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Ministry of health of the Russian Federation

Department of Traumatology and Orthopedics

Anatomy and physiology of the musculoskeletal system

Educational and methodical manual for students

Traumatology and orthopedics

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«APPROVED»

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Lesson №2.

" Anatomy and physiology of the musculoskeletal system".

The purpose of the lesson.

To introduce students to the anatomy and physiology of the musculoskeletal system.

At the completion of this practical lesson, the student should KNOW:

1. The various types of biological tissue o the musculoskeletal system.
2. Structure and mechanics of muscles, tendons, fasciae, and ligaments.
3. The different types of joints and their various characteristics.
4. The planes of the body, the body's center of mass, the axes of the body
5. The motions of the body

At the completion of this practical lesson, the student should BE ABLE to:

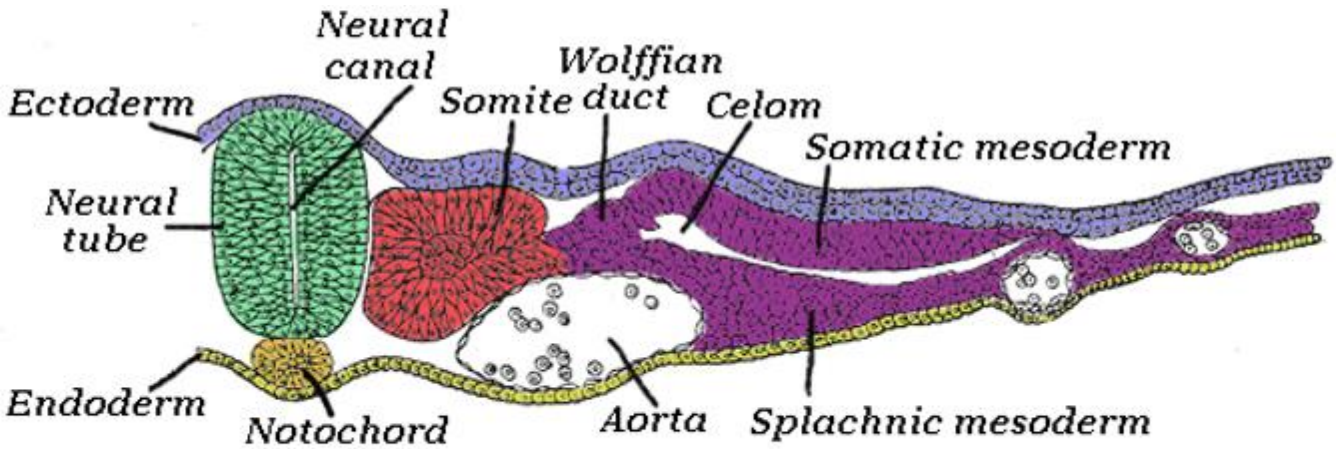
1. Describe the various types of biological tissue of the musculoskeletal system.
2. Describe the tissue mechanics and structural differences and similarities between muscle, tendons, fascia, and ligaments.
3. Describe the different types of joints and their various characteristics.
4. Defne the various terminologies used to describe the joint position, movements, and relationships.
5. Give defnitions of commonly used biomechanical terms.
6. Describe the different planes of the body.
7. Defne the body's center of mass and its location.
8. Describe the different axes of the body and the motions that occur around them.
9. Defne the terms osteokinematic motion and arthrokinematic motion.
10. Diferentiate between the diferent types of motion that can occur at the joint surfaces.
11. Describe the basic biomechanics of joint motion in terms of their concave–convex relationships.
12. Defne the terms close-packed and open-packed.

Lesson content:

The correct embryonic development of the musculoskeletal system requires a coordinated morphogenesis of the fundamental tissues of the body. Throughout the human body, there are four major types of tissues:

Epithelial. Covers all internal and external body surfaces and includes structures such as the skin and the inner lining of the blood vessels.

Connective. Connective tissue (CT), which includes our different classes: connective tissue proper, bone, cartilage, and blood tissue. In the embryo, muscle tissue and its fascia form as a differentiation of the paraxial mesoderm that divides into somites on either side of the neural tube and notochord. The cartilage and bone of the vertebral column and ribs develop from the sclerotome which is the anterior (ventral) part of the somite. The dermomyotome, which is the posterior (dorsal) part of the somite, gives rise to the overlying dermis of the back and the skeletal muscles of the body and limbs.



Connective tissue provides structural and metabolic support or other tissues and organs of the body.

Muscle. Muscles are classied functionally as either voluntary or involuntary, and structurally as either smooth, striated (skeletal), or cardiac. There are approximately 430 skeletal muscles in the body, each of which can be considered anatomically as a separate organ. Of these 430 muscles, about 75 pairs provide the majority of body movements and postures.

Nervous. Nervous tissue provides a two-way communication system between the central nervous system (brain and spinal cord) and muscles, sensory organs, and various systems.

Connective tissue (CT)

CT proper has a loose, exible matrix, called ground substance. The most common cell within CT proper is the fibroblast. Fibroblasts produce collagen, elastin, and reticular fibers:

- Collagen is a group of naturally occurring proteins. The collagens are a family of extracellular matrix (ECM) proteins that play a dominant role in maintaining the structural integrity of various tissues and in providing tensile strength to tissues. The ECM is formed from glycosaminoglycans (GAGs) subunits, long polysaccharide chains containing amino sugars, and are strongly hydrophilic to allow rapid diffusion of water-soluble molecules and easy migration of cells. Proteoglycans, which are a major component of the ECM, are macromolecules that consist of a protein backbone to which the GAGs are attached. There are two types of GAGs: chondroitin sulfate and keratin sulfate. A simple way to visualize the proteoglycan molecule is to consider a test tube brush, with the stem representing the protein core and the GAGs representing the bristles. Glycoproteins, another component of the ECM, consist of bronectin and thrombospondin and function as adhesive structures for repair and regeneration.
- Reticular fibers are composed of a type of collagen, which is secreted by reticular cells. These fibers crosslink to form a fine meshwork, called reticulin, which acts as a supporting mesh in bone marrow, and the tissues and organs of the lymphatic system, and the liver.

The various characteristics of collagen differ depending on whether it is loose or dense collagen. The anatomic and functional characteristics of loose and dense collagen are summarized in Table 1. Collagenous and elastic fibers are sparse and irregularly arranged in loose CN but are tightly packed in dense CT.

Table 1.

Loose and Dense Collagen

Joint Type	Anatomic Location	Fiber Orientation	Mechanical Specialization
Dense irregular connective tissue	Composes the external fibrous layer of the joint capsule, forms ligaments, bone, aponeuroses, and tendons	Parallel, tightly aligned fibers	Ligament: binds bones together and restrains unwanted movement at the joints; resists tension in several directions Tendon: attaches muscle to bone
Loose irregular connective tissue	Found in capsules, muscles, nerves, fgascia, and skin	Random fiber orientation	Provides structural support

The various types of CT, as they relate to the musculoskeletal system, are described as follows:

Fascia

Fascia, for example, the thoracolumbar fascia and the plantar fascia, is viewed as a loose CT that provides support and protection to a joint, and acts as an interconnection between tendons, aponeuroses, ligaments, capsules, nerves, and the intrinsic components of muscle. Fascia may be categorized as fibrous or nonfibrous, with the fibrous components consisting mainly of collagen and elastin fibers, and the non-fibrous portion consisting of amorphous ground substance. Three different types of fascia have been identifed, namely, superficial, deep, and visceral fascia. Various three-dimensional biomechanical models of the human fascial system have been developed, which correlate dysfunctional movement with various interrelated abnormal amounts of tension throughout the network of fascia. In particular, deep fascia has been implicated in being involved with the deep venous return, in having a possible role in proprioception, and responding to mechanical traction induced by muscular activity in different regions. Histological studies of deep fascia in the limbs show that it consists of elastic fibers and undulated collagen fibers arranged in layers. Each collagen layer is aligned in a different direction, and this permits a certain degree of stretch as well as a capacity to recoil.

Tendons

Tendons are dense, regularly arranged connective tissues, composed of 70% water and 30% dry mass that attach muscle to the bone at each end of the muscle. Tendons produce joint motion by transferring force from muscle to bone, and, when stretched, store elastic energy that contributes to movement. Also, tendons enable the muscle belly to be an optimal distance from the joint upon which it is acting. The collagen fibers of tendons (70–80% of the collagen in tendons is type I, with the remaining 20–30% of dry weight composed of proteoglycans, GAGs, elastin, and other collagens - being type III, V, and VII) are arranged in a quarter-stagger arrangement, which gives it a characteristic banding pattern and provides high strength and stability. Tenoblasts, or immature tendon cells, transform into tenocytes that synthesize collagen and components of the ECM network. The ECM surrounds collagen and tenocytes and is composed of several components for specific functions (e.g., glycoproteins, and Tenascin-C, which may play a role in collagen fiber orientation and alignment). Tendon structure is highly regular with collagen- forming triple helices (tropocollagen), which pack together to form microfibrils, which interdigitate to form brils, which coalesce to form fibers, which combine to form fascicles, which are bundled together to form a tendon. The thickness of each tendon varies and is proportional to the size of the muscle from which it originates. Vascularity within the tendon is relatively sparse and corresponds with the lower metabolic/turnover rate of these tissues. Within the fascicles of tendons, which are held together by loose CT called endotenon, the collagen components are oriented in a unidirectional way. Endotenon contains blood vessels, lymphatics, and nerves and permits longitudinal movements of individual fascicles when tensile forces are applied to the structure. The CT surrounding groups of fascicles, or the entire structure, is called the epitenon. The epitenon contains the vascular, lymphatic, and nerve supplies to the tendon. A peritendinous sheath (paratenon), which is composed of loose areolar connective tissue in addition to sensory and autonomic nerve fibers, surrounds the entire tendon. This sheath consists of two layers: an inner (visceral) layer and an outer (parietal) layer with occasional connecting bridges (mesotenon). If there is synovial fluid between these two layers, the paratenon is called tenosynovium; if not, it is termed tenovagium.

Tendons are metabolically active and are provided with a rich and vascular supply during development. Tendons receive their vascular supply through the musculotendinous junction (MTJ), the osteotendinous junction, and the vessels from the various surrounding tissues including the paratenon and mesotenon. Tendons in different areas of the body receive different amounts of blood supply, and tendon vascularity can be compromised by the junctional zones and sites of friction, torsion, or compression—a number of tendons are known to have reduced tendon vascularity, including the supraspinatus, the biceps, the Achilles, the patellar, and the posterior tibial tendon.

The mechanical properties of tendon come from its highly oriented structure. Tendons display viscoelastic mechanical properties that confer time- and rate-dependent effects on the tissue. Specifically, tendons are more elastic at lower strain rates

and stiffer at higher rates of tensile loading.

Tendons deform less than ligaments under an applied load and are able to transmit the load from muscle to bone. Material and structural properties of the tendon increase from birth

through maturity and then decrease from maturity through old age. Although tendons withstand strong tensile forces well, they resist shear forces less well and provide little resistance to a compression force.

A tendon can be divided into three main sections

- The bone–tendon junction. At most tendon–bone interfaces, the collagen fibers insert directly into the bone in a gradual transition of material composition. The

physical junction of tendon and bone is referred to as an enthesis, and is an interface

that is vulnerable to acute and chronic injury. One role of the enthesis is to absorb and distribute the stress concentration that occurs at the junction over a broader area.

- The tendon midsubstance. Overuse tendon injuries can occur in the midsubstance of the tendon, but not as requently as at the enthesis
- MTJ. The MTJ is the site where the muscle and tendon meet. Tge MTJ comprises numerous interdigitations between muscle cells and tendon tissue, resembling interlocked fingers. Despite its viscoelastic mechanical characteristics, the MTJ is very vulnerable to tensile failure.

Ligaments

Skeletal ligaments are fibrous bands of dense CT that connect bones across joints. Ligaments can be named or the bones into which they insert (coracohumeral), their shape (deltoid of the ankle), or their relationships to each other (cruciate). The gross structure of a ligament varies according to location (intra-articular or extra-articular, capsular), and function. Ligaments, which appear as dense white bands or cords of CT, are composed primarily of water (approximately 66%), and of collagen (largely type I collagen [85%], but with small amounts of type III) making up most of the dry weight. The collagen in ligaments has a less unidirectional organization than it does in tendons, but its structural framework still provides stifness (resistance to deformation. Small amounts of elastin (1% of the dry weight) are present in ligaments, with the exception of the ligamentum flavum and the nuchal ligament o the spine, which contain more. The cellular organization of ligaments makes them ideal or sustaining tensile loads, with many containing functional subunits that are capable of tightening or loosening in different joint positions. At the microscopic level, closely spaced collagen fibers (fascicles) are aligned along the long axis of the ligament and are arranged into a series of bundles that are delineated by a cellular layer, the endoligament, and the entire ligament is encased in a neurovascular biocellular layer referred to as the epiligament. Ligaments contribute to the stability of joint function by preventing excessive motion, acting as guides or checkreins to direct motion, and providing proprioceptive information or joint function through sensory nerve

endings and the attachments of the ligament to the joint capsule. Many ligaments share functions. For example, while the anterior cruciate ligament of the knee is considered the primary restraint to anterior translation of the tibia relative to the femur, the collateral ligaments and the posterior capsule of the knee also help in this function. The vascular and nerve distribution to ligaments is not homogeneous. For example, the middle of the ligament is typically avascular, while the proximal and distal ends enjoy a rich blood supply. Similarly, the insertional ends of the ligaments are more highly innervated than the midsubstance.

TABLE 1-1	Loose and Dense Collagen		
Joint Type	Anatomic Location	Fiber Orientation	Mechanical Specialization
Dense irregular connective tissue	Composes the external brous layer of the joint capsule, forms ligaments, bone, aponeuroses, and	Parallel, tightly aligned fibers	Ligament: binds bones together and restrains unwanted movement at the joints; resists tension in several

	tendons		directions Tendon: attaches muscle to bone
Loose irregular connectivetissue	Found in capsules, muscles, nerves, fascia, and skin	Random fiber orientation	Provides structural support

Cartilage

Cartilage tissue exists in three forms: hyaline, elastic, and fibrocartilage.

 Hyaline cartilage, also referred to as articular cartilage, covers the ends of long bones and permits almost frictionless motion to occur between the articular surfaces of a diarthrodial (synovial) joint. Articular cartilage is a highly organized viscoelastic material composed of cartilage cells called chondrocytes, water, and an ECM.

CLINICAL PEARL

Chondrocytes are specialized cells that are responsible or the development of cartilage and the maintenance of the ECM. Chondrocytes produce aggrecan, link protein, and hyaluronan, all of which are extruded into the ECM, where they aggregate spontaneously. The aggrecan forms a strong, porous-permeable, fiber-reinforced composite material with collagen. The chondrocytes sense mechanical changes in their surrounding matrix through intracytoplasmic filaments and short cilia on the sur ace of the cells.

Articular cartilage, the most abundant cartilage within the body, is devoid of any blood vessels, lymphatics, and nerves. Most of the bones of the body form first as hyaline cartilage, and later become bone in a process called endochondral ossification. The normal thickness of articular cartilage is determined by the contact pressures across the joint—the higher the peak pressures, the thicker the cartilage. Articular cartilage functions to distribute the joint forces over a large contact area, thereby dissipating the forces associated with the load. This distribution of forces allows the articular cartilage to remain healthy and fully functional throughout decades of life. The patellar has the thickest articular cartilage in the body. Articular cartilage may be grossly subdivided into our distinct zones with differing cellular morphology, biomechanical composition, collagen orientation, and structural properties, as follows:

- The superficial zone. The superficial zone, which lies adjacent to the joint cavity, comprises approximately 10–20% of the articular cartilage thickness and functions to protect deeper layers from shear stresses. The collagen fibers within this zone are packed tightly and aligned parallel to the articular surface. This zone is in contact with the synovial fluid and handles most of the tensile properties of cartilage
- The middle (transitional) zone. In the middle zone, which provides an anatomic and functional bridge between the superficial and deep zones, the collagen fibril orientation is obliquely organized. This zone comprises 40–60% of the total

cartilage volume. Functionally, the middle zone is the first line of resistance to compressive forces.

- The deep or radial layer. The deep layer comprises 30% of the matrix volume. It is characterized by radially aligned collagen fibers that are perpendicular to the surface of the joint, and which have a high proteoglycan content. Functionally the deep zone is responsible or providing the greatest resistance to compressive forces.
- The tidemark. The tidemark distinguishes the deep zone from the calcified cartilage, the area that prevents the diffusion of nutrients from the bone tissue into the cartilage.
- Elastic (yellow) cartilage is a very specialized CT, primarily found in locations such as the outer ear, and portions of the larynx.
- Fibrocartilage, also referred to as white cartilage, functions as a shock absorber in both weight-bearing and nonweight-bearing joints. Its large fiber content, reinforced with numerous collagen fibers, makes it ideal or bearing large stresses in all directions. Fibrocartilage is an avascular, alymphatic, and aneural tissue and derives its nutrition by a doublediffusion system. Examples of fibrocartilage include the symphysis pubis, the intervertebral disk, and the menisci of the knee.

Bone

Bone is a highly vascular form of CT, composed of collagen, calcium phosphate, water, amorphous proteins, and cells. It is the most rigid of the CTs (Table 1-2). Despite its rigidity, bone is a dynamic tissue that undergoes constant metabolism and remodeling. The collagen of bone is produced in the same manner as that of ligament and tendon but by a different cell, the osteoblast. At the gross anatomical level, each bone has a distinct morphology comprising both cortical bone and cancellous bone. Cortical bone is found in the outer shell. Cancellous bone is found within the epiphyseal and metaphyseal regions of long bones, as well as throughout the interior of short bones. Skeletal development occurs in one of the two ways:

Intramembranous ossification. Mesenchymal stem cells within mesenchyme or the medullary cavity of a bone initiate the process of intramembranous ossification. This type of ossification occurs in the cranium and facial bones and, in part, the ribs, clavicle, and mandible.

TABLE 1-2	General Structure of Bone		
Site	Comment	Conditions	Result
Epiphysis	Mainly develops under pressure Apophysis orms under traction Forms bone ends Supports articular surface	Epiphyseal dysplasias Joint sur ace trauma Overuse injury Damaged blood supply	Distorted joints Degenerative changes Fragmented development Avascular necrosis
Physis	Epiphyseal or growth plate Responsive to growth and sex hormones	Physeal dysplasia Trauma Slipped epiphysis	Short stature Deformed or angulated growth or growth arrest

	Vulnerable prior to growth spurt Mechanically weak		
Metaphysis	Remodeling expanded bone end Cancellous bone heals rapidly Vulnerable to osteomyelitis Affords ligament attachment	Osteomyelitis Tumors Metaphyseal dysplasia	Sequestrum ormation Altered bone shape Distorted growth
Diaphysis	Forms shaft of bone Large surface or muscle origin Significant compact cortical bone Strong in compression	Fractures Diaphyseal dysplasias Healing slower than at metaphysis	Able to remodel angulation Cannot remodel rotation Involucrum with in ection Dysplasia gives altered density and shape
Data from Reid DC. Sports Injury Assessment and Rehabilitation. New York, NY: Churchill Livingstone; 1992.			

Endochondral ossification. The first site of ossification occurs in the primary center of ossification, which is in the middle od the diaphysis (shaft). About the time of birth, a secondary ossification center appears in each epiphysis (end) od long bones. Between the bone formed by the primary and secondary ossification centers, cartilage persists as the epiphyseal (growth) plates between the diaphysis and the epiphysis of a long bone. This type of ossification occurs in the appendicular and axial bones.

The periosteum is formed when the perichondrium, which surrounds the cartilage, becomes the periosteum. Chondrocytes in the primary center of ossification begin to grow (hypertrophy) and begin secreting alkaline phosphatase, an enzyme essential or mineral deposition. Calcification o the matrix follows, and apoptosis (a type of cell death involving a programmed sequence of events that eliminates certain cells) of the hypertrophic chondrocytes occurs. This creates cavities within the bone. The exact mechanism of chondrocyte hypertrophy and apoptosis is currently unknown. The hypertrophic chondrocytes (before apoptosis) also secrete a substance called vascular endothelial cell growth factor that induces the sprouting of blood vessels from the perichondrium. Blood vessels forming the periosteal bud invade the cavity left by the chondrocytes, and branch in opposite directions along the length of the shaft . The blood vessels carry osteoprogenitor cells and hemopoietic cells inside the cavity, the latter of which later form the bone marrow. Osteoblasts, differentiated from the osteoprogenitor cells that enter the cavity via the periosteal bud, use the calcified matrix as a scaffold and begin to secrete osteoid, which forms the bone trabecula. Osteoclasts, formed from macrophages, break down the spongy bone to form the medullary cavity (bone marrow). The function of bone is to provide support, enhance leverage, protect vital structures, provide attachments or both tendons and ligaments, and store minerals, particularly calcium. From a clinical perspective, bones may serve as useful landmarks during the palpation phase of the examination. The strength of bone is related directly to its density. Of importance to the clinician, is the difference between maturing bone and mature bone. The epiphyseal plate or growth plate of a maturing bone can be divided into our distinct zones.

- Reserve zone: produces and stores matrix.
- Proliferative zone: produces matrix and is the site for longitudinal bone cell growth.
- Hypertrophic zone: subdivided into the maturation zone, degenerative zone, and the zone o provisional calcification. It is within the hypertrophic zone that the matrix is prepared or calcification and is here that the matrix is ultimately calcified. The hypertrophic zone is the most susceptible of the zones to injury because of the low volume of bone matrix and the high amounts of developing immature cells in this region.
- Bone metaphysis: the part of the bone that grows during childhood.

Skeletal Muscle Tissue

The microstructure and composition of skeletal muscle have been studied extensively. The class of tissue labeled skeletal muscle consists of individual muscle cells or fibers that work together to produce the movement of bony levers. A single muscle cell is called a muscle fiber or myofiber. As muscle cells differentiate within the mesoderm, individual myofibers are wrapped in a CT envelope called endomysium. Bundles of myofibers, which form a whole muscle (fasciculus), are encased in the perimysium (Fig. 1-1). The perimysium is continuous with the deep fascia. This relationship allows

the fascia to unite all of the fibers of a single motor unit and, there ore, adapt to variations in form and volume of each muscle according to muscular contraction and intramuscular modifications induced by joint movement. Groups of fasciculi are surrounded by a connective sheath called the epimysium (Fig. 1-1). Under an electron microscope, it can be seen that each of the myofibers consists of thousands of myofibrils (Fig. 1-1), which extend throughout its length. Myofibrils are composed of sarcomeres arranged in series.

CLINICAL PEARL

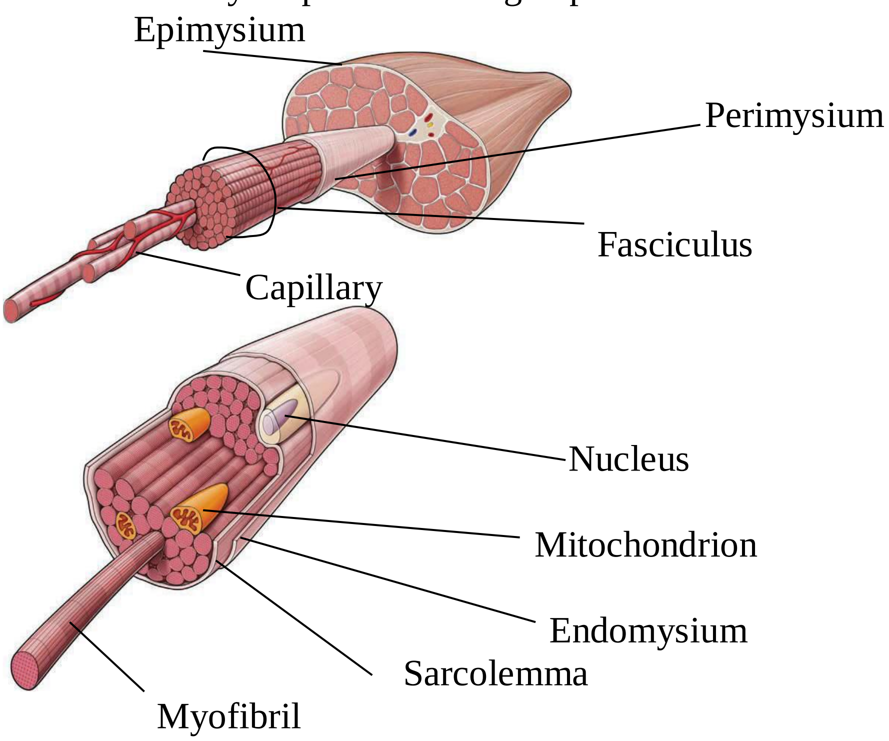
The sarcomere (Fig. 1 2) is the contractile machinery of the muscle. The graded ontractions of a whole muscle occur because the number of bers participating in the contraction varies. Increasing the force of movement is achieved by recruiting more cells into cooperative action.

All skeletal muscles exhibit our characteristics:

1. Excitability, the ability to respond to stimulation from the nervous system.
2. Elasticity, the ability to change in length or stretch.
3. Extensibility, the ability to shorten and return to normal length.
4. Contractility, the ability to shorten and contract in response to some neural command.

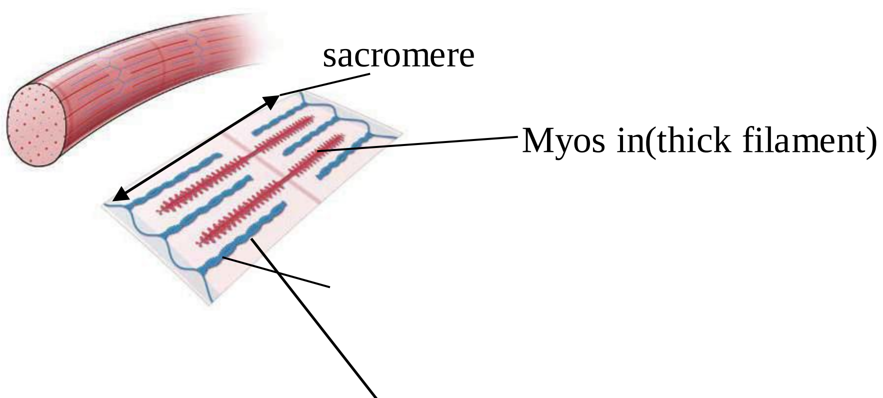
The tension developed in skeletal muscle can occur passively (stretch) or actively (contraction). When an activated muscle develops tension, the amount of tension present is constant throughout the length of the muscle, in the tendons, and at the sites of the musculotendinous attachments to the bone. The tensile force produced by the muscle pulls on the attached bones and creates torque at the joints crossed by the muscle. The magnitude of the tensile force is dependent on a number of factors.

One of the most important roles of CT is to transmit mechanically the forces generated by the skeletal muscle cells to provide movement. Each of the myofibrils contains many fibers called myofilaments, which run parallel to the myofibril axis. The myofilaments are made up of two different proteins: actin (thin myofilaments) and myosin (thick myofilaments) that give skeletal muscle fibers their striated (striped) appearance (Fig. 1-2). The striations are produced by alternating dark (A) and light (I) bands that appear to span the width of the muscle fiber. The A bands are composed of myosin filaments, whereas the I bands are composed of actin filaments. The actin filaments of the I band overlap into the A band, giving the edges of the A band a darker appearance than the central region (H band), which contains only myosin. At the center of each I band is a thin, dark Z line. A sarcomere (Fig. 1-2) represents the distance between each Z line. Each muscle fiber is limited by a cell membrane called a sarcolemma (Fig. 1-1). The protein dystrophin plays an essential role in the mechanical strength and stability of the sarcolemma. Dystrophin is lacking in patients with Duchenne muscular dystrophy.



CLINICAL PEARL

The sarcoplasm is the specialized cytoplasm of a muscle cell that contains the usual subcellular elements along with the Golgi apparatus, abundant myofibrils, a modified endoplasmic reticulum known as the sarcoplasmic reticulum (SR), myoglobin, and mitochondria. Transverse tubules (T-tubules) invaginate the sarcolemma, allowing impulses to penetrate the cell and activate the SR.



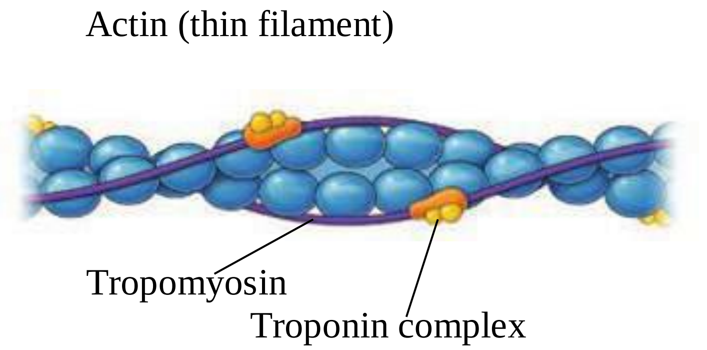


FIGURE: Troponin and tropomyosin action during a musclecontraction.

The basic function of muscle is to contract. The word contraction, used to describe the generation of tension within muscle fibers, conjures up an image of shortening o muscle fibers during a resistance exercise. However, a contraction can produce shortening or lengthening of the muscle, or no change in the muscle length. T us, three types of contraction are commonly recognized: isometric, concentric, and eccentric.

Isometric contraction. Isometric exercises provide a static contraction with a variable and accommodating resistance without producing any appreciable change in muscle length.

Concentric contraction. A concentric contraction produces a shortening of the muscle. This occurs when the tension generated by the agonist muscle is suf?cient to overcome an external resistance and to move the body segment of one attachment toward the segment of its other attachment.

Eccentric contraction. An eccentric contraction occurs when a muscle slowly lengthens as it gives in to an external force that is greater than the contractile force it is exerting. In reality, the muscle does not lengthen, it merely returns from its shortened position to its normal resting length. Eccentric muscle contractions, which are capable of generating greater forces than either isometric or concentric contractions, are involved in activities that require a deceleration to occur. Such activities include slowing to a stop when running, lowering an object, or sitting down. Because the load exceeds the bond between the actin and myosin laments during an eccentric contraction, some of the myosin laments probably are torn from the binding sites on the actin lament while the remainder are completing the contraction cycle. The resulting force is substantially larger or a torn crossbridge than or one being created during a normal cycle of muscle contraction. Consequently, the combined increase in force per cross-bridge and the number of active crossbridges results in a maximum lengthening muscle tension that is greater than the tension that could be created during a shortening muscle action.

CLINICAL PEARL

Both concentric and eccentric muscle action comprise the type oa exercise called isotonic. An isotonic contraction is a contraction in which the tension within the muscle remains constant as the muscle shortens or lengthens. This state is very difficult to produce and measure. Although the term isotonic is used in many texts to describe concentric and eccentric contractions alike, its use in this context is erroneous because in most exercise forms the muscle tension during exercise varies based upon the weight used, joint velocity, muscle length, and type o muscle contraction.

Four other contractions are worth mentioning:

 Isokinetic contraction. An isokinetic contraction occurs when a muscle is maximally contracting at the same speed throughout the whole range of its related lever. Isokinetic contractions require the use of special equipment that produces an accommodating resistance. Both highspeed/low-resistance and low-speed/high-resistance regimens result in excellent strength gains. The major disadvantage of this type of exercise is its expense. Also, there is the potential or impact loading and incorrect joint axis alignment. Isokinetic exercises may also have questionable functional carryover.
 Econcentric contraction. This type of contraction combines both a controlled concentric and a simultaneous eccentric contraction of the same muscle over two separate joints. Examples of an econcentric contraction include the standing hamstring curl, in which the hamstrings work concentrically to ex the knee while the hip tends to flex eccentrically, lengthening the hamstrings. When rising from a squat, the hamstrings work concentrically as the hip extends and work eccentrically as the knee extends. Conversely, the rectus femoris work eccentrically as the hip extends and work concentrically as the knee extends.
 Isolytic contraction. An isolytic contraction is an osteopathic term used to describe a type o eccentric contraction that makes use of a greater force than the patient can overcome. The difference between an eccentric contraction and an isolytic contraction is that, in the former, the contraction is voluntary whereas, in the latter, it is involuntary. The isolytic contraction can be used in certain manual techniques to stretch fibrotic tissue.

Structures called cross-bridges serve to connect the actin and myosin filaments. Increased synthesis of actin and myosin stimulates new myofibrils that are added to the external layers of the pre-existing myofibrils. The myosin filaments contain two exible, hinge-like regions, which allow the crossbridges to attach and detach from the actin filament. During contraction, the cross-bridges attach and undergo power strokes, which provide the contractile force. During relaxation, the cross-bridges detach. This attaching and detaching is asynchronous, so that some are attaching while others are detaching. Thus, at each moment, some of the cross-bridges are pulling, while others are releasing. The regulation of cross-bridge attachment and detachment is a function of two proteins found in the actin filaments: tropomyosin and troponin (Fig. 1-2). Tropomyosin attaches directly to the actin filament, whereas troponin is attached to the tropomyosin rather than directly to the actin filament.

CLINICAL PEARL

Tropomyosin and troponin function as the switch or muscle contraction and relaxation. In a relaxed state, the tropomyosin physically blocks the cross-bridges from binding to the actin. For contraction to take place, the tropomyosin must be moved.

Each muscle fiber is innervated by a somatic motor neuron. One neuron and the muscle fibers it innervates constitute a motor unit or functional unit of the muscle. Each motor neuron branches as it enters the muscle to innervate a number of muscle fibers.

TABLE 1-3	Comparison of Muscle Fiber Types		
Characteristics	Type I	Type II A	Type II B
Size (diameter)	Small	Intermediate	Very large
Resistance to atigue	High	Fairly high	Low
Capillary density	High	High	Low
Glycogen content	Low	Intermediate	High

Twitch rate	Slow	Fast	Fast
Energy system	Aerobic	Aerobic	Anaerobic
Maximum muscle shortening velocity	Slow	Fast	Fast
Major storage uel	Triglycerides	Creatine phosphate glycogen	Creatine phosphate glycogen

CLINICAL PEARL

The area of contact between a nerve and muscle fiber is known as the motor end plate, or neuromuscular junction (NMJ).

The release of a chemical acetylcholine from the axon terminals at the NMJ causes electrical activation of the skeletal muscle fibers. When an action potential propagates into the transverse tubule system (narrow membranous tunnels formed from and continuous with the sarcolemma), the voltage sensors on the transverse tubule membrane signal the release of Ca2+ rom the terminal cisternae portion of the SR (a series of interconnected sacs and tubes that surround each myofibril). The released Ca2+ then diffuses into the sarcomeres and binds to troponin, displacing the tropomyosin, and allowing the actin to bind with the myosin cross-bridges (Fig. 1-2). Whenever a somatic motor neuron is activated, all of the muscle fibers that it innervates are stimulated and contract with all-or-none twitches. Although the muscle fibers produce all-or-none contractions, muscles are capable of a wide variety of responses, ranging from activities requiring a high level of precision, to activities requiring high tension.
At the end of the contraction (the neural activity and action potentials cease), the SR actively accumulates Ca2+ and muscle relaxation occurs. The return of Ca2+ to the SR involves active transport, requiring the degradation of adenosine triphosphate (ATP) to adenosine diphosphate (ADP). Because SR function is closely associated with both contraction and relaxation, changes in its ability to release or sequester Ca2+ markedly a ect both the time course and magnitude of force output by the muscle fiber.

CLINICAL PEARL

The SR forms a network around the myofibrils, storing and providing the Ca2+ that is required or muscle contraction.

On the basis of their contractile properties, two major types of muscle fiber have been recognized within skeletal muscle based on their resistance to fatigue: type I (tonic, slow-twitch fibers), and type II (phasic fast-twitch fibers). Type II muscle fibers are further divided into two additional classifications (Types IIA and IIB) (Table 1-3). Scott et al. subdivide type II fibers into three classifications, including a type IIIC. Type I fibers are richly endowed with mitochondria and have a high capacity or oxygen uptake. They are, therefore, suitable or activities o long duration or endurance (aerobic), including the maintenance of posture. In contrast, fast-twitch fibers, which generate a great amount of tension within a short period, are suited to quick, explosive actions (anaerobic), including such activities as sprinting. The type II (fast-twitch) fibers are separated based on mitochondria content into those that have a high complement of mitochondria (type IIA) and those that are mitochondria-poor (type IIB). This results in type IIB fibers having a tendency to fatigue more quickly than the type IIA fibers (Table 1-3).

CLINICAL PEARL

In fast-twitch fibers, the SR embraces every individual myofibril. In slow-twitch fibers, it may contain multiple myofibrils.

Theory dictates that a muscle with a large percentage of the total cross-sectional area occupied by slow-twitch type I fibers should be more fatigue resistant than one in which the fast-twitch type II fibers predominate. Different activities place differing demands on a muscle (Table 1-4). For example, dynamic movement activities involve a predominance of fast-twitch fiber recruitment, whereas postural activities and those activities requiring stabilization entail more involvement of the slow-twitch fibers. In humans, most limb muscles contain a relatively equal distribution of each muscle fiber type, whereas the back and trunk demonstrate a predominance of slow-twitch fibers. Although it would seem possible that physical training may cause fibers to convert from slow twitch to fast twitch or the reverse, this has not been shown to be the case.6 However, fiber conversion from type IIB to type IIA, and vice versa, has been found to occur with training.

TABLE 1-4	**Functional Division of Muscle Groups**
Movement Group	Stabilization Group
Primarily type IIa	Primarily type I
Prone to adaptive shortening	Prone to develop weakness
Prone to develop hypertonicity	Prone to muscle inhibition
Dominate in atigue and new movement situations	Fatigue easily
Generally cross two joints	Primarily cross one joint
Examples	Examples
Gastrocnemius/Soleus	Fibularis (peronei)
Tibialis posterior	Tibialis anterior
Short hip adductors	Vastus medialis and lateralis
Hamstrings	Gluteus maximus, medius, and minimus
Rectus femoris	Serratus anterior
Tensor fascia lata	Rhomboids
Erector spinae	Lower portion of trapezius
Quadratus lumborum	Short/deep cervical flexors
Pectoralis major	Upper limb extensors
Upper portion of trapezius	Rectus abdominis
Levator scapulae	
Sternocleidomastoid	

Scalenes	
Upper limb flexors	
Data rom Jull GA, Janda V. Muscle and motor control in low back pain. In: Twomey LT, Taylor JR, eds. Physical Therapy o the Low Back: Clinics in Physical Therapy. New York, NY: Churchill Livingstone; 1987:258–278.	

The effectiveness of muscle to produce movement depends on some factors. These include the location and orientation of the muscle attachment relative to the joint, the limitations or laxity present in the musculotendinous unit, the type of contraction, the point of application, and the actions of other muscles that cross the joint.

CLINICAL PEARL

Following the stimulation of muscle, a brief period elapses before a muscle begins to develop tension. The length of this period, the electromechanical delay (EMD), varies considerably among muscles. Fast-twitch fibers have shorter periods of EMD when compared with slow-twitch fibers. EMD is affected by muscle fatigue, muscle length, muscle training, passive muscle stretching, and the type of muscle activation. A tissue injury may increase the EMD and, therefore, increases the susceptibility to future injury if full healing does not occur. One of the purposes of neuromuscular re-education is to return the EMD to a normal level.

Muscles serve a variety of roles depending on the required movement:

- Prime mover (agonist). This is a muscle that is directly responsible or producing a desired movement.
- Antagonist. This is a muscle that has an effect directly opposite to that of the agonist.
- Synergist (supporter). This is a muscle that performs a cooperative muscle function relative to the agonist. Synergists can function as stabilizers or neutralizers.

Stabilizers (fixators). Muscles that contract statically to steady or support some part of the body against the pull of the contracting muscles, against the pull of gravity, or against the effect of momentum and recoil in certain vigorous movements.

Neutralizers. Muscles that act to prevent an undesired action from one of the movers.

As previously mentioned, depending on the type o muscular contraction, the length of a muscle can remain the same (isometric), shorten (concentric), or "lengthen" (eccentric). The velocity at which muscle contracts significantly affects the tension that the muscle produces and subsequently affects a muscle's strength and power.

- Concentric contractions. As the speed of a concentric contraction increases, the force it is capable of producing decreases. The slower speed o contraction is thought to produce greater forces than can be produced by increasing the number of cross-bridges formed. This relationship is a continuum, with the optimum velocity or the muscle somewhere between the slowest and fastest rates. At very slow speeds, the force that a muscle can resist or overcome rises rapidly up to 50% greater than the maximum isometric contraction.
- Eccentric contractions. During a maximum-effort eccentric contraction, as the velocity of active muscle lengthening increases, force production in the muscle initially increases

to a point, but then quickly levels of. The following changes in force production occur during an eccentric contraction:

Rapid eccentric contractions generate more force than do slower eccentric contractions.

During slow eccentric muscle actions, the work produced approximates that of an isometric contraction.

CLINICAL PEARL

The number of cross-bridges that can be formed is dependent on the extent of the overlap between the actin and myosin laments. Thus, the force a muscle is capable of exerting depends on its length. For each muscle cell, there is an optimum length, or range of lengths, at which the contractile force is strongest. At the optimum length of the muscle, there is a near-optimal overlap of actin and myosin, allowing or the generation of maximum tension at this length.

 If the muscle is in a shortened position, the overlap of actin and myosin reduces the number of sites available or the cross-bridge formation. Active insufficiency of a muscle occurs when the muscle is incapable of shortening to the extent required to produce a full range of motion (ROM) at all joints crossed simultaneously. For example, the finger flexors cannot produce a closed fist when the wrist is fully flexed, as they can when it is in neutral position.

 If the muscle is in a lengthened position compared with its optimum length, the actin filaments are pulled away from the myosin heads such that they cannot create as many cross-bridges. Passive insufficiency of the muscle occurs when the two-joint muscle cannot stretch to the extent required or full ROM in the opposite direction at all joints crossed. For example, when an individual attempts to make a closed fist with the wrist fully flexed, the active shortening of the finger and wrist flexors results in passive lengthening of the finger extensors. In this example, the length of the finger extensors is insufficient to allow full ROM at both the wrist and the fingers.

The force and speed of a muscle contraction depend on the requirements of the activity, which in turn, are dependent on the ability of the central nervous system to control the recruitment of motor units. The motor units o slow-twitch fibers have lower thresholds and are easier to activate than those of the fast-twitch motor units. Consequently, the slow twitch fibers are recruited first, even when the resulting limb movement is rapid.
As the force requirement, speed requirement, or duration of activity increases, motor units with higher thresholds are recruited. Type IIa units are recruited before type IIb.

CLINICAL PEARL

The term temporal summation refers to the summation of individual contractile units. The summation can increase the muscular force by increasing the muscle activation frequency.

Although each muscle contains the contractile machinery to produce the forces or movement, it is the tendon that transmits these forces to the bones to achieve movement or stability of the body in space. The angle of insertion the tendon makes with a bone determines the line of pull, whereas the tension generated by a muscle is a function of its angle of insertion. A muscle generates the greatest amount of torque when its line of pull is oriented at a 90-degree angle to the bone, and it is attached anatomically as far from the joint center as possible.

Just as there are optimal speeds of length change and optimal muscle lengths, there are optimal insertion angles or each of the muscles. The angle of insertion of a muscle, and, therefore, its line of pull, can change during dynamic movements. The angle of pennation is the angle created between the fiber direction and the line of pull. When the fibers of a muscle lie parallel to the long axis of the muscle, there is no angle of pennation. The number of fibers within a fixed volume of a muscle increases with the angle of pennation. Although pennation can enhance the maximum tension, the range of shortening of the muscle is reduced. Muscle fibers can contract to about 60% of their resting length. Since the muscle fibers in pennate muscles are shorter than the no-pennate equivalent, the amount of contraction is similarly reduced. Muscles that need to have large changes in length without the need or very high tension, such as the sartorius muscle, do not have pennate muscle fibers. In contrast, pennate muscle fibers are found in those muscles in which the emphasis is on a high capacity or tension generation rather than ROM (e.g., gluteus maximus).

CLINICAL PEARL

Skeletal muscle blood flow increases 20- fold during muscle contractions. The muscle blood flow increases in proportion to the metabolic demands of the tissue, a relationship reflected by positive correlations between muscle blood flow and exercise. As body temperature elevates, the speeds of nerve and muscle functions increase, resulting in a higher value of maximum isometric tension and a higher maximum velocity of shortening possible with fewer motor units at any given load. Muscle function is most efficient at 38.5°C (101°F).

During physical exercise, energy turnover in skeletal muscle may increase by 400 times compared with muscle at rest and muscle oxygen consumption may increase by more than 100 times. The hydrolysis of ATP to ADP and inorganic phosphate (P_i) provides the power or muscular activity. Despite the large fluctuations in energy demand just mentioned, muscle ATP remains practically constant and demonstrates a remarkable precision of the system in adjusting the rate of the ATP-generating processes to the demand. There are three energy systems that contribute to the resynthesis of ATP via ADP rephosphorylation. These energy systems are as follows:

- Phosphagen system. The phosphagen, or ATP-PCr, system is an anaerobic process—it can proceed without oxygen (O2). The skeletal muscle cell stores the phosphocreatine (PCr) and ADP, of which PCr is the chemical fuel source. At the onset of muscular contraction, PCr represents the most immediate reserve or the rephosphorylation of A P. The phosphagen system provides ATP primarily or short-term, high-intensity activities (i.e., sprinting), and is the major source of energy during the first 30 seconds of intense exercise, but it is also active at the start of all exercises, regardless of intensity. Once a muscle returns to rest, the supply of ATP-PCr is replenished. While the maximum power of this system is great, one disadvantage of the phosphagen system is that because of its significant contribution to the energy yield at the onset of near-maximal exercise, the concentration of PCr can be reduced to less than 40% of resting levels within 10 seconds of the start of intense exercise, which translates into a small maximum capacity of the system.

 Glycolytic system. The glycolytic system is an anaerobic process that involves the breakdown oh carbohydrates— either glycogen stored in the muscle or glucose delivered through the blood—into pyruvate to produce ATP in a process called glycolysis. Pyruvate is then transformed into lactic acid as a byproduct of the anaerobic glycolysis. Because this system relies on a series of nine different chemical reactions, it is slower to become fully active. However, glycogenolysis has a greater capacity to provide energy than does PCr, and therefore it supplements PCr during maximal exercise and continues to rephosphorylate ADP during maximal exercise after PCr reserves have become essentially depleted. The process of glycolysis can be in one of the two ways, termed fast glycolysis and slow glycolysis, depending on the energy demands within the cell. If energy must be supplied at a high rate, fast glycolysis is used primarily. If the energy demand is not so high, slow glycolysis is activated. The main disadvantage of the fast glycolysis system is that during very high-intensity exercise, hydrogen ions dissociate from the glycogenolytic end product of lactic acid. The accumulation of lactic acid in the contracting muscle is recognized in sports and resistance training circles. An increase in hydrogen ion concentration is believed to inhibit glycolytic reactions and directly interfere with muscle excitation–contraction and coupling, which can potentially impair contractile force during an exercise. This inhibition occurs once the muscle pH drops below a certain level, prompting the appearance of phospho ructokinase (PFK), resulting in local energy production ceasing until replenished by oxygen stores.

CLINICAL PEARL

Lactic acid is the major energy source or providing the muscle with ATP during exercise bouts that last 1–3 minutes (e.g., running 400–800 m).

 Oxidative system. As its name suggests, the oxidative system requires O2 and is consequently termed the “aerobic” system. The fuel sources or this system are glycogen, fats, and proteins. This system is the primary source of ATP at rest and during low-intensity activities. The ATP is resynthesized in the mitochondria of the muscle cell such that the ability to metabolize oxygen and other substrates is related to the number and concentration of the mitochondria and cells. It is worth noting that at no time during either rest or exercise does any single energy system provide the complete supply of energy. While being unable to produce ATP at an equivalent rate to that produced by PCr breakdown and glycogenolysis, the oxidative system is capable of sustaining low-intensity exercise or several hours. However, because of increased complexity, the time between the onset of exercise and when this system is operating at its full potential is around 45 seconds.

The relative contribution of these energy systems to ATP resynthesis has been shown to depend upon the intensity and duration of exercise, with the primary system used being based on the duration of the event:

 0–10 seconds: ATP–PCr. These bursts of activity develop muscle strength and stronger tendons and ligaments, with the ATP being supplied by the phosphagen system.

 10–30 seconds: ATP–PCr plus anaerobic glycolysis.

 30 seconds to 2 minutes: anaerobic glycolysis. These longer bursts of activity, if repeated after 4 minutes of rest or mild exercise, enhance anaerobic power with the ATP being supplied by the phosphagen and anaerobic glycolytic system.

 2–3 minutes: anaerobic glycolysis plus oxidative system.

 > 3 minutes and rest: oxidative system. These periods of activity using less than maximum intensity may develop aerobic power and endurance capabilities, and the phosphogen, anaerobic glycotic, and anaerobic systems supply the ATP.

Respiratory Muscles

Although the respiratory muscles share some mechanical similarities with skeletal muscles, they are distinct from skeletal muscles in several aspects as follows:

 Whereas skeletal muscles of the limbs overcome inertial loads, the respiratory muscles overcome primarily elastic and resistive loads.

 The respiratory muscles are under both voluntary and involuntary control.

 The respiratory muscles are similar to the heart muscles, in that they have to contract rhythmically and generate the required forces or ventilation throughout the entire lifespan of the individual. The respiratory muscles, however, do not contain pacemaker cells and are under the control of mechanical and chemical stimuli, requiring neural input from higher centers to initiate and coordinate contraction.

 The resting length of the respiratory muscles is a relationship between the inward recoil forces of the lung and the outward recoil forces of the chest wall. Changes in the balance of recoil forces will result in changes in the resting length of the respiratory muscles. Thus, simple and everyday life occurrences such as changes in posture may alter the operational length and the contractile strength of the respiratory muscles. If uncompensated, these length changes can lead to decreases in the output of the muscles, and hence, a reduction in the ability to generate lung volume changes. The skeletal muscles of the limbs, on the other hand, are not constrained to operate at a particular resting length.

CLINICAL PEARL

The primary respiratory muscles of the body include the diaphragm; the internal, external, and transverse intercostals; the levator costae; and the serratus posterior inferior and superior.

JOINTS

Arthrology is the study of the classification, structure, and function of articulations (joints or arthroses). A joint represents the junction between two or more bones. Joints are regions where bones are capped and surrounded by CTs that hold the bones together and determine the type and degree of movement between them. An understanding of the anatomy and biomechanics of the various joints is required to be able to assess and treat a patient thoroughly. When classified according to movement potential, joints may be classified into two broad categories synarthrosis (nonsynovial) or diarthrosis (synovial).

Synarthrosis

The type of tissue uniting the bone surfaces determines the major types of synarthroses:

 Fibrous joints, which are joined by dense brous CT.

Three types exist:

Suture (e.g., suture of the skull).

Gomphosis (e.g., tooth and mandible or maxilla articulation).

Syndesmosis (e.g., tibio bular or radioulnar joints).

These joints usually allow a small amount of motion.

 Cartilaginous joints originally referred to as amphiarthrosis joints, are stable joints that allow or minimal or little movement. These joints exist in humans in one of two ways: synchondrosis (e.g., manubriosternal joints) and symphysis (e.g., symphysis pubis). A synchondrosis is a joint in which the material used to connect the two components is hyaline cartilage. In a symphysis joint, the two bony components are covered with a thin lamina o hyaline cartilage and directly joined by brocartilage in the form of disks or pads.

Diarthrosis

This joint unites long bones and permits free bone movement and greater mobility. A fibroelastic joint capsule, which characterizes these joints, is filled with a lubricating substance called synovial fluid. Consequently, these joints are often referred to as synovial joints.

Examples include, but are not limited to, the hip, knee and shoulder, and elbow joints.

Synovial joints are further classied based on complexity:

 Simple (uniaxial): a single pair of articular surfaces one male, or convex, surface and one female, or concave, surface. Examples include hinge joint and trochoid (pivot) joints.

 Compound (biaxial): a single joint capsule that contains more than a single pair of mating articulating surfaces. The two types of biaxial joint in the body include the condyloid and saddle.

 Complex (triaxial or multiaxial): contain an intra-articular inclusion within the joint class such as a meniscus or disk that increases the number of joint surfaces. The two types of joint in this category are plane joints and ball-and socket joints.

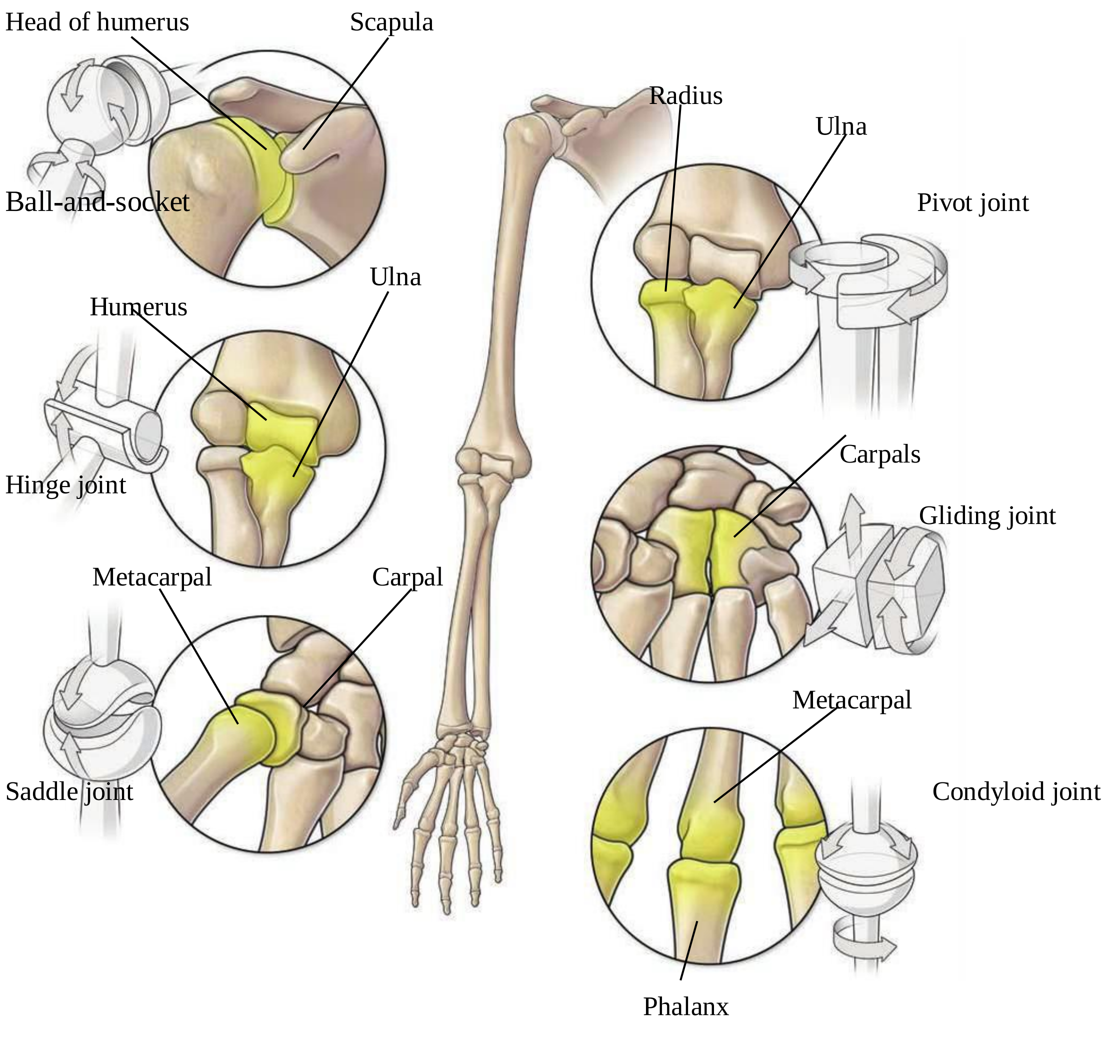
Synovial joints have five distinguishing characteristics: a joint cavity that is enclosed by the joint capsule, hyaline articular cartilage that covers the surfaces of the enclosed contiguous bones, synovial fluid that forms a film over the joint surfaces, synovial membrane that lines the inner surface of the capsule, and a joint capsule that is composed of two layers. All synovial joints of the body are provided with an array of corpuscular (mechanoreceptors) and noncorpuscular (nociceptors) receptor endings embedded in articular, muscular, and cutaneous structures with varying characteristic behaviors and distributions depending on the articular tissue. One intra-articular structure worth mentioning is the articular disk or meniscus. A meniscus, which consists of a dense ECM, is not covered by a synovial membrane and occurs between articular surfaces where congruity is low. The cells of the meniscus are referred to as brochondrocytes because they appear to be a mixture of fibroblasts and chondrocytes. A meniscal disk may extend across a synovial joint, dividing it structurally and functionally into two synovial cavities. Complete disks occur in the sternoclavicular and distal radioulnar joints, while that in the temporomandibular joint may be complete or incomplete. Peripherally disks are connected to fibrous capsules, usually by vascularized connective tissue, so that they become invaded by vessels and a afferent and motor nerves. Mechanoreceptors within the menisci function as transducers, converting the physical stimulus of tension and compression into a specific electrical nerve impulse.

Synovial joints can be broadly classified according to structure or analogy into the following categories:

 Spheroid. As the name suggests, a spheroid joint is a freely moving joint in which a sphere on the head of one bone fits into a rounded cavity in the other bone. Spheroid (ball-and-socket) joints allow motions in three planes. Examples of a spheroid joint surface include the heads of the femur and humerus.

 Trochoid. The trochoid, or pivot, joint is characterized by a pivot-like process turning within a ring, or a ring on a pivot, the ring being formed partly of bone, partly of ligament (Fig. 1-3). Trochoid joints permit only rotation. Examples of a trochoid joint include the humeroradial joint and the atlantoaxial joint.

 Condyloid (ovoid). This joint is characterized by an ovoid articular surface, or condyle. One bone may articulate with another by one surface or by two, but never more than two. If two distinct surfaces are present, the joint is called condylar, or bicondylar. The elliptical cavity of the joint is designed in such a manner as to permit the motions o flexion, extension, adduction, abduction, and circumduction, but no axial rotation. The wrist joint is an example of this form of articulation.
 Ginglymoid. A ginglymoid joint is a hinge joint. It is characterized by a spool-like surface and a concave surface. An example of a ginglymoid joint is the humeroulnar joint.
 Ellipsoid. Ellipsoid joints are similar to spheroid joints in that they allow the same type of movement albeit to a lesser magnitude. The ellipsoid joint allows movement in two planes (flexion, extension; abduction, adduction)



Types of diarthrosis or synovial joints.

and is biaxial. Examples of this joint can be found at the radiocarpal articulation at the wrist and the metacarpophalangeal articulation with the phalanges.
 Planar. As its name suggests, a planar joint is characterized by at surfaces that slide over each other. Movement at this joint does not occur about an axis and is termed nonaxial. Examples of a planar joint include the intermetatarsal joints and some intercarpal joints.

 Saddle (sellar). Saddle joints are characterized by a convex surface in one cross-sectional plane and a concave surface in the plane perpendicular to it. Examples of a saddle joint include the interphalangeal joints, the carpometacarpal joint of the thumb, the humeroulnar joint, and the calcaneocuboid joints.

In reality, no joint surface is planar or resembles a true geometric form; that is they resemble either the outer or inner surface of a piece of eggshell.

Synovial Fluid

Articular cartilage is subject to a great variation of loading conditions, so joint lubrication through the synovial fluid is necessary to minimize frictional resistance between the weight-bearing surfaces. Fortunately, synovial joints are blessed with a very superior lubricating system, which permits a remarkably frictionless interaction at the joint surfaces. A cartilaginous lubricated interface has a coefficient of friction* of 0.002. By way of comparison, ice on ice has a higher coefficient of friction (0.03). The composition of synovial fluid is nearly the same as blood plasma, but with a decreased total protein content and a higher concentration of hyaluronan.

*Coefficient of friction is a ratio of the force needed to make a body glide across a surface compared with the weight or force holding the two surfaces in contact.

CLINICAL PEARL

Hyaluronan is a critical constituent component of normal synovial fluid and an important contributor to joint homeostasis. Hyaluronan imparts anti-inflammatory and anti-nociceptive properties to normal synovial fluid and contributes to joint lubrication. It also is responsible or the viscoelastic properties of synovial fluid, and contributes to the lubrication of articular cartilage surfaces.

Indeed, synovial fluid is essentially a dialysate of plasma to which hyaluronan has been added. Hyaluronan is a GAG that is continually synthesized and released into the synovial fluid by specialized synoviocytes. The mechanical properties of synovial fluid permit it to act as both a cushion and a lubricant to the joint. Diseases such as osteoarthritis, affect the thixotropic properties (thixotropy is the property of various gels becoming fluid when disturbed, as by shaking) of synovial fluid, resulting in reduced lubrication and subsequent wear of the articular cartilage and joint surfaces. It is well established that damaged articular cartilage in adults has a very limited potential or healing because it possesses neither a blood supply nor lymphatic drainage.

Bursae

Closely associated with some synovial joints are attened, saclike structures called bursae that are lined with a synovial membrane and filled with synovial fluid. The bursa produces small amounts of fluid, allowing or smooth and almost frictionless motion between contiguous muscles, tendons, bones, ligaments, and skin. A tendon sheath is a modified bursa. A bursa can be a source of pain if it becomes inflamed or infected.

KINESIOLOGY

When describing movements, it is necessary to have a starting position as the reference position. This starting position is referred to as the anatomic reference position. The anatomic reference position or the human body is described as the erect standing position with the feet just slightly separated and the arms hanging by the side, the elbows straight, and the palms of the hand acing forward.

Directional Terms

Directional terms are used to describe the relationship of body parts or the location of an external object with respect to the body. The following are commonly used directional terms:

- Superior or cranial. Closer to the head.
- Inferior or caudal. Closer to the feet.
- Anterior or ventral. Toward the front of the body.
- Posterior or dorsal. Toward the back of the body.
- Medial. Toward the midline of the body.
- Lateral. Away from the midline of the body.
- Proximal. Closer to the trunk.
- Distal. Away from the trunk.
- Superficial. Toward the surface of the body.
- Deep. Away from the surface of the body in the direction of the inside of the body.

The anatomical position.

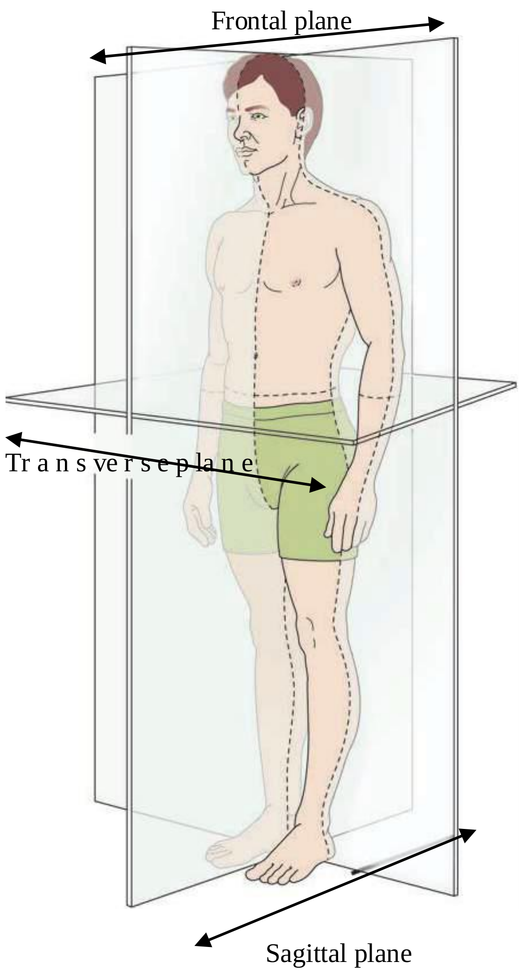
MOVEMENTS OF THE BODY SEGMENTS

In general, there are two types of motions: translation, which occurs in either a straight or curved line, and rotation, which involves a circular motion around a pivot point. Movements of the body segments occur in three dimensions along imaginary planes and around various axes o the body.

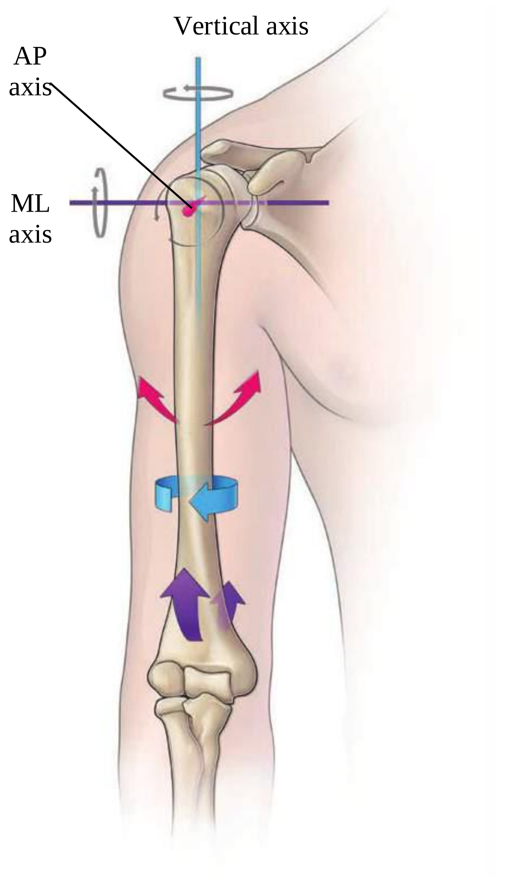
Planes of the Body

There are three traditional planes of the body corresponding to the three dimensions of space: sagittal, frontal, and transverse.

 Sagittal. The sagittal plane, also known as the anterior– posterior or median plane, divides the body vertically into left and right halves of equal size.
 Frontal. The frontal plane, also known as the lateral or coronal plane, divides the body equally into front and back halves.
 Transverse. The transverse plane, also known as the horizontal plane, divides the body equally into top and bottom halves.



Planes o the body.



Axes o the body.

Because each of these planes bisects the body, it follows that each plane must pass through the center of gravity (COG) or center of mass (COM).* Where a gravity field can be considered to be uniform, the COG and COM are the same. If the movement described occurs in a plane that passes through the center of gravity, that movement is deemed to have occurred in a cardinal plane. An arc of motion represents the total number of degrees traced between the two extreme positions of movement in a specific plane of motion. If a joint has more than one plane of motion, each type of motion is referred to as a unit of motion. For example, the wrist has two units of motion: flexion– extension (anterior–posterior plane) and ulnar–radial deviation Few movements involved with functional activities occur in the cardinal planes. Instead, most movements occur in an infinite number of vertical and horizontal planes parallel to the cardinal planes.

*The COG, or COM, may be defined as the point at which the three planes of the body intersect each other. The line of gravity is defined as the vertical line at which the two vertical planes intersect each other and is always vertically downward toward the center of the earth.

Axes of the Body

Three reference axes are used to describe human motion. The axis around which the movement takes place is always perpendicular to the plane in which it occurs.

- Mediolateral. The mediolateral (ML) or coronal, axis, is perpendicular to the sagittal plane.
- Vertical. T e vertical or longitudinal axis is perpendicular to the frontal plane.
- Anteroposterior (AP). The AP axis is perpendicular to the transverse plane.

Most movements occur in planes and around axes that are somewhere in between the traditional planes and axes. Thus, nominal identification of every plane and axis of movement is impractical. The structure of the joint determines the possible axes of motion that are available. The axis of rotation remains stationary only if the convex member of a joint is a perfect sphere and articulates with a perfect reciprocally shaped concave member.

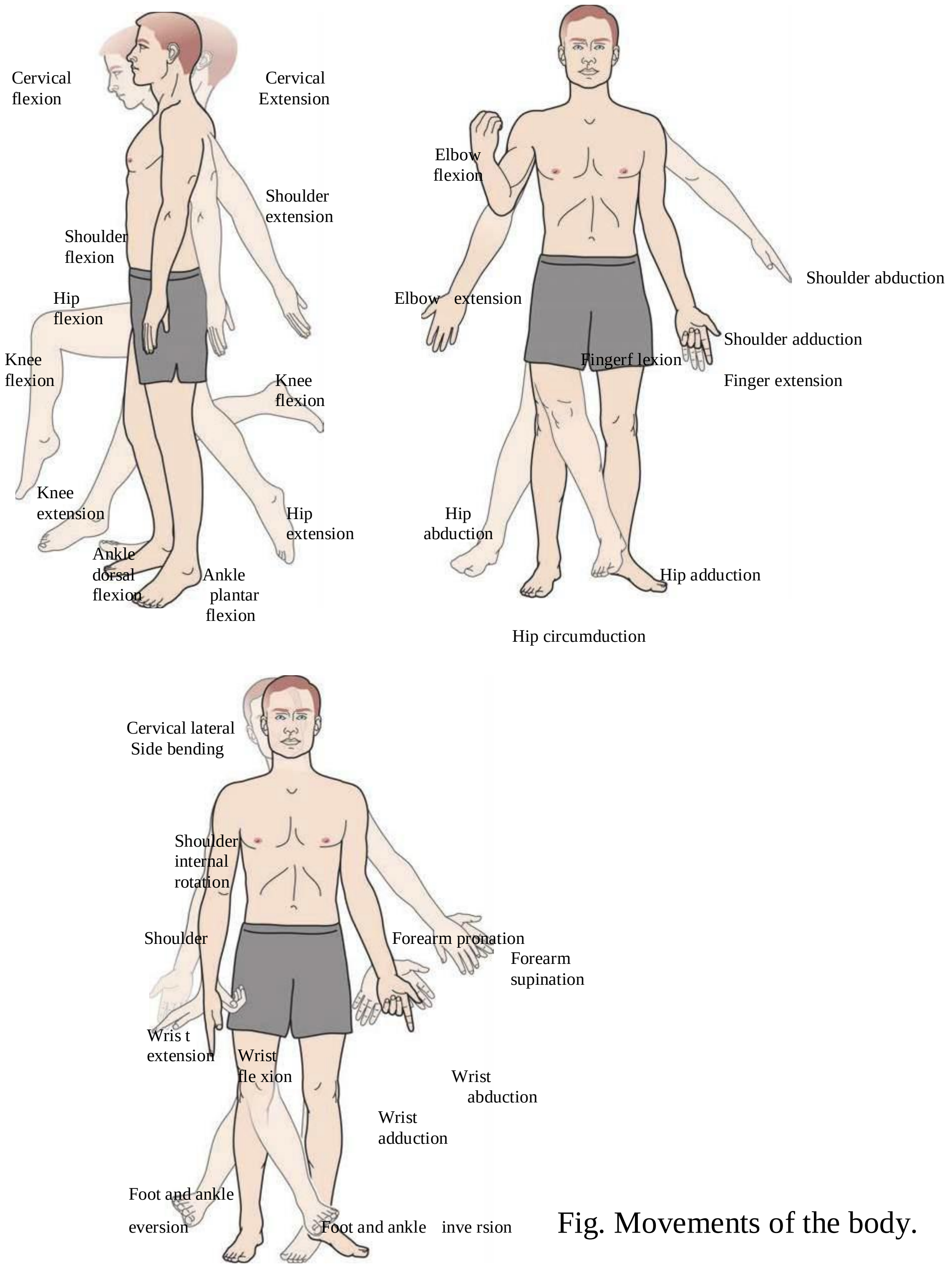


Fig. Movements of the body.

The planes and axes or the more common planar movements are as follows:

- Flexion, extension, hyperextension, dorsiflexion, and plantar flexion occur in the sagittal plane around an ML axis. Exceptions to this include carpometacarpal flexion and extension of the thumb.
- Abduction and adduction, side flexion of the trunk, elevation and depression of the shoulder girdle, radial and ulnar deviation of the wrist, and eversion and inversion of the foot occur in the frontal plane around an AP axis.
- Rotation of the head, neck, and trunk; internal rotation and external rotation of the arm or leg; horizontal adduction and abduction of the arm or thigh; and pronation and supination of the forearm usually occur in the transverse plane around the vertical axis. Rotary motions involve the curved movement of a segment around a fixed axis, or center of rotation (COR). When a curved movement occurs around an axis that is not fixed, but instead shifts in space as the object moves, the axis around which the segment appears to move is referred to as the instantaneous axis of rotation or instantaneous COR.
- Arm circling and trunk circling are examples of circumduction. Circumduction involves an orderly sequence of circular movements that occur in the sagittal, frontal, and intermediate oblique planes, so that the segment as a whole incorporates a combination of flexion, extension, abduction, and adduction. Circumduction movements can occur at biaxial and triaxial joints. Examples of these joints include the tibiofemoral, radiohumeral, hip, glenohumeral, and the spinal joints.

Both the configuration of a joint and the line of pull o the muscle acting at a joint determine the motion that occurs at a joint:

- A muscle whose line of pull is lateral to the joint is a potential abductor.
- A muscle whose line of pull is medial to the joint is a potential adductor.
- A muscle whose line of pull is anterior to a joint has the potential to extend or flex the joint. At the knee, an anterior line of pull may cause the knee to extend, whereas, at the elbow joint, an anterior line of pull may cause flexion of the elbow.
- A muscle whose line of pull is posterior to the joint has the potential to extend or flex a joint (refer to preceding example).

Center of Gravity

Every object or segment can be considered to have a single COG, or COM—the point at which all the mass of the object or segment appears to be concentrated. In a symmetrical object, the COG is always located in the geometric center of the object. However, in an asymmetrical object such as the human body, the COG becomes the point at which the line of gravity balances the object. The line of gravity can best be visualized as a string with the weight on the end (a plumb-line), with a string attached to the COG of an object. If the human body is considered as a rigid object, the COG of the body lies approximately anterior to the second sacral vertebra (S2). Since the human body is not rigid, an individual’s COG continues to change with movement with the amount of change in the location depending on how disproportionately the segments are rearranged. During static standing, the body’s line of gravity is between the individual’s feet (base of support). The BOS includes the part of the body in contact with the supporting surface and the intervening area. If an individual bends forward at the waist, the line of gravity moves outside of the BOS. The size of the BOS and its relation to the COG are important factors in the maintenance of balance and, thus, the stability of an object. The COG must be maintained over the BOS if an equilibrium is to be maintained. If the BOS of an object is large, the line of gravity is less likely to be displaced outside the BOS, which makes the object more stable.

Degrees of Freedom

The number of independent modes of motion at a joint is referred to as the available degrees of freedom (DOF). A joint can have up to 3 degrees of angular freedom, corresponding to the three dimensions of space. If a joint can swing in one direction or can only spin, it is said to have 1 DOF. The proximal interphalangeal joint is an example of a joint with 1 DOF. If a joint can spin and swing in one way only, or it can swing in two completely distinct ways, but not spin, it is said to have 2 DOF. The tibiofemoral joint, temporomandibular joint, proximal and distal radioulnar joints, subtalar joint, and talocalcaneal joint are examples of joints with 2 DOF. If the bone can spin and also swing in two distinct directions, then it is said to have 3 DOF. Ball-and-socket joints, such as the shoulder and hip, have 3 DOF.

CLINICAL PEARL

Joint motion that occurs only in one plane is designated as 1 DOF; in two planes, 2 DOF; and in three planes, 3 DOF.

Because of the arrangement of the articulating surfaces—the surrounding ligaments and joint capsules—most motions around a joint do not occur in straight planes or along straight lines. Instead, the bones at any joint move through space in curved paths. This can best be illustrated using Codman’s paradox.

1. Stand with your arms by your side, palms acing inward, thumbs extended. Notice that the thumb is pointing forward.
2. Flex one arm to 90 degrees at the shoulder so that the thumb is pointing up.
3. From this position, horizontally extend your arm so that the thumb remains pointing up, but your arm is in a position of 90 degrees of glenohumeral abduction.
4. From this position, without rotating your arm, return the arm to your side and note that your thumb is now pointing away from your thigh.

Referring to the start position, and using the thumb as the reference, the arm has undergone an external rotation of 90 degrees. But where and when did the rotation take place? Undoubtedly, it occurred during the three separate, straight-plane motions or swings that etched a triangle in space. What you have just witnessed is an example of a conjunct rotation—a rotation that occurs as a result of joint surface shapes—and the effect of inert tissues rather than contractile tissues. Conjunct rotations can only occur in joints that can rotate internally or externally. Although not always apparent, most joints can so rotate. Consider the motions of elbow flexion and extension. While fully flexing and extending your elbow a few times, watch the pisiform bone and forearm. If you watch carefully, you should notice that the pisiform and the forearm move in a direction of supination during flexion, and pronation during extension of the elbow. The pronation and supination motions are examples of conjunct rotations.

Most habitual movements, or those movements that occur most frequently at a joint involve a conjunct rotation. However, the conjunct rotations are not always under volitional control. In act, the conjunct rotation is only under volitional control in joints with 3 DOF (e.g., glenohumeral and hip joints). In joints with fewer than 3 DOF (hinge joints, such as the tibiofemoral and ulnohumeral joints), the conjunct rotation occurs as part of the movement but is not under voluntary control. The implications for this become important when attempting to restore motion at these joints: the mobilizing techniques must take into consideration both the relative shapes of the articulating surfaces as well as the conjunct rotation that is associated with a particular motion.

JOINT KINEMATICS

Kinematics is the study of motion and describes how something is moving without stating the cause. Kinetics is the term used to explain why an object moves the way it does due to the forces acting on that object. In studying joint kinematics, two major types of motion are involved: (1) osteokinematic and (2) arthrokinematic

Osteokinematic Motion

The normal ROM of a joint is sometimes called the physiologic or anatomic ROM. Physiologic movements of the bones termed osteokinematics, are movements that can be performed voluntarily, for example, flexion of the shoulder. Osteokinematic motion occurs when any object forms the radius of an imaginary circle about a fixed point. The axis of rotation or osteokinematic motions is oriented perpendicular to the plane in which the rotation occurs. The distance traveled by the motion may be a small arc or a complete circle and is measured as an angle, in degrees. All human body segment motions involve osteokinematic motions. Examples of osteokinematic motion include abduction or adduction of the arm, flexion of the hip or knee, and side bending of the trunk. A number of factors determine the amount of available physiologic joint motion, including

- the integrity of the joint surfaces and the amount of joint motion;
- the mobility and pliability of the soft tissues that surround a joint;
- the degree of soft -tissue approximation that occurs;
- the amount of scarring that is present—interstitial scarring or fibrosis can occur in and around the joint capsules, within the muscles, and within the ligaments as a result of previous trauma;
- age—joint motion tends to decrease with increasing age;
- gender—in general, females have more joint motion than males.

ROM is considered to be pathological when motion at a joint either exceeds or fails to reach the normal physiologic limits of motion

Moment Arm

To understand the concept of a moment arm, an understanding of the anatomy and movement (kinematics) of the joint of interest is necessary. Although muscles produce linear forces, motions at joints are all rotary. For example, some joints can be considered to rotate about a fixed point. A good example of such a joint is the elbow. At the elbow joint, where the humerus and ulna articulate, the resulting rotation occurs primarily about a fixed point, referred to as the COR. In the case of the elbow joint, this COR is relatively constant throughout the joint ROM. However, in other joints (e.g., the knee) the COR moves through space as the knee joint flexes and extends because the articulating surfaces are not perfect circles. In the case of the knee, it is not appropriate to discuss a single COR—rather we must speak of a COR corresponding to a particular joint angle, or, using the terminology of joint kinematics, we must speak of the instantaneous center of rotation (ICR), that is, the COR at any "instant" in time or space. Thus, the moment arm is defined as the perpendicular distance from the line of force application to the axis of rotation.

Arthrokinematic Motion

The term arthrokinematics is used to describe the motions of the bone surfaces within the joint. These movements cannot be performed voluntarily and can only occur when resistance to active motion is applied, or when the patient's muscles are completely relaxed. Both the physiologic (osteokinematic) and joint play (arthrokinematic) motions occur simultaneously during movement and are directly proportional to each other, with a small increment of arthrokinematic motion resulting in a larger increment of osteokinematic motion. Normal arthrokinematic motions must occur or a full-range of physiologic motion to occur. Mennell introduced the concept that full, painless, active ROM is not possible without these motions and that a restriction of arthrokinematic motion results in a decrease in osteokinematic motion. At each synovial articulation, the articulating surface of each bone moves in relation to the shape of the other articulating surface. A normal joint has an available range of active, or physiologic, motion, which is limited by a physiologic barrier as tension develops within the surrounding tissues, such as the joint capsule, ligaments, and CT . Beyond the available passive ROM, the anatomic barrier is found. This barrier cannot be exceeded without disruption to the integrity of the joint. Accessory or component motions, which are also not under voluntary control occur during active motion. These include examples such as rotation of the ulna during forearm pronation and supination. At the physiologic barrier, there is an additional amount of passive ROM. This small motion, which is available at the joint surfaces, is referred to as joint-play motion. The type and amount of motion occurring at the joint surfaces is influenced by the shape of their respective joint surfaces. Three fundamental types of joint-play motions exist based on the different types of joint surfaces

- Roll. A roll occurs when the points of contact on each incongruent joint surface are constantly changing so that new point on one surface meets a new point on the opposite surface. This type of movement is analogous to a tire on a car as the car rolls forward. In a normal functioning joint, pure rolling does not occur alone but instead occurs in combination with joint sliding and spinning. The term rock is of en used to describe small rolling motions. Rolling is always in the same direction as the swinging bone motion irrespective of whether the surface is convex or concave. If the rolling occurs alone, it causes compression of the surfaces on the side to which the bone is swinging and separation on the other side.
- Slide. A slide is a pure translation if the two surfaces are congruently at or curved. It occurs if only one point on the moving surface makes contact with new points on the opposing surface. This type of movement is analogous to a car tire skidding when the brakes are applied suddenly on a wet road. This type of motion also is referred to as translatory motion. Although the roll of a joint always occurs in the same direction as the swing of a bone, the direction of the slide is determined by the shape of the articulating surface. This rule is often referred to as the concave–convex rule: If the joint surface is convex relative to the other surface, the slide occurs in the opposite direction to the osteokinematic motion. If, on the other hand, the joint surface is concave, the slide occurs in the same direction as the osteokinematic motion.

 Spin. A spin is defined as any movement in which the bone moves, but the mechanical axis remains stationary. A spin involves a rotation of one surface on an opposing surface around a vertical axis. This type of motion is analogous to the pirouette performed by a ballet dancer. Spinning rarely occurs alone in joints but instead occurs in combination with rolling and sliding. Spin motions in the body include internal and external rotation of the glenohumeral joint when the humerus is abducted to 90 degrees; and at the radial head during forearm pronation and supination.

As osteokinematic and arthrokinematic motions are directly proportional to each other, such that one cannot occur completely without the other, it follows that if a joint is not functioning correctly, one or both of these motions may be at fault. When examining a patient with movement impairment, it is critical that the clinician determine whether the osteokinematic motion or the arthrokinematic motion is restricted so that the intervention can be made as specific as possible. This is particularly important when trying to regain motion using traditional stretching methods which employ osteokinematic motions, as these methods magnify the force at the joint and cause compression of the joint surfaces in the direction of the rolling bone. In contrast, using an arthrokinematic technique to increase the joint play allows the force to be applied close to the joint surface and in the direction that replicates the sliding component of the joint mechanics.

CLINICAL PEARL

Two other accessory motions are used by clinicians in various manual techniques, compression and distraction:

 Compression. This occurs when there is a decrease in the joint space between bony partners and although it occurs naturally throughout the body whenever a joint is weight bearing, it can be applied manually to help move synovial fluid and maintain cartilage health.

 Distraction. This involves an increase in the joint space between bony partners. The terms traction and distraction are not synonymous, as the former involves a force applied to the long axis of a bone, which does not always result in the joint space increasing between the bony partners. For example, if traction is applied to the shaft of the femur, it results in a glide occurring at the hip joint surface, whereas if a distraction force is applied at right angles to the acetabulum, distraction at the hip joint occurs.

In the extremities, osteokinematic motion is controlled by the amount of flexibility of the surrounding so tissues of the joint, where flexibility is defined as the amount of internal resistance to motion. In contrast, the arthrokinematic motion is controlled by the integrity of the joint surfaces and the supporting tissues of the joint. This characteristic can be noted clinically in a chronic rupture of the anterior cruciate ligament of the knee. Upon examination of that knee, the arthrokinematic motion (joint slide or glide) is found to be increased, illustrated by a positive Lachman test, but the ROM of the knee, its osteokinematic motion, is not affected.

In contrast, in the spine, the osteokinematic motion is controlled by both the flexibility of the surrounding so tissues and by the integrity of the joint surfaces and the supporting tissues of the joint. This characteristic can be noted clinically when examining the craniovertebral joint, where a restriction in the arthrokinematic motion (joint slide or glide) can be caused by either a joint restriction or an adaptively shortened sub-occipital muscle.