs. For example, among the posterior muscles of the leg, the soleus, which has a predominantly postural function, is formed primarily of red fibers, whereas the gastrocnemius, more closely linked to dynamic functions, is formed primarily of white fibers. Among the muscles with a prevalence of red fibers is the diaphragm, which is characterized by its continuous and repetitive action.

Muscle function

The muscle function consists of moving, slowing and stopping a body segment.
The greater or lesser excursion of the body segment, in addition to the characteristics of the joint, depends on the biomechanical factors represented by:

- mass of the body segment
- moment of force
- action of the force of gravity.

(See Chapter 2 "Movements and biomechanics").

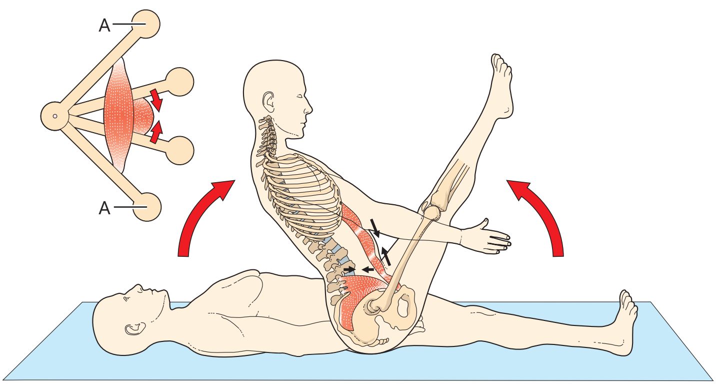
Muscular force

Contractile force, as well as neural factors (number of motor units activated and their discharge rate), depends on muscle factors represented by:

- reciprocity of muscle action
- type of muscle contraction
- shape and diameter of the muscles
- shortening (contraction), elongation (stretching) and contraction velocity of the muscle fibers
- muscle power
- moment of force
- angle of insertion of the muscle.

Reciprocity of muscle action

The body segments on which a muscle has origin and insertion tend to get closer during muscle contraction. This tendency due to the muscle action is called reciprocity and occurs when both body segments are free (not blocked).



Muscle reciprocity.

Type of muscle contraction

- Isometric (static):
  - resistance (opposed by the two muscle insertion heads) is equal to the force expressed by the muscle fibers

  - at the macroscopic level there is no variation in the length of muscle fibers (at the ultrastructural level there is shortening of the sarcomeres – contractile components – and elongation of the elastic elements in series)
  - the work is zero
  - the energy expended is used to balance the resistance produced by the body segment in question with the muscular force and is less than that used in concentric isotonic contraction and greater than that used in eccentric isotonic contraction.
- Concentric isotonic (in shortening):
  - the force exerted is greater than the resistance
  - the work is positive (movement occurs)
  - the energy expended is used to overcome the resistance and to shorten the muscle (therefore, it is maximal compared to isometric and eccentric isotonic contractions).
- Eccentric isotonic (elongation):
  - the force exerted is lesser than the resistance
  - the work is negative
  - the energy expended is used to slow and gradually stop the stretching of the muscle fibers (therefore, it is minimal compared to isometric and concentric isotonic contractions).
- Isokinetic (does not exist in nature):
  - resistance is self-adapting (i.e., an increased resistance is applied to the joint involved in the movement, taking into account the subject's ability to move the joint at a fixed velocity, which can vary gradually from 0 to 300-500 degrees/second; the velocity and resistance applied are established in relation to the subject's ability, assessed using computerized diagnostic-therapeutic tests; in normal human movement, resistance is fixed)
  - it is used for recovery from muscle deficits.

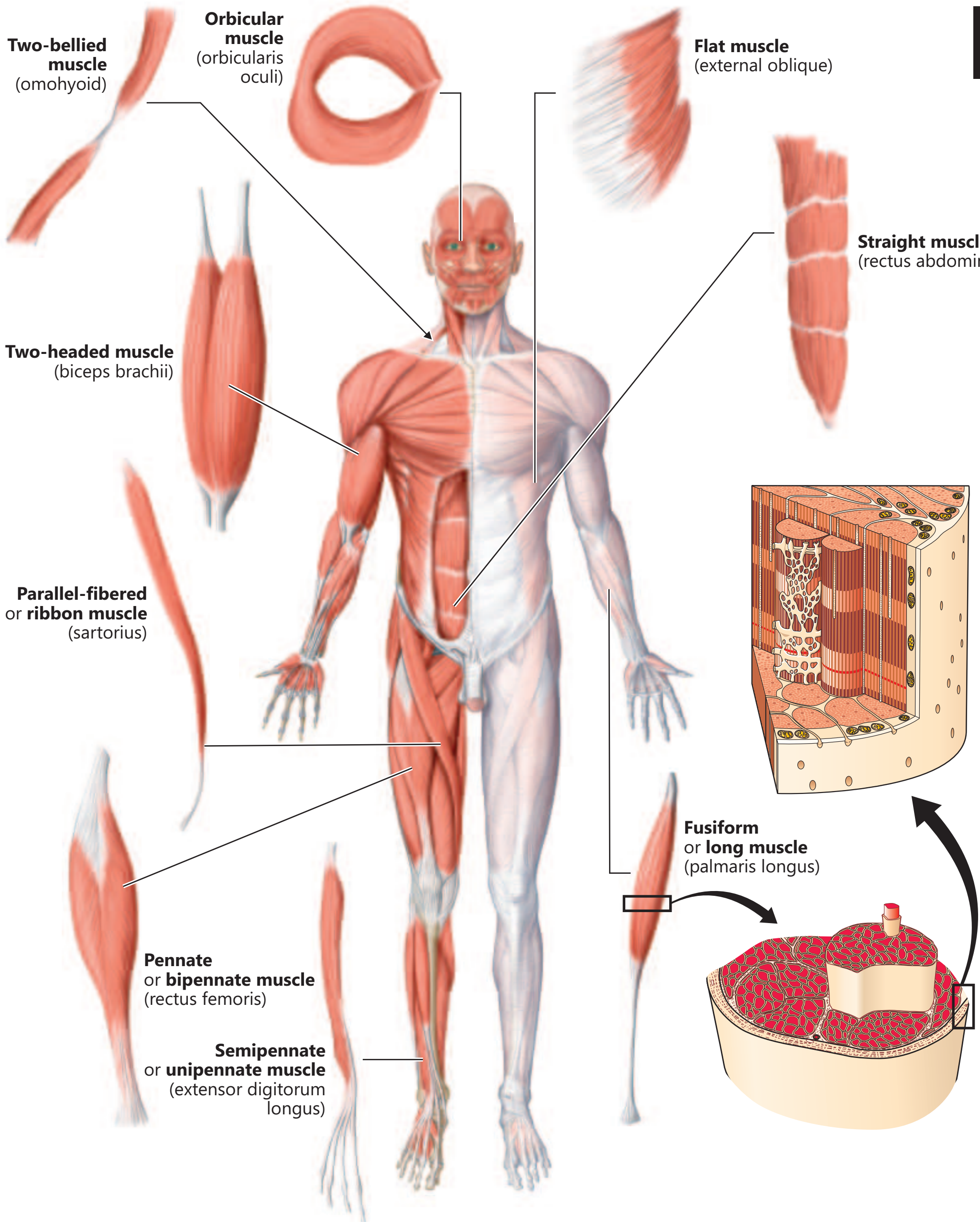
Shape and diameter of the muscles

The quality of muscular work almost always depends on the shape and diameter of the muscles.

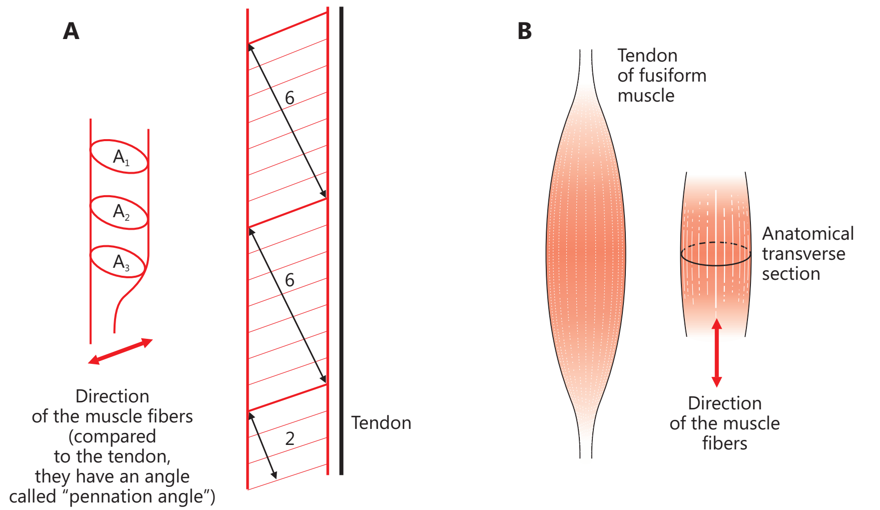
Shape of the muscles

- Parallel or fusiform fibers (greater shortening and elongation, lesser force) (examples: sartorius and biceps brachii)
- Oblique fibers (lesser shortening and elongation, greater force) (examples: gluteus maximus and acromial part of the deltoid) that can be divided into:
  - semipennate (or unipennate)
  - pennate (or bipennate)
  - multipennate
- Orbicular (example: orbicularis oculi)
- Fan-shaped (triangular) (examples: pectoralis major and pectoralis minor, gluteus medius)
- Multipennate (examples: serratus muscles)
- Straight fibers (examples: rectus abdominis and digastric)
- Quadrilateral fibers (four-sided) (example: quadratus lumborum)
- Multi-tendons (examples: biceps brachii, triceps brachii and quadriceps femoris).

The more muscle fibers a muscle contains, the more force it can exert (the greater force of the pennate muscles depends on the greater number of fibers they have, obtained thanks to the oblique orientation of the fibers).



Types of muscles according to their shape.



A, Semipennate muscle. Physiological transverse section: 6 + 6 + 2 = 14 x 2.5 = 35 cm^2. (**Note**: the mean muscle thickness is 2.5 cm). Trigonometry must be used for greater precision when indicating muscular force. **B**, Fusiform muscle. Anatomical transverse section: 3 x 3 = 9 cm^2. (**Note**: the mean transverse diameter is 3 cm).

Diameter of the muscles

The potential force of a muscle can be assessed from a quantitative point of view by two methods:

- measuring the diameter in anatomical transverse section:
  - this is only possible in fusiform muscles
  - the point of the muscle where the diameter has the greatest amplitude is selected (the area of the section is the square of the diameter)
- measuring the diameter in physiological transverse section:
  - in the pennate muscles and when it is not possible to measure the diameter at its mid-point
  - the sum of the length of the lines that cut the muscle fibers perpendicularly (the transverse section area is obtained by multiplying this data by the average thickness of the muscle, obtained from the anatomical section).

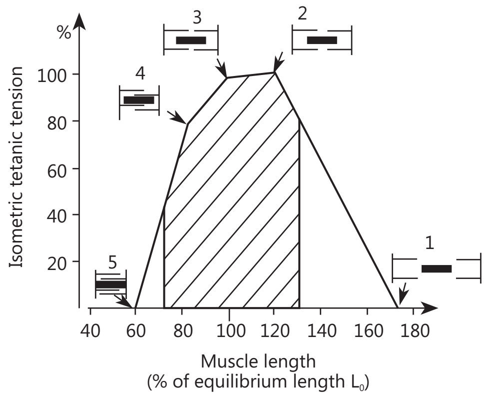
The muscular force, referring to diameter, is between 30 and 50 Newton × cm^2.

Shortening (contraction), elongation (stretching) and contraction velocity of the muscle fibers

The contractile function is influenced by the following mechanical properties of the muscle:

- stiffness (rigidity) – the muscle's reaction to elongation produced by the contractile (active) and elastic (passive) elements: it is directly proportional to the increase in elongation
- viscosity – the muscle's reaction to the contraction velocity and elongation for which small frictions between the elastic elements in series and large frictions between the contractile elements (actin and myosin filaments) are responsible: the former are propor-

Active tension/length curve. When the muscle has a length greater than 100% (L_0 = length of equilibrium of the isolated muscle) this depends on stretching. Stretching imparts a passive tension that has been subtracted. The curve therefore expresses the active tension developed by the muscle stimulated at various lengths (from Cremaschi D. *Fisiologia generale. Principî*. Milan, Edi.Ermes, 1996).



tional to the increase in contraction velocity, and the latter are not (the consequence of the viscosity is the dissipation of part of the energy used for muscle action).

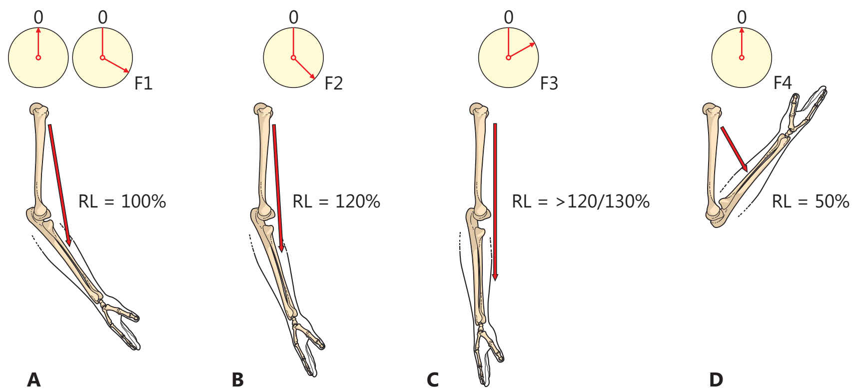
Tension/length curve

Stiffness is well highlighted by the tension/length curve, which relates the force applied with the elongation undergone by the fibers.

Elongation of the muscle from the resting length. In this case:
- muscle tension begins just after the resting length (when the muscle was previously elongated, the stimulus necessary for the contraction may be smaller)
- for values greater than 190% of the resting length, the muscle breaks.

Elongation of the muscle from 50% of the resting length, in the contraction phase (contraction is not possible below 50% of the resting length). In this case:
- for values between 50 and 100% of the resting length, tension is supported by the contractile structures (at 50% of the resting length there is an overlap of the actomyosin cross-bridges, which corresponds to a lower contractile efficiency)
- for values between 100 and 130% of the resting length, the tension is also supported by the elastic structures (the maximum number of actomyosin cross-bridges is determined at values equal to 120-130% of the resting length)
- for values greater than 130% of the resting length, the tension is supported only by the elastic structures (in fact, separation of the actin and myosin filaments occurs, with a reduction in the contractile force until it disappears)
- for values greater than 190% of the resting length, the muscle breaks.

The force exerted by a muscle is proportionally equal to:
- 0 for values 50% of the resting length
- 20 for values 100% of the resting length
- 25 for values 120% of the resting length
- 10 for values 120-130% of the resting length.



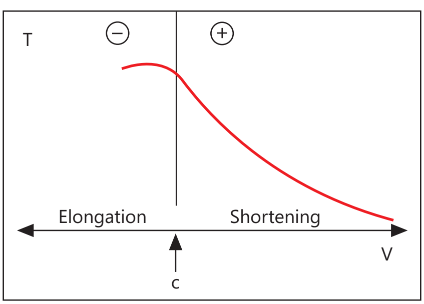
Extent of the forced exerted by the muscle stimulated to contract at four different starting lengths: **A**, at RL = its resting length; **B**, at 120% of its RL; **C**, at values greater than 120% of its RL; **D** at values equal to 50% of its RL. The extent of the different force values are obtained as a result of muscle electrical stimulation (neural factor) and the state of the elastic forces (mechanical factor). In the different quadrants above, the force can be verified (maximum in F2 and zero in F4).

Muscle tone

Definition: slight tension of the relaxed muscle fibers (with a length equal to the resting length) produced by the tension of the elastic elements in series and by intermittent active contractions in response to stresses such as palpation and passive mobilization.

Tension/velocity curve

It relates the force exerted by the muscle with the contraction velocity.



Tension/velocity (T/V) curve. *In the center* (c): zero overall muscle shortening velocity (isometric contraction). The contractile component is shortened, whereas the elastic component is elongated. *On the left*: the velocity is negative because the work is negative in the eccentric contraction. *On the right*: concentric contraction always exerts positive work.

Elongation (stretching) of the muscle:
- increased contraction velocity (eccentric) corresponding to an increase in tension, which then stabilizes.

Shortening (contraction) of the muscle:
- increased contraction velocity corresponding to a reduction in tension, until zero (i.e., the contraction force is reduced to the point of exhaustion).

The reduction in tension (contractile force) is due to the friction (viscosity) caused during sliding of the actin and myosin filaments (contractile elements). Therefore, a greater contraction force corresponds to a lesser contraction velocity.

Maintenance of the contraction velocity without reducing the contractile force is obtained by the intervention of non-muscular factors (neural) represented by:

- recruitment (spatial summation) – activation of an increasing number of motor units with the increase of the load to be sustained or overcome
- summation (temporal summation) – greater frequency of stimulation of the activated motor units (greater discharge rate or greater number of neural stimuli directed at the activated motor units)
- synchronization – greater number of muscle fibers activated at the same time (simultaneous activation of motor units that normally work asynchronously).

The simultaneous intervention of these factors allows efficient contraction for brief periods of time.

Muscle power

Definition: product of muscular force and contraction velocity (P = F × V).

The maximum muscle power (the greatest force and contraction velocity possible with minimum energy expenditure, i.e., the maximum function corresponding to optimal F and V values) is obtained for intermediate values of contraction and shortening velocity. It can be maintained by varying the contraction velocity in relation to the load:

- with small loads (lower F), V can be high (reduced V in the presence of small loads causes maintenance of F for very long periods)
- with large loads (higher F), V can be reduced (high V in the presence of large loads requires an excessive number of muscle fibers to be recruited and therefore more motor units to be activated).

Moment of force

The rigid body segment (bone), on which the muscle is inserted, which as a result of the muscle action rotates around one or more axes of the corresponding joint, constitutes a lever. The muscle insertion represents the point of application of the power (P) (which here assumes the simplest meaning of "muscular force"), the center of gravity of the body segment represent the point of application of resistance (R) and the axis around which the movement is carried out (usually the center of the joint) is the fulcrum (f). The distances from f of P and R constitute the P and R arms, respectively. The location of f in relation to P and R, with greater or lesser length of the P and R arms, conditions the muscular force (see sections "Forces", page 57, and "Lever", page 69).

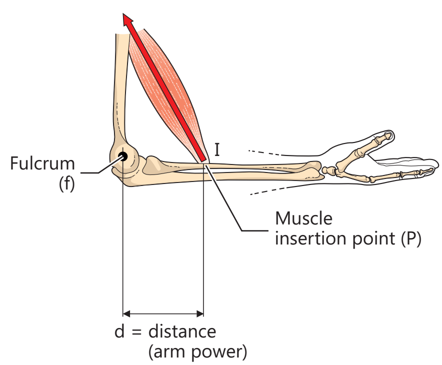


Illustration of the variation of muscular force according to the distance from the point of insertion.

Angle of insertion of the muscle

It is the angle formed by the axis of the muscle with the axis of the body segment of the insertion, of variable width during the various degrees of joint excursion. There are angles of insertion that depend on certain positions of the body segment in which the muscle is inserted, from which the movement can begin by improving the contractile capacity (see figure on page 24).
The muscle axis is the resultant force (A) of two component forces R (rotary or motor component, orthogonal to the body segment) and S (stabilizing component, directed along the axis of the body segment). Although each muscle has its own behavior, the biceps brachii can be taken as an example, for which, based on biomechanical analyses, when the width of the angle of insertion is:

- 0-45°, S tends to prevail
- = 45°, → S = R
- 45-120°, R tends to prevail (it is from these angles that it is convenient to start the contraction).

(See section “Lever”, page 69).

Muscle role

Definition: specific function assumed by a muscle (or by a muscle group) in relation to an aspect of the movement carried out.

Types of roles:

- agonist (motor or activator)
  - primary (examples: iliopsoas and rectus femoris, main hip flexors)
  - accessory (example: sartorius, which assist the flexion of the hip)
  - emergency (example: brachioradialis, innervated by the radial nerve, which intervenes in the flexion of the elbow when the other two main flexor muscles are unable to do so, for example, because of a musculocutaneous nerve injury)
- antagonist (muscle or muscle group that opposes movement, stopping it initially and then releasing it)
- neutralizer (muscle that neutralizes another muscle or its action to allow the execution of a movement; for example: the inhibition of the clavicular and spinal parts of the deltoid allows abduction of the shoulder)
- fixator (stabilizer: muscle that contracts isometrically by fixing one or more body segments to avoid destabilizing factors such as gravity, traction by other muscles or rebounds produced by very fast movements)
- support (general stabilization against gravity, especially in dynamic movements such as throwing a weight, kicking a ball, etc.)
- synergistic (muscle that works together with other muscles by fulfilling the same role as, for example, the agonist role in the flexion movement of the elbow).

Polyarticular muscles

Definition: muscles that cross multiple joints.

The amplitude of a movement can vary depending on the different positions assumed by the body segments of the affected joints.

Example: flexion-extension of the wrist and the digits of the hand (the movements of flexion of the hand and its digits, as well as the movements of extension of these body segments, are carried out by the same muscles). When the wrist is flexed whilst the fingers are flexed, the joint excursion of the wrist is reduced, as is the excursion of the metacarpophalangeal and interphalangeal joints when the fingers are flexed whilst the wrist is flexed. This occurs because the traction of the muscles is exerted both at the origin and at the insertion with:

- consequent shortening of the agonist muscles (state of active insufficiency due to incomplete contraction of the flexor muscles)
- consequent elongation of the antagonist muscles (state of passive insufficiency due to incomplete stretching of the extensor muscles).

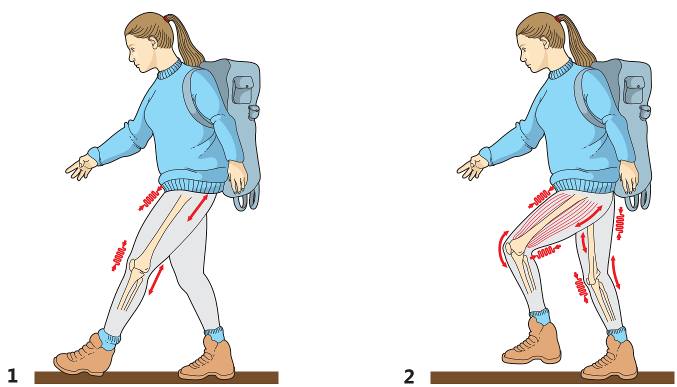
This tension mechanism, during both shortening and elongation, is defined as countercurrent (or non-cooperating).

However, if a joint is positioned contrary to the movement that the other joint(s) must perform, the movement carried out will be considered concurrent or cooperative. For example, using the extension of the wrist to fully flex the fingers, the flexion movement of the fingers will be facilitated through the defined concurrent mechanism. Instead, extending the fingers will facilitate flexion of the wrist. In this way there is alternation of tension between shortening and stretching (alternating between shortening and stretching in the two joints).

An example of concurrent and countercurrent mechanisms in walking occurs in the flexion of the knee associated with flexion of the hip and extension of the knee associated with flexion of the hip, respectively.

A further advantage of the polyarticular muscles (associated with concurrent mechanism) compared to monoarticular muscles is exemplified by movements of the lower limbs during walking, when the left leg (with hip and knee flexed) surpasses the right (with hip and knee extended). In this case there will be:

- left limb (concurrent mechanism) in the oscillatory advancement
  - rectus femoris – shortening at the hip and elongation at the knee (figure 1)



The right leg extended on the heel support, performing the countercurrent mechanism of both the rectus femoris (contraction of the two insertions) and the hamstring muscles (stretching of the two insertions), produces a state of active and passive insufficiency that leads, due to the excess tension caused, the leg to be brought back into knee flexion and hip flexion. = Elongated insertion. = Shortened insertion.

  - hamstring muscles (semimembranosus, semitendinosus and biceps femoris) – elongation at the hip and shortening at the knee
- left limb (countercurrent mechanism) when leaning on the heel (figure 2)
  - opposite situation compared to the previous position of the rectus femoris and hamstring muscles.

The gait movement (alternating the two limbs) occurs through the transfer of elastic and muscular tensions from the antagonist to the agonist and from one joint to the other, with considerable energy savings compared to the monoarticular muscles (2nd advantage of polyarticular muscles).

Biarticular muscles

Definition: muscles that cross two joints.

Biarticular muscles are characterized by two different force arms (related to the two joints they cross). The diversity of the two force arms allows one movement to be privileged over the other.

Examples: the hamstring muscles have a major force arm at the hip (6.7 cm) and a minor force arm at the knee (3.4 cm), favoring the extension movement of the hip over flexion of the knee. The rectus femoris, however, has a major force arm at the knee (4.4 cm) and a minor force arm at the hip (3.9 cm), favoring the extension movement of the knee over flexion of the hip. When the hamstring muscles and rectus femoris work together, it is easier to obtain extension of the hip and simultaneous extension of the knee rather than opposing movement.

Neural stimulation of muscle contraction

The excitability of muscle tissue in response to a neural stimulus is achieved through the production of an action potential at the level of the sarcolemma (plasma membrane of the muscle fiber) that, by propagating along the membrane, reaches the sarcotubule system (longitudinal canaliculi of the smooth endoplasmic reticulum that give rise to transverse cisternae) and T-tubules (invaginations of the sarcolemma of the muscle fiber) in contact with the myofibrils. It depends on:
- the adequate intensity of the neural impulse (corresponding to the threshold value or liminal value of excitation, i.e., the minimum intensity sufficient to produce the contraction), which can be achieved:
  - gradually (accommodation phenomenon), corresponding to a modest contractile action
  - quickly, corresponding to a greater contractile efficiency
- the sufficient duration of the neural impulse.

Simple muscle twitch

Definition: excitation of a muscle due to a single stimulus of short duration.

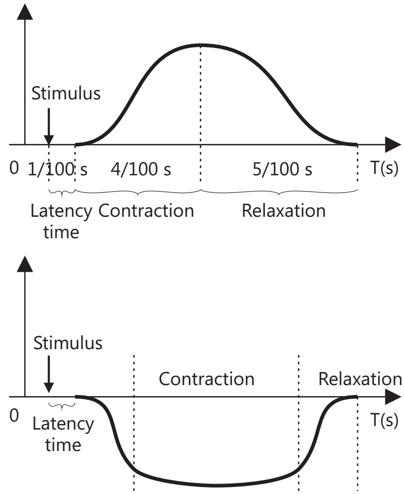
The duration of the simple muscle twitch is 5-10 hundredths of a second and can be subdivided into three phases:
- initial phase (mechanical latency) – time between the action of the stimulus and the beginning of the muscle contraction (1 hundredth of a second)
- contraction phase (4 hundredths of a second)
- relaxation phase (5 hundredths of a second).

The simple muscle twitch represents the lowest level of neuromuscular excitation. It corresponds to a minimal contractile force, which can be increased up to the maximum contractile capacity through:

- the activation of an ever-increasing number of motor units (recruitment of spatial summation)
- the greater stimulation rate greater of the motor units activated (temporal summation)
- the simultaneous activation of the motor units normally activated asynchronously: stimulation asynchrony consists of the alternate partial use of the muscle fibers during the execution of a movement (synchronization).

These mechanisms depend on:

- the refractory nature of the muscle fibers
- the discharge frequency of the neural stimuli.



Simple muscle twitch. Above, isotonic contraction. Below, isometric contraction.

Refractory nature of the muscle fibers

Definition: period of time in which the capacity of the muscle to respond to neural stimuli is diminished or hindered (it is included in the mechanical latency phase of muscle contraction).

It can be divided into:

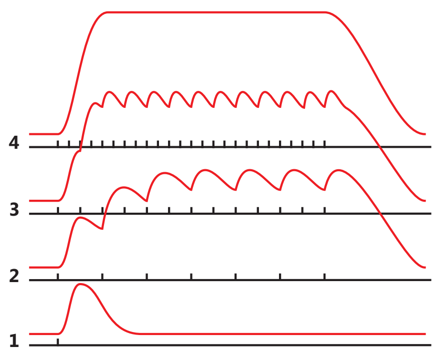
- absolute (the contraction is not possible even with maximal neural stimulus)
- relative (the contraction is possible only if the intensity of the stimulus is higher than normal due to an increase in the activation threshold).

Discharge frequency of the neural stimuli

Starting from a succession of simple twitches, the increase in the discharge frequency of neural stimuli may be such that the next stimulus is found:

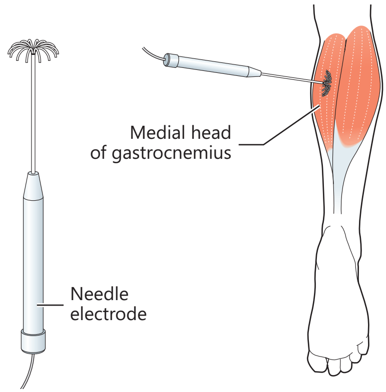
- in the relaxation phase of the muscle – incomplete tetany (frequency between 20 and 40 Hz; more frequent mode of muscle contraction)
- in the contraction phase of the muscle – complete tetany.

Note: The force developed in the tetanic contraction (4) is around twice that produced by the simple muscle twitch (1).



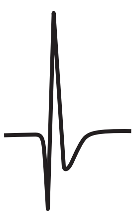
Isotonic myogram of: **1**, a simple muscle twitch; **2-3**, incomplete tetany; **4**, complete tetany. The stimuli are indicated in the abscissa.

Electromyography



Electromyography.

Definition: recording of the electrical activity of a muscle (at rest or during activity) expressed by the potential difference between an indicator electrode (needle electrode inserted into a muscle belly) and a reference electrode (fixed potential chemical electrode, consisting, for example, of a needle lining cannula).
The potential difference between the two electrodes is amplified and visualized by a cathode oscilloscope that can be connected to a camera that photographs the trace, a magnetic tape recorder and an amplification system for sound made audible by an external source.



Normal triphasic action potential of a motor unit.

Recording normal electrical activity

- The introduction of the needle generates a discharge potential that is rapidly extinguished (duration of 2-3 s)
- At rest, no electrical activity is recorded (electrically silent muscle).

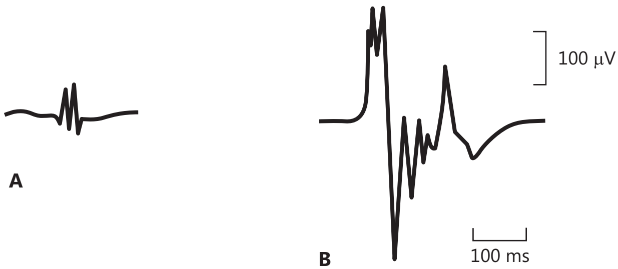
Slow voluntary contraction of the muscle causes activation of a reduced number of motor units with the onset of compound action potentials (resulting from the action potentials generated by all the muscle fibers of the activated motor units that are within the recording radius of the electrode), called motor unit potentials, represented by biphasic or triphasic waves.

Parameters of motor unit action potentials under normal conditions:

- variable in relation to muscle and age of the patient
- in general:
  - duration of 5-15 ms
  - amplitude of 0.2-2 millivolts
  - frequency of 5/s.

When the contraction force increases:
- the discharge rate of the individual motor units increases
- the number of motor units recruited increases, which corresponds to increases in amplitude and frequency of motor unit action potentials, maintaining the characteristics of biphasic or triphasic waves.

In case of maximum contraction, the number of motor units recruited is so high that, if the needle electrode is not very selective, it is no longer possible to distinguish the motor unit action potentials (interference trace).



A, Reduced motor unit action potential, of short duration, polyphasic, as often observed in myopathies. **B**, Motor unit action potential, long-lasting, polyphasic, that can be present in neuropathies.

Recording pathological electrical activity

Onset at rest (complete relaxed muscle) of:

- fibrillation potentials and positive pointed waves
- repetitive discharge complexes (in the case of denervation or muscle trauma, but also in the course of inflammatory myopathies)
- fasciculation potentials (in chronic neuropathies)
- myotonic discharges (in muscle tone disorders).

Motor unit action potentials:

- of short duration and polyphasic (in myopathies)
- of long duration and polyphasic (in neuropathies).

The electromyogram can detect motor unit abnormalities and characterized them as neurogenic or myogenic.

Electromyography of an individual muscle fiber

A needle electrode is inserted into the slightly contracted muscle on which a surface electrode has been positioned laterally to increase the recording area. The action potentials of two muscle fibers belonging to the same motor unit can thus be recorded. The time interval (latency) between the two potentials is constant in normal muscle and is called jitter (mean difference between consecutive interpotential intervals).

Jitter variability indicates the presence of an abnormality in neuromuscular transmission (myasthenia) resulting from impulse blockage at the neuromuscular junction.

Electromyography of an individual muscle fiber can also be used to:
- determine the mean density of the motor unit fibers (average number of muscle fibers per motor unit in the recording area)
- evaluate the number of motor units in a muscle.

Surface electromyography

Recording of the potential differences between the electrodes located linearly on the surface of a muscle with the onset of action potentials of different motor units.

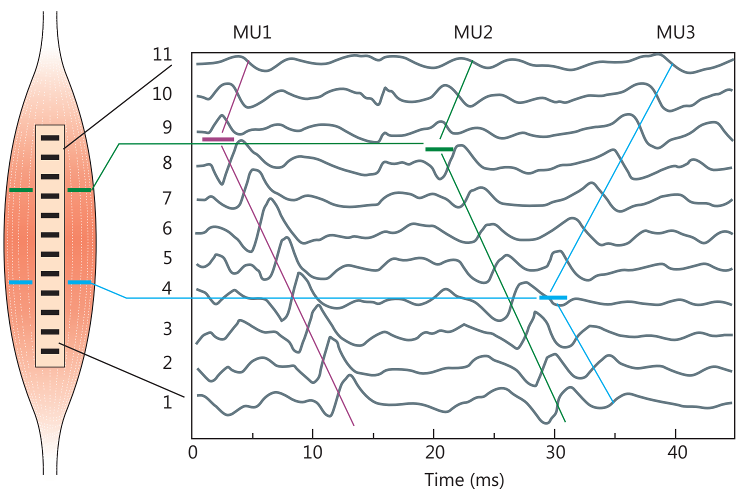
During the maximal voluntary contraction of a muscle (force increasing linearly from 0 to 100%), based on the onset of different action potentials that identify different motor units, it is possible to assess the phenomenon of motor unit recruitment and, more precisely, the type of motor units:

- always active
- recruited at low contraction levels
- recruited at high contraction levels.

By extrapolating each motor unit potential from the overall signal recorded on the skin, it is possible to calculate the motor unit conduction velocity. During a contraction sustained over time, this can be maintained only for a certain period, after which there is a decrease in force (mechanical fatigue). The point of decline in force is preceded, among other things, by a reduction in the motor unit conduction velocity, which is related to the prevalence of type II (fast) fibers over the type I (slow) fibers. Surface electromyography can indicate the composition of muscle fibers during endurance effort.

In general, surface electromyography provides information on:

- moment, duration and extent of the activation of one or more muscles during movement
- overall activity of a muscle or muscle group
- anatomy and geometry of superficial motor units.



This image shows 11 recordings obtained from a linear series of 12 electrodes placed at a distance of 5 mm from each other on the surface of the biceps brachii during a low-level contraction. The traces show three different action potentials attributable to three different motor units (MU).

Muscles most frequently subjected to electromyography

Head and neck
- Frontal
- Masseter
- Orbicularis oculi
- Orbicularis oris
- Sternocleidomastoid
- Temporal

Intrinsic muscles of the vertebral column
- C5-C6
- C6-C7
- C7-T1
- L2-L3
- L3-L4
- L4-L5
- L5-L1

Shoulder and trunk
- Deltoid
- Serratus anterior
- Latissimus dorsi
- Pectoralis major
- Rhomboid major
- Teres major
- Infraspinatus
- Supraspinatus
- Trapezius

Arm
- Abductor pollicis longus
- Biceps brachii
- Brachialis
- Brachioradialis
- Extensor pollicis brevis
- Extensor digitorum
- Extensor indicis
- Extensor carpi radialis brevis
- Extensor carpi radialis longus
- Extensor carpi ulnaris
- Flexor digitorum profundus
- Pronator quadratus
- Flexor carpi radialis
- Flexor digitorum superficialis
- Flexor carpi ulnaris
- Pronator teres
- Supinator
- Triceps brachii

Hand
- Abductor pollicis brevis
- Adductor pollicis longus
- Abductor digiti minimi
- Flexor pollicis brevis
- First dorsal interosseous

Pelvis
- Gluteus maximus
- Gluteus medius

Thigh
- Biceps femoris
- Rectus femoris
- Sartorius
- Vastus lateralis
- Vastus medialis

Leg
- Extensor digitorum longus
- Gastrocnemius
- Peroneus longus
- Soleus
- Tibialis anterior

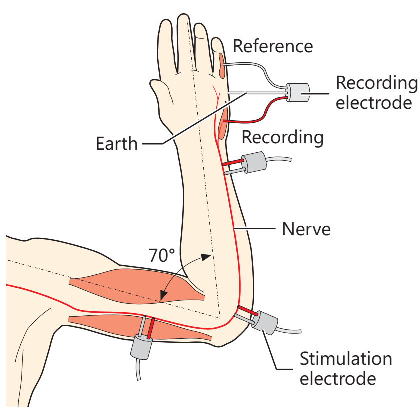
Foot
- Abductor digiti minimi
- Abductor hallucis
- Extensor digitorum brevis

Study of the motor nerve conduction velocity

Definition: recording of the electrical response of a muscle (muscular action potential) to stimulation of its motor nerve fibers in two or more points along their course.

Two or more stimulation electrodes are used, each at a different point of the nerve, and a recording electrode in the innervated muscle (surface electrode).

Motor conduction velocity: relationship between the distance (s) between two stimulation sites and the difference between the two corresponding muscular action potentials, given by the difference ($\Delta t_1 - \Delta t_2$) be-

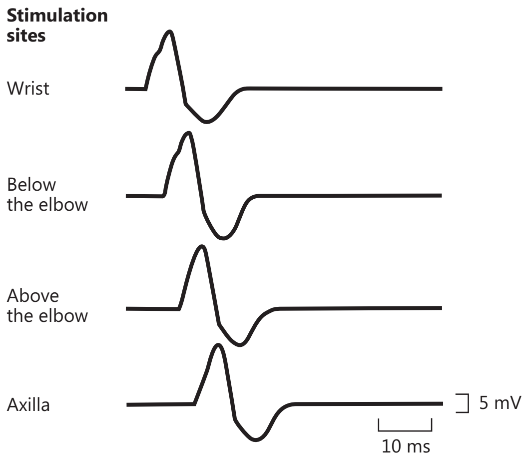


Recording of the electrical response of a muscle to stimulation of the motor fibers.

tween the proximal interval (latency) (Δt_1) and the distal interval (latency) (Δt_2) of the action potential (the value obtained is compared with the normal reference values stable for the majority of nerves tested).

Amplitude of the action potential

The amplitude of the muscular action potential is measured by applying the recording electrode (surface electrode) over the muscle and stimulating (through stimulation electrodes) the motor fibers of the nerve at different frequencies or in different locations.



This image shows the action potential of an abductor digiti minimi recorded after high-frequency stimulation of the ulnar nerve in different locations.

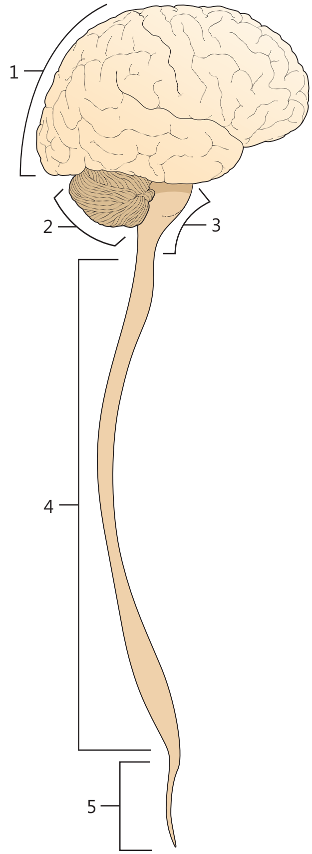
More commonly studied nerves

- Accessory nerve
- Axillary nerve
- Lateral cutaneous nerve of the thigh
- Facial nerve
- Femoral nerve
- Median nerve
- Musculocutaneous nerve
- Fibular (or peroneal) nerve
- Plantar nerve
- Radial nerve
- Suprascapular nerve
- Sural nerve
- Tibial nerve
- Ulnar nerve

Models to study movement

In the past hundred years, many researchers have contributed to models to study movement derived mainly from analyses of neuropsychology. The most important schools that have dealt with movement are, in chronological order:
- behavioral school
- cognitive school
- ecological school.

None of these models can be considered outdated. The applications of each of these schools, in both sports and rehabilitation medicine, are sometimes alternative or complementary depending on the subjects, the type of exercise and/or pathology to be treated.



General lateral view of the central nervous system. **1**, Brain; **2**, cerebellum; **3**, brainstem; **4**, spinal cord; **5**, filum terminale.

Behavioral model

It has been developed and disseminated in the first fifty years of the 20th century.
Main proponents:
- in USA: E.L. Thorndike, J.B. Watson, C. Hull, E.C. Tolman, B.F. Skinner
- in Russia: I.P. Pavlov.

Theories and methods

It answers the question: what?
Since the neurophysiological and emotional phenomena underlying autonomous movement or in response to environmental stimuli that can determine or favor it are not objectively verifiable, it is possible to verify or induce an action only through what is visible or comparable. In fact, the behavioral school does not deal with the modalities in which a movement can be performed.

Examples
- Pavlov’s “conditioned movements”: after switched on a light bulb, a dog was usually given a steak. The repetition of these two modalities induced the animal to always expect a steak after switched on the light bulb, so it reacted with salivary hypersecretion even if after the light stimulus the food did not appear.
- Mutilations to experimental animals in parts of the central nervous system (CNS) to verify correspondences between the site of injury and peripheral damage.
- Thorndike and Skinner’s programs related to the theory of “positive and negative reinforcement”, which are followed by different behaviors by subjects to whom they are applied (operant conditioning). Operant conditioning differs from Pavlov’s “classical conditioning,” in which the organism’s action is a response to a stimulus, in that it represents “an operation that the organism performs on the environment in view of a purpose... it can be regarded as

a form of behavioral therapy where the therapist rewards or reinforces with his/her attitude certain speech or actions of the patient that are in line with the desired behavior" [1].

Cognitive model

It emerged in the 1960s largely replacing the behavioral model.
It has its origins in cognitive psychology and neuropsychophysiology studies.
Main proponents:
- in Russia: P.K. Anochin, N.A. Bernstein, A.R. Luria
- in USA: J.A. Adams, F. Bartlett, S.W. Keele, S. Miller, U. Neisser, etc.
- in Switzerland: J. Piaget.

Theories and methods

It answers the question: how?
For cognitivists, it is important to research and evaluate, in a straightforward manner, what underlies the movement, that is, "what are the processes that the nervous system implements to carry it out and which of these processes need to be strengthened to achieve the best results". Therefore, cognitive functions are important: memory, language, attention, perception, space-time orientation, reaction times, motor skills, etc. These functions can interact in the environment using information received from sensitive and sensory structures, such as: vision, hearing, touch, proprioceptive receptors, etc. The result is, for the athlete, an optimal use of his/her motor skills and, for the disabled person, a better reorganization of his/her impaired motor skills.

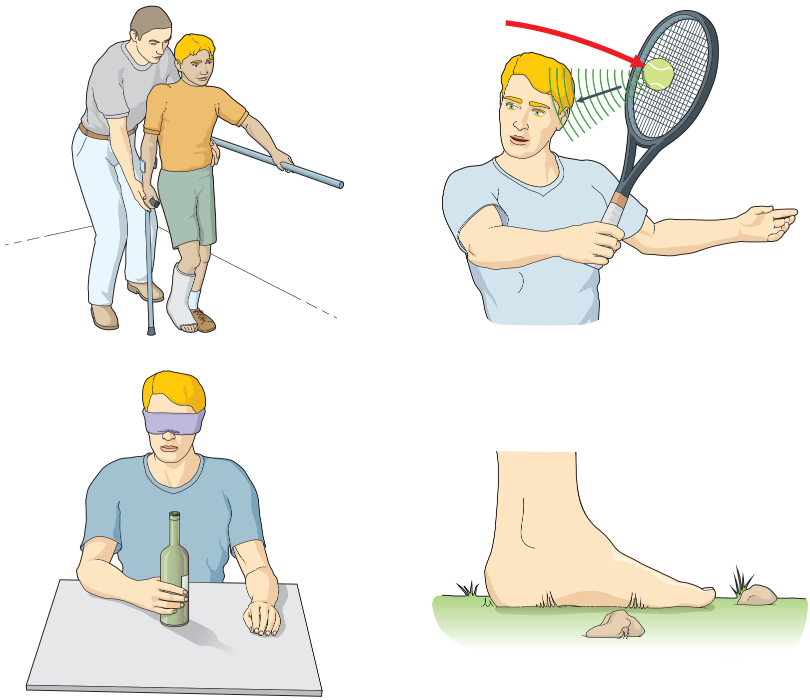
Examples
- In rehabilitation, an example of the use of cognitive theories is "the cognitive therapeutic exercise" by the Italian C. Perfetti.
- In sport, the best-known example involves teams of experts associated with large teams whose aim is to sharpen neurosensory skills, with particular regard to vision, to make gestures and actions more effective in a specific sport and/or in a particular role the athlete plays in that sport.

The phases of the movement are divided into:
- perceptive (or afferent synthesis)
- organizational
- execution.

The *perceptive phase* is divided into two stages:
- perception of the stimulus
- identification of the stimulus.

A stimulus can be internal, for example, when a thought activates a decision. Examples of external stimuli, whose response can still make use of internal data contained in the individual's memory, are:
- the sound produced by the racket hitting the ball alerts the tennis player to the imminent arrival of the opponent's response

[1] Galimberti U. *Dizionario di Psicologia*. Utet ed.; 2006.



Perception of the stimulus.

- the carrier of a lower limb injury often also acoustically evidences an "escape limp" by showing a faster and acoustically sharper half-step than that of the healthy limb
- manipulating an object in the dark still allows to perceive its shape, consistency and weight
- by placing the feet on a ground, information is obtained regarding the friction that characterizes it: soft, firm, hard, slippery, etc.

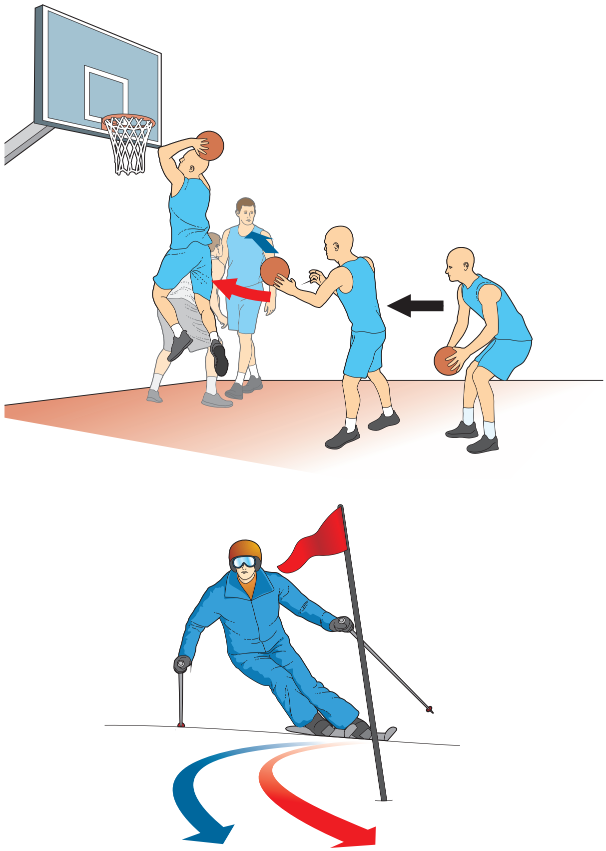
In this way the stimulus is first perceived, then identified.
It should be noted that the speed of perception and identification depends on:
- filtering of stimuli (attentiveness)
- identification of the most important information (ability to choose).

The *organizational phase* is divided into two stages:
- choice of the motor response
- programming of the response.

The choice answers the question, "what to do?"

Examples

- In volleyball and basketball, the choice can be between passing the ball to a teammate or shooting towards the goal.



Choice of motor response.

- In skiing, the decision can be to make a wide or narrow turn or to stop.
- In contact sports (boxing, karate, fencing, etc.) the choice can be to attack, retreat or defend.

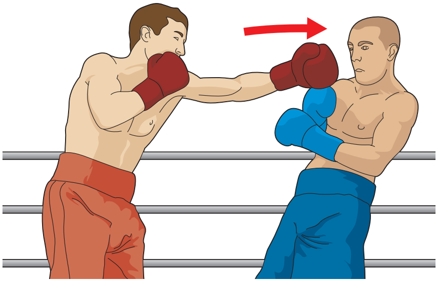
The programming answers the questions, "how and when to do?"

Examples
- In basketball, it is decided when and how to pass or shoot to the basket.
- In contrast sports, it is chosen when and how to stop, hit or retreat.

The *execution phase* represents the realization of the motor act.

Reaction time and movement time

Reaction time (RT): represents the time interval between the moment the stimulus is presented to the subject and the start of the movement. A premotor or cognitive reaction time (PRT) and a motor reaction time (MRT) can be distinguished.



MT (movement time) very short.

Movement time (TM): is the interval time between the beginning and the end of the movement.

Total time (TT): is the time required to execute the response to a stimulus. It is given by the sum of RT + TM.
During PRT, nothing is still happening at the muscle level.
The MRT is signaled by the EMG detected at the level of the muscles responsible for executing the response. It indicates the start of neuromuscular activity that is not yet visually evident as movement. It is, in fact, the tension due to anticipatory (feedforward) muscle actions.

In many sports, and in particular motor situations, such as in contract sports and penalty kicks, there are TMs so fast that the RTs are too long to be able to respond with the same speed. So almost always the response relies on chance.

In rehabilitation, speed turns less importance even if the final and possible goal is still to improve it. It should be kept in mind that, in the case of peripheral injuries not caused by CNS damage, the most frequent impediment is related to pain and, if the injured site is in the lower limbs, also to the fear of falling. In damage caused by CNS injuries, however, the entire movement system is unstructured.
The latter condition is far more serious. The most classic example is hemiplegia (paralysis of half of the body) where, due to the destructuring of the CNS and PNS (peripheral nervous system), there are at least five penalizing conditions, namely:
- total or partial deficit on the affected side
- postural tone abnormality on the affected side
- central loss of general movement patterns
- psychological deficits related to the patient's new situation
- slowing down or/and abnormal responses of RT, PRT, MRT, MT.

The task of the rehabilitation team will be to:
- adapt to the patient's RTs and MTs
- avoid the acceleration of his/her time
- promote a recovery that aims at a gradual autonomy through voluntary and conscious movement patterns that, before the injury, were mainly automatic and unconscious.

Movement realization according to the cognitive school

PHASES **of the movement**	**TIMES** **of the movement**	**ANATOMICAL SITES** **of origin of movement**
Perceptive phase **1** Perception of the stimulus ↓ **2** Identification of the stimulus ↓	**Total time (TT)** *Reaction time* (RT) Cognitive or premotor reaction time (PRT) ↓ Motor reaction time (MRT) detectable at EMG	**Sensitive** *Central sites*: occipital cortex, temporal cortex, parietal cortex (areas 3-1-2...), limbic system (mental impulses) *Intermediate central site*: thalamus *Peripheral sites*: receptor structures of eyes (70-80%), ears, skin, muscles, tendons, joints...
Organizational phase **3** Choice of the answer ↓↑ **4** Programming of the answer	*Movement time* (MT)	**Organizational** *Central sites*: – premotor cerebral cortex (area 6) – cerebellum – extrapyramidal systems – hippocampus, mammillothalamic tract and opposite hemisphere (for the evocation of data from motor experiences) *Peripheral sites*: the same as those indicated above
Execution phase **5** Execution of the answer		**Motor** *Central sites*: – motor cerebral cortex (area 4) – cerebellum (only through the cerebral cortex) – extrapyramidal systems – medulla oblongata – pons – spinal cord *Peripheral sites*: – peripheral axon – motor plate – muscle fiber

Note - From the "ontogenetic" point of view, it should be remembered that the prefrontal regions mature late: from 4 to 7 years. "Phylogenetically" these regions have a strong development in humans: they are more than a quarter of the brain.

Ecological school

It emerged in the 1970s.
Main supporters:

- J. Gibson, M. Turvey, P. Kugler, J.A.S. Kelso and, for Italy, L. Grimaldi.

Theories and methods

Main observations of the ecological school:

- the CNS has too many tasks to deal in detail with all aspects of movement. Its main function is to deal with thinking, that is, with ideas, theories, programs
- the memory (computer hardware) of the CNS is too limited to intervene in both individual muscles and individual movements. Just think of how many muscles are part of our locomotor system and all the possible variations during their use
- the CNS uses the reflex to perform the movements, and the stretch threshold of the muscle is independent of the central commands that go to the motor neurons α and γ
- there is an equilibrium point (EP) in the various muscle groups that depends on the joint excursion achieved during movement and the degree of tension present at the level of the muscles
- there are various activation thresholds in the muscle, which should be viewed as a spring. A first stretch may simply deform the muscle without it reacting. A second elongation may cause the typical "spindle reflex," which is a phasic contraction of short duration. Further stretching causes more resistance called the tonic stretch reflex
- from the idea that the brain does not know the muscles but the movements, it has passed to the hypothesis that the brain does not know the movements but the objectives to be achieved, therefore, it must be assumed that the neural architecture of the CNS possesses, especially at the spinal level, all the details of knowledge useful for carrying out the different muscle kinetics
- cognitive afferences of the cognitivists and behaviorists should be interpreted not as fundamental factors of movement, but only as elements that facilitate it.

Postural control

There are two main models to refer to when discussing postural control: the feedback model, which implies the activation of strategies when moving away from an ideally correct posture, and the feedforward model, which instead predicts that voluntary movements that determine an alteration of the ideal posture are anticipated, in turn, by postural adjustments that compensate for these deviations [1].

The feedback model is fundamentally based on two theories.

According to the first, postural control would be fundamentally conditioned by a single predominant variable (such as the position of the center of mass, or the orientation of the longitudinal axis of the body); if this predominant variable deviates from what is preprogrammed in terms of position in space, the motor centers are activated, which in turn compensate for the deviation with a motor response.

The other theory hypothesizes instead that posture is somehow determined and conditioned by a series of reflex activities and by an innumerable series of interactions between these reflexes (vestibular, visual, somatosensory in origin): this reflex activity may have convergent components to the determination of the posture itself or divergent components.

The postural system normally functions as a functional unit, with a main characterization for the associated control of the head and trunk. However, under certain conditions, the system clearly dissociates into subsystems the control of these two segments, and it now also seems to be well established that the two body antimeres may have separate control as a function of lateralized sensory input.

A similar situation seems to be established in the cat for the anterior part of the body compared to the posterior.

These data are difficult to explain within the framework of the hypothesis of control over a single predominant variable; instead, it is possible to hypothesize that a complex system of reflex activities independently controls different portions of the body.

A similar functional organization is present in quadrupeds at the level of the locomotor system, where the pectoral (shoulder) girdle and the pelvic girdle have autonomous control mechanisms, even with respect to the most distal control of the four limbs: thus, an extremely complex system is configured, capable of responding in a decidedly timely and precise manner at the segmental level.

This organized model ensures, on the one hand, the optimization of the response to destabilizing stimuli with respect to ideal postural alignment and simultaneously their self-amplification: in fact, it has been suggested that a control system consisting of semiautonomous subsystems better adapts to the complex of environmental conditions and stimulations [2].

Control optimization would then be ensured by a model that can be functionally considered an outgrowth of feedback or feedforward systems: the central nervous system would be able to control instantly with a response that is not pre-established, but rather correlated and parameterized to the destabilizing stimulus in place: learning would then guarantee, for a portion of the repeated responses, the anticipatory capacity in counteracting a destabilizing stimulus when it has already been experienced and known.

It is reasonably to say that good postural alignment can reduce incongruous overloads on the joint support surfaces and periarticular soft tissues, thus preventing natural responses to misalignment, such as increased stiffness and decreased muscle strength.

In addition, there is no incontrovertible speculative certainty that an imperfect muscular alignment can be the cause of some symptomatology: a much-discussed topic in recent years is, for example, the relationship between malocclusion and postural problems; some authors have demonstrated their coexistence, while in many clinical studies there is no proven correlation [3].

More generally, generic associations between postural attitudes of non-adjacent segments of the body (cervical spine/anterior cruciate ligament) have been demonstrated, and some studies based on mathematical examples have highlighted the possibility that alterations in the position of one segment may cause similar problems for an adjacent segment [4].

Another topic with a strong epidemiological impact is certainly low back pain: even for this pathological condition, there are conflicting results regarding the search for an incontrovertible relationship between symptomatology and posture alteration.

Although there is a plausible relationship between the position of the head of the femur, pelvic tilt and decreased lumbar lordosis, there are strong doubts as to whether the alteration of these relationships is a causal factor for low back pain. Finally, more certainty seems to be in studies on the lower limb between static tibial alignment and patellofemoral pain syndrome or excessive pronation of the subtalar joint and between some foot pathologies (cavus and/or planus) and pathologies due to overload of the lower limb.

Thus, it cannot be certain about the causal factors of postural defect (asymptomatic deviation, only morphological, from ideal postural alignment) and even less of the postural dysfunction (which may be consequent to a prolonged state of postural defect, characterized by the presence of structural alterations and pain): although without any certainty, it is not possible to exclude that, in some subjects, asymmetries between body segments may be identified as the main causes of symptomatology.

[1] Deliagina T, Zelenin P, Beloozerova I, et al. Nervous mechanisms controlling body posture. Physiol Behav 2007; 92(1-2): 148-54.
[2] Gelfand IM, Zetlin ML. On the mathematical modeling of mechanisms of the central nervous system. In: Gelfand IM, Fomin SV, Zetlin ML, eds. Models of the structural and functional organization of certain biological systems. Cambridge (MA): MIT Press; 1971: 2-23.
[3] Ben-Bassat Y, Yitschaky M, Kaplan L, Brin I. Occlusal patterns in patients with idiopathic scoliosis. Am J Orthod Dentofacial Orthop 2006; 130(5): 629-33.
[4] Berthonnaud E, Dimnet J, Roussouly P, Labelle H. Analysis of the sagittal balance of the spine and pelvis using shape and orientation parameters. J Spinal Disord Tech 2005; 18(1): 40-7.