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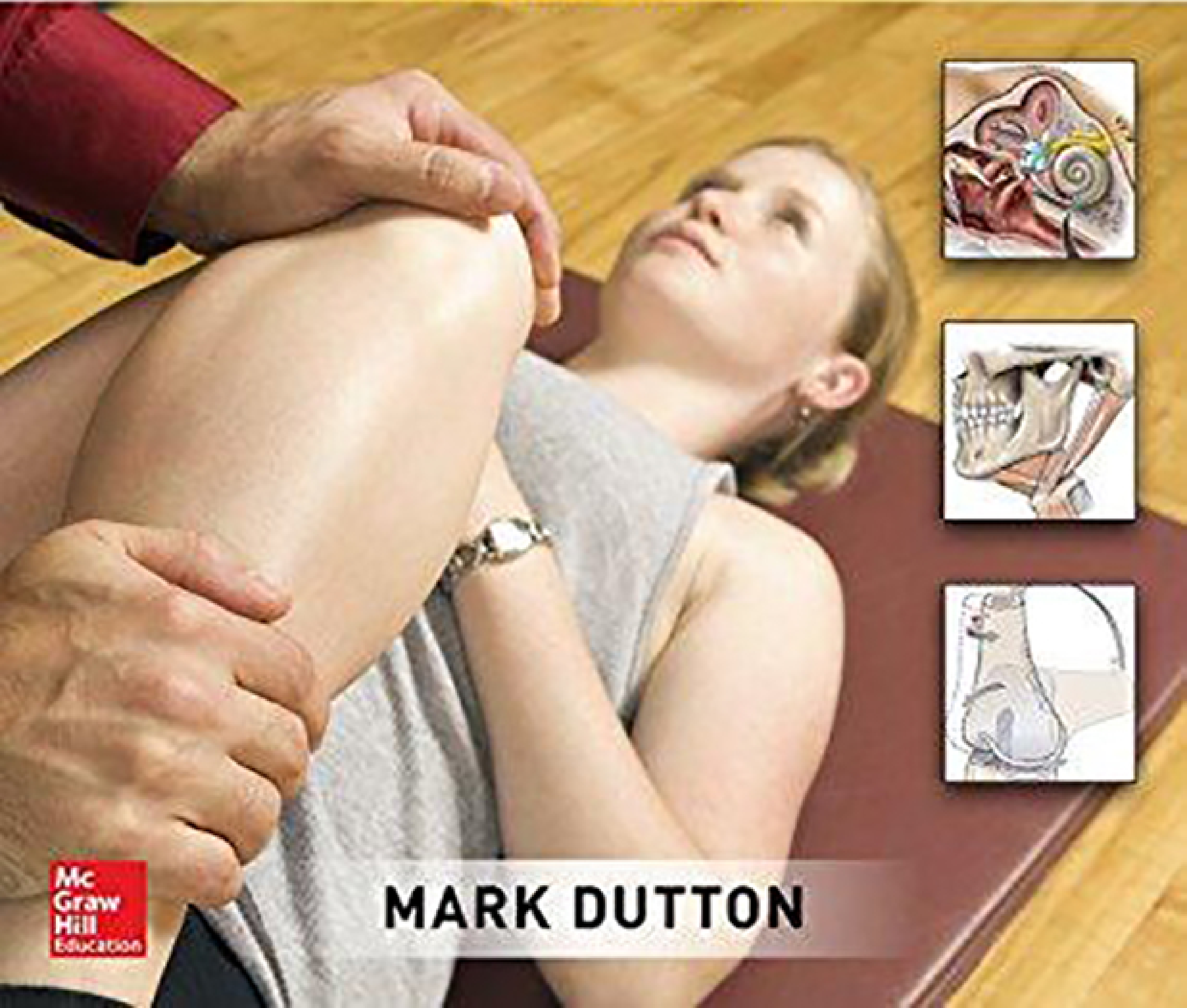
ORTHOPAEDIC

Examination, Evaluation and Intervention

FOURTH EDITION



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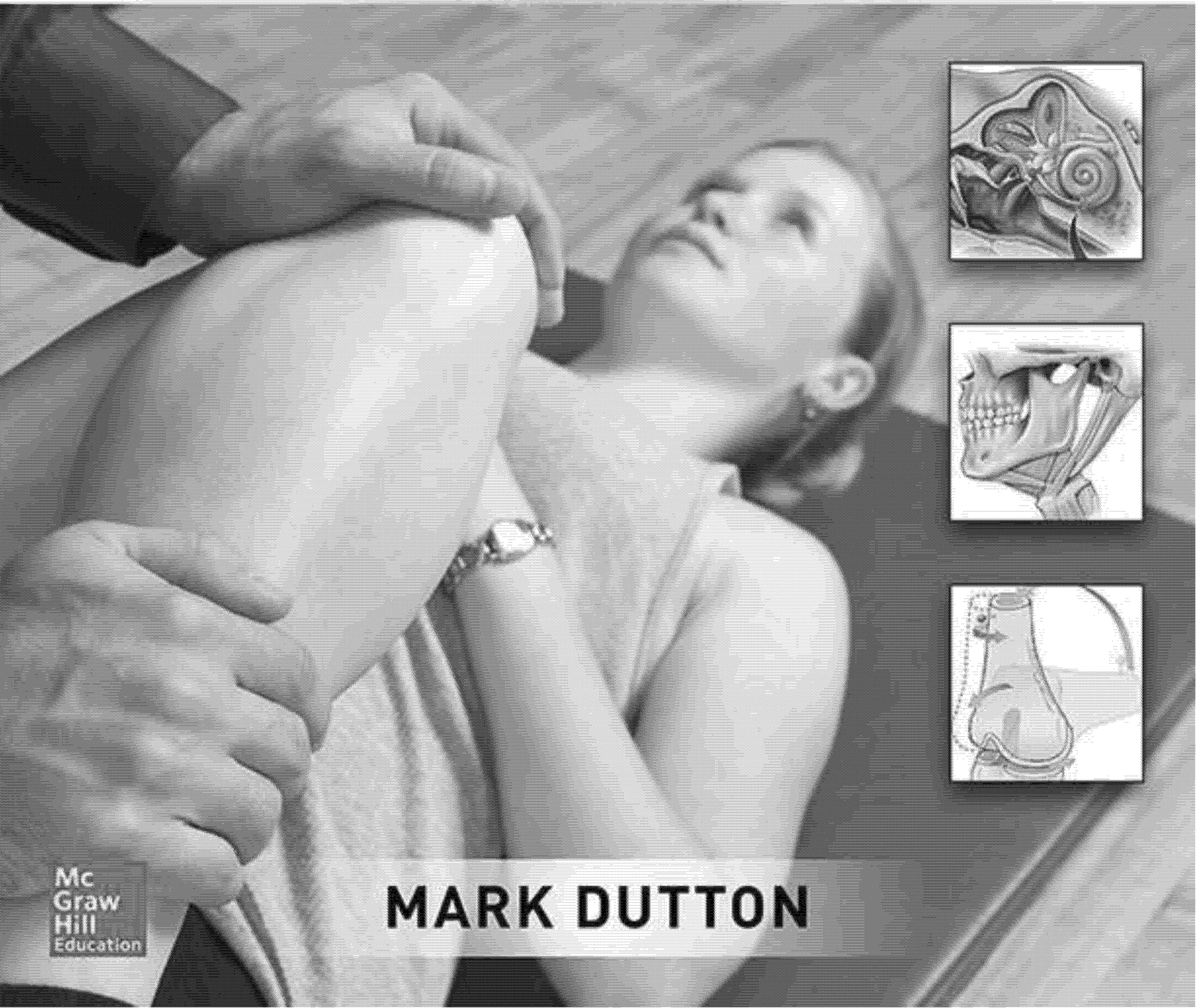

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FOURTH EDITION

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For my parents,
Ron and Brenda, who have always helped, guided, and inspired me
and to my two daughters, Leah and Lauren, who provide me with such joy.

Your Legacy

Will you have earned the respect of your peers and the admiration of your critics?

Will you have acted humbly during success and gracefully in the face of adversity?

Will you be remembered for how often you brought smiles to the hearts of others?

Will you have looked for the very best, and done your utmost to build worth, in others?

Will you have left this world a better place by the life you have lived?

Modified from The Legacy You Leave ©2000 by Rick Beneteau

Contents

SECTION I

ANATOMY

SECTION II

EXAMINATION AND EVALUATION

SECTION III

INTERVENTION

SECTION IV

THE EXTREMITIES

SECTION V

THE SPINE AND TMJ

SECTION VI

SPECIAL CONSIDERATIONS

Preface

The fourth edition of this book is an update of information and bibliography provided in the previous versions together with a reorganization of various chapters.

The United States currently spends more money on healthcare per person than any other country in the world, with current projections indicating that 20% of the gross domestic product of the United States will be spent on healthcare by the year 2019.[1] As the population continues to age, the treatment of musculoskeletal conditions, and their subsequent expenses, will also increase. This will place an increasing burden on the clinician to provide value for money—the achievement of a health outcome relative to the costs incurred. Gone are the days when a clinician can rely on an expensive shotgun approach to treatment. Instead, emphasis is now placed on outcomes such as patient satisfaction and accurate measures of clinical outcomes, for it is the consistent measurement and reporting of clinical outcomes that is the most powerful tool in moving toward a value-based system.[2]

To that end, the aim of this book is to provide the reader with a systematic and evidence-based approach to the examination and intervention of the orthopaedic patient. Such an approach must be eclectic because no single method works all of the time. Thus, this book attempts to incorporate the most reliable concepts currently available.

I hope that this book will be seen as the best available textbook, guide, review, and reference for healthcare students and clinicians involved in the care of the orthopaedic population.

Mark Dutton, PT

Comments about this book may be sent to me at pt@mcgraw-hill.com.

Acknowledgments

From inception to completion, the various editions span almost 12 years. Such an endeavor cannot be completed without the help of many. I would like to take this opportunity to thank the following:

- The faculty of the North American Institute of Manual and Manipulative Therapy (NAIOMT)—especially, Jim Meadows, Erl Pettman, Cliff Fowler, Diane Lee, and the late Dave Lamb.
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- To the countless clinicians throughout the world who continually strive to improve their knowledge and clinical skills.

Introduction

> “The very first step towards success in any occupation is to become interested in it.”
>
> —Sir William Osler (1849–1919)

Until the beginning of the last century, knowledge about the mechanism of healing and the methods to decrease pain and suffering were extremely limited. Although we may scoff at many of the interventions used in the distant past, many of the interventions we use today, albeit less radical, have still to demonstrate much more in the way of effectiveness. That may soon change with the recent emphasis within many healthcare professions on evidence-based clinical practice. The process of evidence-based practice is outlined in Table I-1. When combining clinical expertise with the best available external clinical evidence, clinicians can make informed decisions regarding patient management, including the selection and interpretation of the most appropriate evaluation procedures. Also, intervention strategies based on the best available evidence will have a greater likelihood of success with the least associated risk.[3,4]

TABLE I-1 The Process of Evidence-Based Practice

1. Identify the patient problem. Derive a specific question.
2. Search the literature.
3. Appraise the literature.
4. Integrate the appraisal of literature with your clinical expertise, experience, patient values, and unique circumstances.
5. Implement the findings.
6. Assess outcome and reappraise.

Data from Sackett DL, Strauss SE, Richardson WS, et al. Evidence Based Medicine: How to Practice and Teach EBM. 2nd ed. Edinburgh, Scotland: Churchill Livingstone; 2000.

The goal of every clinician should be to enhance patient/client satisfaction, increase efficiency, and decrease unproven treatment approaches.[4] The management of the patient/client is a complex process involving an intricate blend of experience, knowledge, and interpersonal skills. Obtaining an accurate diagnosis requires a systematic and logical approach. Such an approach should be eclectic because no single method works all of the time. For any intervention to be successful, an accurate diagnosis must be followed by a carefully planned and specific rehabilitation program to both the affected area and its related structures. In this book, great emphasis is placed on the appropriate use of manual techniques and therapeutic exercise based on these considerations. Electrotherapeutic and thermal/cryotherapeutic modalities should be viewed as adjuncts to the rehabilitative process. The accompanying DVD to this book contains numerous video clips of manual techniques and therapeutic exercises, which the reader is encouraged to view. The following icon is used throughout the text to indicate when such clips are available. [VIDEO]

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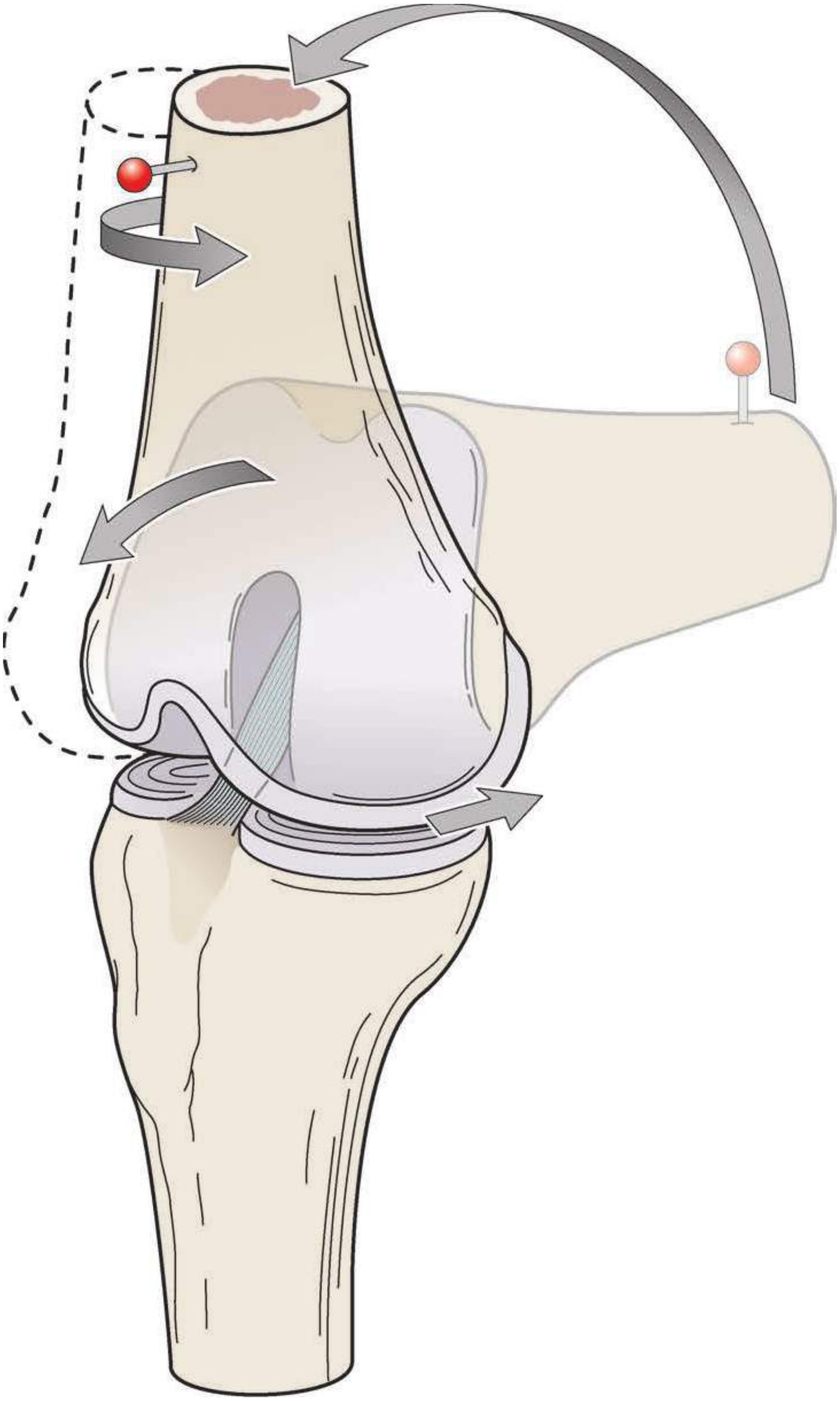
SECTION I ANATOMY



CHAPTER 1

The Musculoskeletal System

CHAPTER OBJECTIVES

At the completion of this chapter,
the reader will 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. Define the various terminologies used to describe the joint position, movements, and relationships.
5. Give definitions for commonly used biomechanical terms.
6. Describe the different planes of the body.
7. Define 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. Define the terms osteokinematic motion and arthrokinematic motion.
10. Differentiate between the different 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. Define the terms close-packed and open-packed.

OVERVIEW

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 four 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.[1] 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.[1] Connective tissue provides structural and metabolic support for other tissues and organs of the body.
- Muscle. Muscles are classified 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.[2]
- 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 (see Chapter 3).

CONNECTIVE TISSUE

CT proper has a loose, flexible 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.[3,4] 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.[5,6] Glycoproteins, another component of the ECM, consist of fibronectin and thrombospondin and function as adhesive structures for repair and regeneration.[7]

- Elastic fibers are composed of a protein called elastin. As its name suggests, elastin provides elastic properties to the tissues in which it is situated.[8] Elastin fibers can stretch, but they normally return to their original shape when the tension is released. Thus, the elastic fibers of elastin determine the patterns of distention and recoil in most organs, including the skin and lungs, blood vessels, and CT. Bundles of collagen and elastin combine to form a matrix of CT fascicles. This matrix is organized within the primary collagen bundles as well as between the bundles that surround them.[9]
- 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 1-1. Collagenous and elastic fibers are sparse and irregularly arranged in loose CT but are tightly packed in dense CT.[10]

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.[11,12] Fascia may be categorized as fibrous or nonfibrous, with the fibrous components consisting mainly of collagen and elastin fibers, and the nonfibrous portion consisting of amorphous ground substance.[13] Three different types of fascia have been identified, 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.[14] Histological studies of deep fascia in the limbs show that it consists of elastic fibers and undulated collagen fibers arranged in layers.[15] Each collagen layer is aligned in a different direction, and this permits a certain degree of stretch as well as a capacity to recoil.[16]

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.[17] Tenoblasts, or immature tendon cells, transform into tenocytes that synthesize collagen and components of the ECM network.[7] 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 fibrils, which coalesce to form fibers, which combine to form fascicles, which are bundled together to form a tendon.[18] 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.[19] This sheath consists of

TABLE 1-1 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, fascia, and skin	Random fiber orientation	Provides structural support

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.[9]

Tendons are metabolically active and are provided with a rich and vascular supply during development.[20] 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.[18] 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.[18]

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 (see Chapter 2). Tendons deform less than ligaments under an applied load and are able to transmit the load from muscle to bone.[9] Material and structural properties of the tendon increase from birth through maturity and then decrease from maturity through old age.[18] Although tendons withstand strong tensile forces well, they resist shear forces less well and provide little resistance to a compression force (see Chapter 2).

A tendon can be divided into three main sections:[21]

- 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,[22] and is an interface that is vulnerable to acute and chronic injury.[23] 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 frequently as at the enthesis.
- MTJ. The MTJ is the site where the muscle and tendon meet. The 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 (see Chapter 2).[24,25]

Ligaments

Skeletal ligaments are fibrous bands of dense CT that connect bones across joints. Ligaments can be named for the bones into which they insert (coracohumeral), their shape (deltoid of the ankle), or their relationships to each other (cruciate).[26] The gross structure of a ligament varies according to location (intra-articular or extra-articular, capsular), and function.[27] 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 stiffness (resistance to deformation—see Chapter 2).[28] Small amounts of elastin (1% of the dry weight) are present in ligaments, with the exception of the ligamentum flavum and the nuchal ligament of the spine, which contain more. The cellular organization of ligaments makes them ideal for sustaining tensile loads, with many containing functional subunits that are capable of tightening or loosening in different joint positions.[29] 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.[26] Ligaments contribute to the stability of joint function by preventing excessive motion,[30] acting as guides or checkreins to direct motion, and providing proprioceptive information for joint function through sensory nerve endings (see Chapter 3) and the attachments of the ligament to the joint capsule.[31–33] 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 (see Chapter 20).[26] 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.

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.[34] 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 for the development of cartilage and the maintenance of the ECM.[35] Chondrocytes produce aggrecan, link protein, and hyaluronan, all of which are extruded into the ECM, where they aggregate spontaneously.[4] 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 surface of the cells.[27]

Articular cartilage, the most abundant cartilage within the body, is devoid of any blood vessels, lymphatics, and nerves.[5,6] 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.[27] 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 four distinct zones with differing cellular morphology, biomechanical composition, collagen orientation, and structural properties, as follows:

- The super*fi*cial 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 for 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 for bearing large stresses in all directions. Fibrocartilage is an avascular, alymphatic, and aneural tissue and derives its nutrition by a double-diffusion system.[36] 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.[10] 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.[24] 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	Epiphyseal dysplasias	Distorted joints
	Apophysis forms under traction	Joint surface trauma	Degenerative changes
	Forms bone ends	Overuse injury	Fragmented development
	Supports articular surface	Damaged blood supply	Avascular necrosis
Physis	Epiphyseal or growth plate	Physeal dysplasia	Short stature
	Responsive to growth and sex hormones	Trauma	Deformed or angulated growth or growth arrest
	Vulnerable prior to growth spurt	Slipped epiphysis	
	Mechanically weak		
Metaphysis	Remodeling expanded bone end	Osteomyelitis	Sequestrum formation
	Cancellous bone heals rapidly	Tumors	Altered bone shape
	Vulnerable to osteomyelitis	Metaphyseal dysplasia	Distorted growth
	Affords ligament attachment		
Diaphysis	Forms shaft of bone	Fractures	Able to remodel angulation
	Large surface for muscle origin	Diaphyseal dysplasias	Cannot remodel rotation
	Significant compact cortical bone	Healing slower than at metaphysis	Involucrum with infection
	Strong in compression		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 of the diaphysis (shaft). About the time of birth, a secondary ossification center appears in each epiphysis (end) of 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 for mineral deposition. Calcification of 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 *f*actor 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 for 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 four distinct zones:[37]

- 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 of provisional calcification. It is within the hypertrophic zone that the matrix is prepared for 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.[38]
- 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 *fi*ber or myo*fi*ber. 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, therefore, adapt to variations in form and volume of each muscle according to muscular contraction and intramuscular modifications induced by joint movement.[15] 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 myo*fi*brils (Fig. 1-1), which extend throughout its length. Myofibrils are composed of sarcomeres arranged in series.[39]

CLINICAL PEARL

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

All skeletal muscles exhibit four characteristics:[40]

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 myo*fi*laments, 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).[39]

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

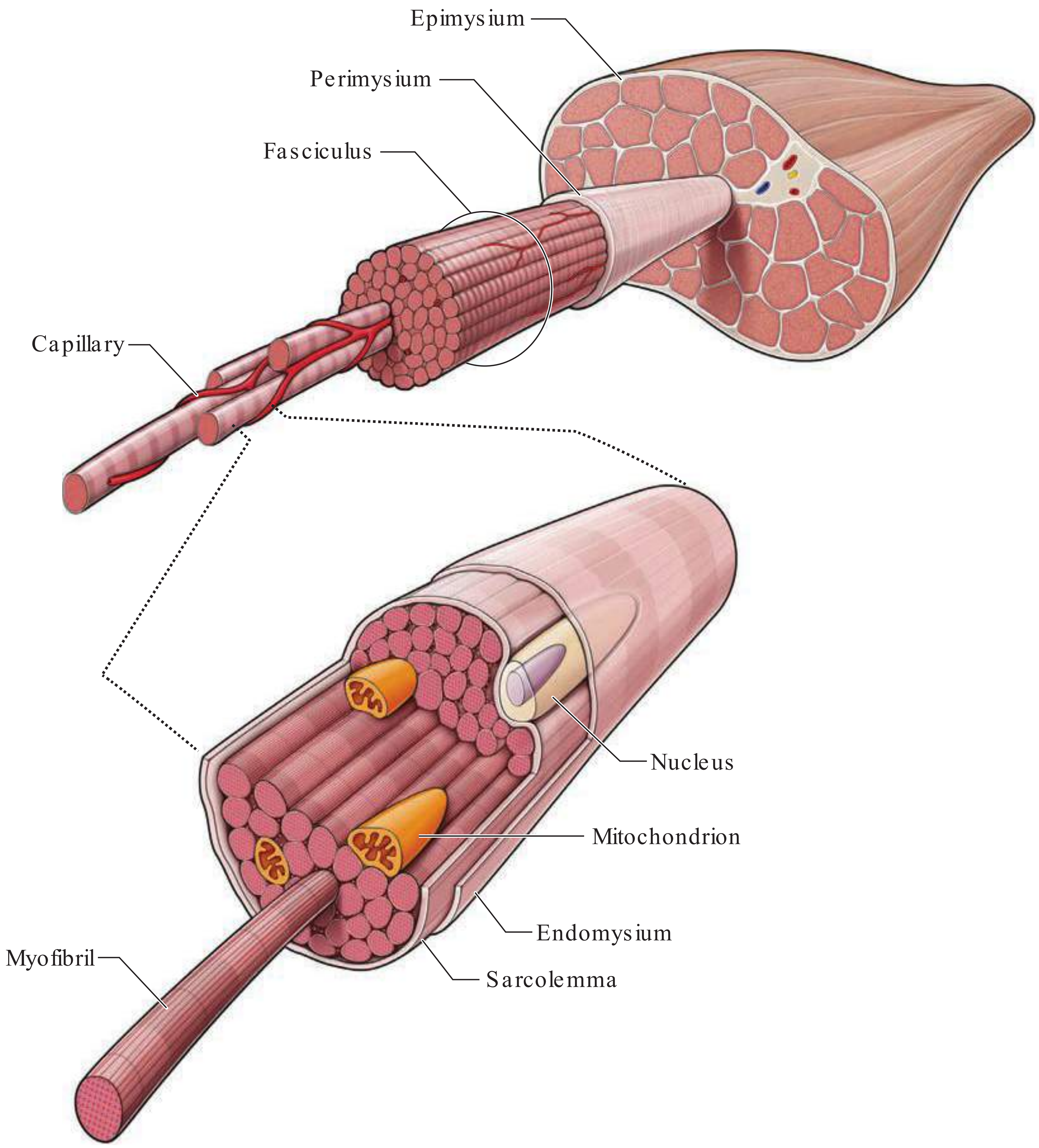


FIGURE 1-1 Microscopic structure of the muscle.

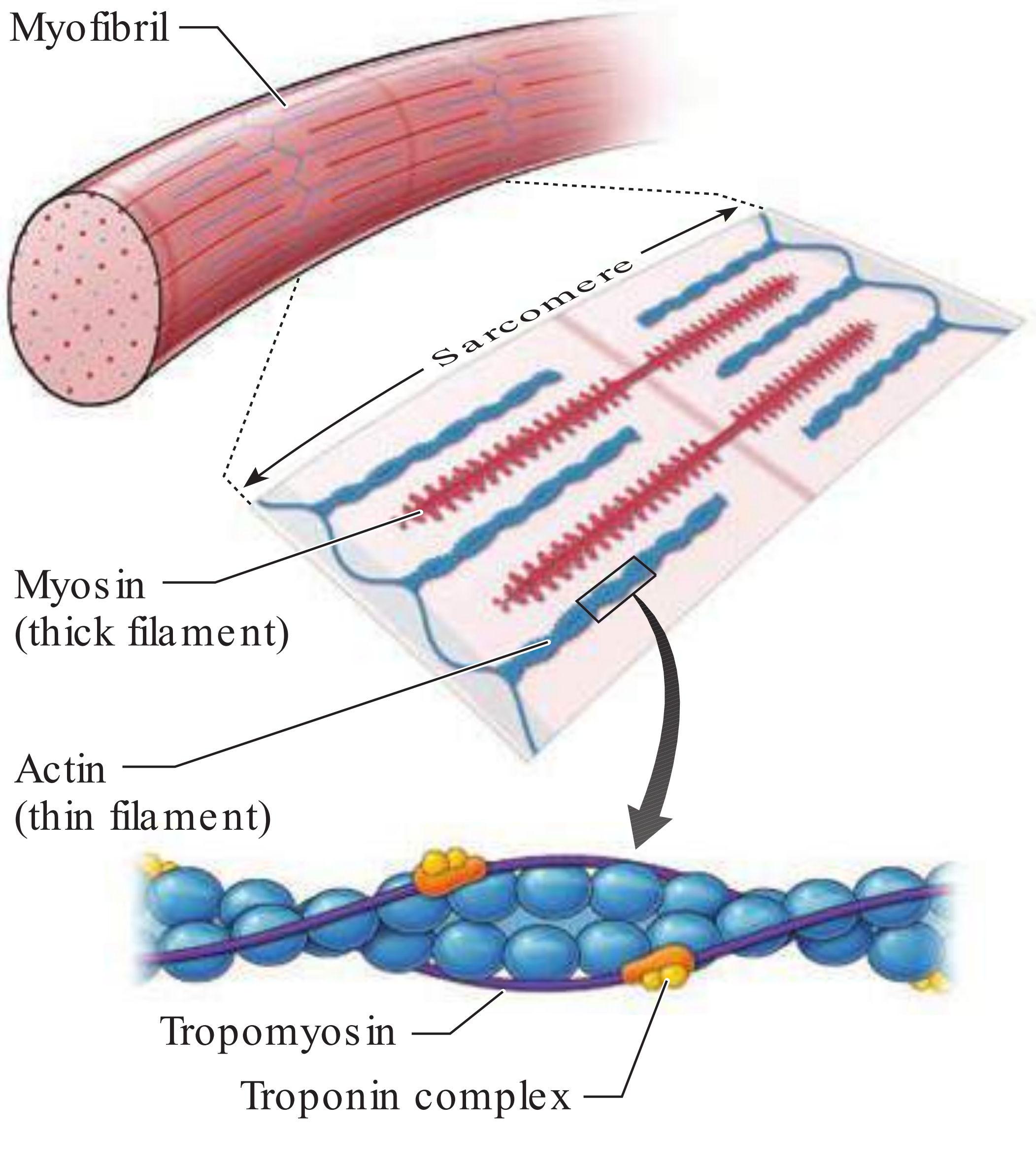


FIGURE 1-2 Troponin and tropomyosin action during a muscle contraction.

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.[41] 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.

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 of muscle fibers during a resistance exercise. However, a contraction can produce shortening or lengthening of the muscle, or no change in the muscle length. Thus, three types of contraction are commonly recognized: isometric, concentric, and eccentric (see Chapter 12).

- **Isometric contraction.** Isometric exercises provide a static contraction with a variable and accommodating resistance without producing any appreciable change in muscle length.[42]
- **Concentric contraction.** A concentric contraction produces a shortening of the muscle. This occurs when the tension generated by the agonist muscle is sufficient to overcome an external resistance and to move the body segment of one attachment toward the segment of its other attachment.[42]
- **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.[42] 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,[43–45] 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 filaments during an eccentric contraction, some of the myosin filaments probably are torn from the binding sites on the actin filament while the remainder are completing the contraction cycle.[46] The resulting force is substantially larger for a torn cross-bridge than for one being created during a normal cycle of muscle contraction. Consequently, the combined increase in force per cross-bridge and the number of active cross-bridges results in a maximum lengthening muscle tension that is greater than the tension that could be created during a shortening muscle action.[46,47]

CLINICAL PEARL

Both concentric and eccentric muscle action comprise the type of exercise called isotonic. An isotonic contraction is a contraction in which the tension within the muscle remains constant as the muscle shortens or lengthens.[42] 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 of muscle contraction.[42]

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.[42] Isokinetic contractions require the use of special equipment that produces an accommodating resistance. Both high-speed/low-resistance and low-speed/high-resistance regimens result in excellent strength gains.[48–51] The major disadvantage of this type of exercise is its expense. Also, there is the potential for impact loading and incorrect joint axis alignment.[52] Isokinetic exercises may also have questionable functional carryover.[53]
- **Econcentric contraction.** This type of contraction combines both a controlled concentric and a simultaneous eccentric contraction of the same muscle over two separate joints.[54] Examples of an econcentric contraction include the standing hamstring curl, in which the hamstrings work concentrically to flex 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 of 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 (see Chapter 10).

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.[55] The myosin filaments contain two flexible, hinge-like regions, which allow the cross-bridges 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 for 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 IIA	Type IIB
Size (diameter)	Small	Intermediate	Very large
Resistance to fatigue	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 fuel	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 Ca^{2+} from the terminal cisternae portion of the SR (a series of interconnected sacs and tubes that surround each myofibril).[56] The released Ca^{2+} 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 Ca^{2+} and muscle relaxation occurs. The return of Ca^{2+} to the SR involves active transport, requiring the degradation of adenosine triphosphate (ATP) to adenosine diphosphate (ADP)*.[56] Because SR function is closely associated with both contraction and relaxation, changes in its ability to release or sequester Ca^{2+} markedly affect both the time course and magnitude of force output by the muscle fiber.[57]

CLINICAL PEARL

The SR forms a network around the myofibrils, storing and providing the Ca^{2+} that is required for 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.[58] subdivide type II fibers into three classifications, including a type IIIC.

Type I fibers are richly endowed with mitochondria and have a high capacity for oxygen uptake. They are, therefore, suitable for activities of 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.[59]

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).[59] 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.[60] However, fiber conversion from type IIB to type IIA, and vice versa, has been found to occur with training.[61]

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*The most readily available energy for skeletal muscle cells is stored in the form of ATP and phosphocreatine (PCr). Through the activity of the enzyme ATPase, ATP promptly releases energy when required by the cell to perform any type of work, whether it is electrical, chemical, or mechanical.

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 fatigue 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 from Jull GA, Janda V. Muscle and motor control in low back pain. In: Twomey LT, Taylor JR, eds. Physical Therapy of 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.[2]

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.[62] EMD is affected by muscle fatigue, muscle length, muscle training, passive muscle stretching, and the type of muscle activation.[63] A tissue injury may increase the EMD and, therefore, increases the susceptibility to future injury if full healing does not occur.[64] One of the purposes of neuromuscular re-education (see Chapter 14) is to return the EMD to a normal level.[65]

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

- **Prime mover (agonist).** This is a muscle that is directly responsible for 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 of 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.[66]

- Concentric contractions. As the speed of a concentric contraction increases, the force it is capable of producing decreases.[43,45] The slower speed of 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 for 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.[43,45]
- 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 off.[67–69] 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.[43,45]

CLINICAL PEARL

The number of cross-bridges that can be formed is dependent on the extent of the overlap between the actin and myosin filaments.[70] 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 for 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 for 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.[2,54,71,72] 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.[46] Passive insufficiency of the muscle occurs when the two-joint muscle cannot stretch to the extent required for full ROM in the opposite direction at all joints crossed.[2,54,71,72] 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.[73]

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.[2] The motor units of 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.[74]

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.[75]

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.[76]

Although each muscle contains the contractile machinery to produce the forces for movement, it is the tendon that transmits these forces to the bones to achieve movement or stability of the body in space.[9] 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.[2]

Just as there are optimal speeds of length change and optimal muscle lengths, there are optimal insertion angles for each of the muscles. The angle of insertion of a muscle, and, therefore, its line of pull, can change during dynamic movements.[46]

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.[46] 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 for very high tension, such as the sartorius muscle, do not have pennate muscle fibers.[46] In contrast, pennate muscle fibers are found in those muscles in which the emphasis is on a high capacity for tension generation rather than ROM (e.g., gluteus maximus).

CLINICAL PEARL

Skeletal muscle blood flow increases 20-fold during muscle contractions.[77] 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.[78] Muscle function is most efficient at 38.5°C (101°F).[79]

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.[80] The hydrolysis of ATP to ADP and inorganic phosphate (P_i) provides the power for 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.[81] 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 (O_2). 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 for the rephosphorylation of ATP. The phosphagen system provides ATP primarily for 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.[82] 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.[83]

- Glycolytic system. The glycolytic system is an anaerobic process that involves the breakdown of 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.[82] 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.[81] 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.[82] This inhibition occurs once the muscle pH drops below a certain level, prompting the appearance of phosphofructokinase (PFK), resulting in local energy production ceasing until replenished by oxygen stores.

CLINICAL PEARL

Lactic acid is the major energy source for 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 O_2 and is consequently termed the "aerobic" system. The fuel sources for 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 for several hours.[82] 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.[84]

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:[85]

- 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:[86,87]

- 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 for 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.[88] 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.[88] 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.[89] 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:[89]

- Fibrous joints, which are joined by dense fibrous CT. Three types exist:
  - Suture (e.g., suture of the skull).
  - Gomphosis (e.g., tooth and mandible or maxilla articulation).
  - Syndesmosis (e.g., tibiofibular 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 for 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.[90] In a symphysis joint, the two bony components are covered with a thin lamina of hyaline cartilage and directly joined by fibrocartilage in the form of disks or pads.[90]

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 classified 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.[90] 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 (see Chapter 3). 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 fibrochondrocytes because they appear to be a mixture of fibroblasts and chondrocytes.[91] 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.[13] Peripherally disks are connected to fibrous capsules, usually by vascularized connective tissue, so that they become invaded by vessels and afferent and motor nerves.[13] Mechanoreceptors within the menisci function as transducers, converting the physical stimulus of tension and compression into a specific electrical nerve impulse (see Chapter 3).[92]

Synovial joints can be broadly classified according to structure or analogy (Fig. 1-3) into the following categories[93]:

- 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 (Fig. 1-3) (see later). 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 (Fig. 1-3). 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 of 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 (Fig. 1-3). 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)

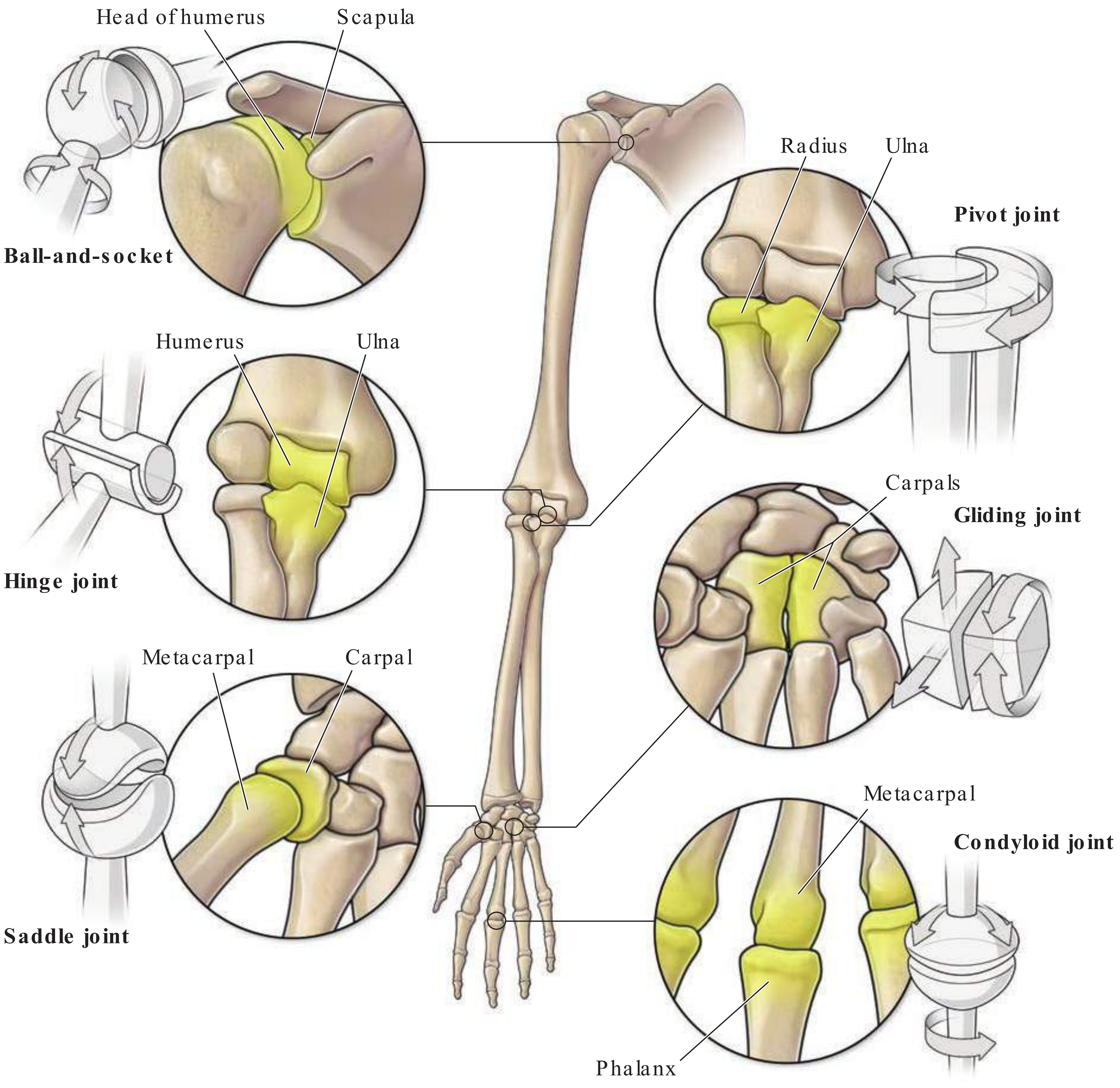

FIGURE 1-3 Types of diarthrosis or synovial joints.

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 flat 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 (Fig. 1-3). 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.[94]

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.[95] By way of comparison, ice on ice has a higher coefficient of friction (0.03).[95] 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.[96]

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*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.[97] Hyaluronan imparts anti-inflammatory and anti-nociceptive properties to normal synovial fluid and contributes to joint lubrication. It also is responsible for the viscoelastic properties of synovial fluid,[96] and contributes to the lubrication of articular cartilage surfaces.

Indeed, synovial fluid is essentially a dialysate of plasma to which hyaluronan has been added.[98] Hyaluronan is a GAG that is continually synthesized and released into the synovial fluid by specialized synoviocytes.[98,99] 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.[100,101] It is well established that damaged articular cartilage in adults has a very limited potential for healing (see Chapter 2) because it possesses neither a blood supply nor lymphatic drainage.[102]

Bursae

Closely associated with some synovial joints are flattened, saclike structures called bursae that are lined with a synovial membrane and filled with synovial fluid. The bursa produces small amounts of fluid, allowing for smooth and almost frictionless motion between contiguous muscles, tendons, bones, ligaments, and skin.[103–105] 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 for 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 facing forward (Fig. 1-4).

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.[106] 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.

FIGURE 1-4 The anatomical position.

- 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.

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 of 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 (Fig. 1-5).

- 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.

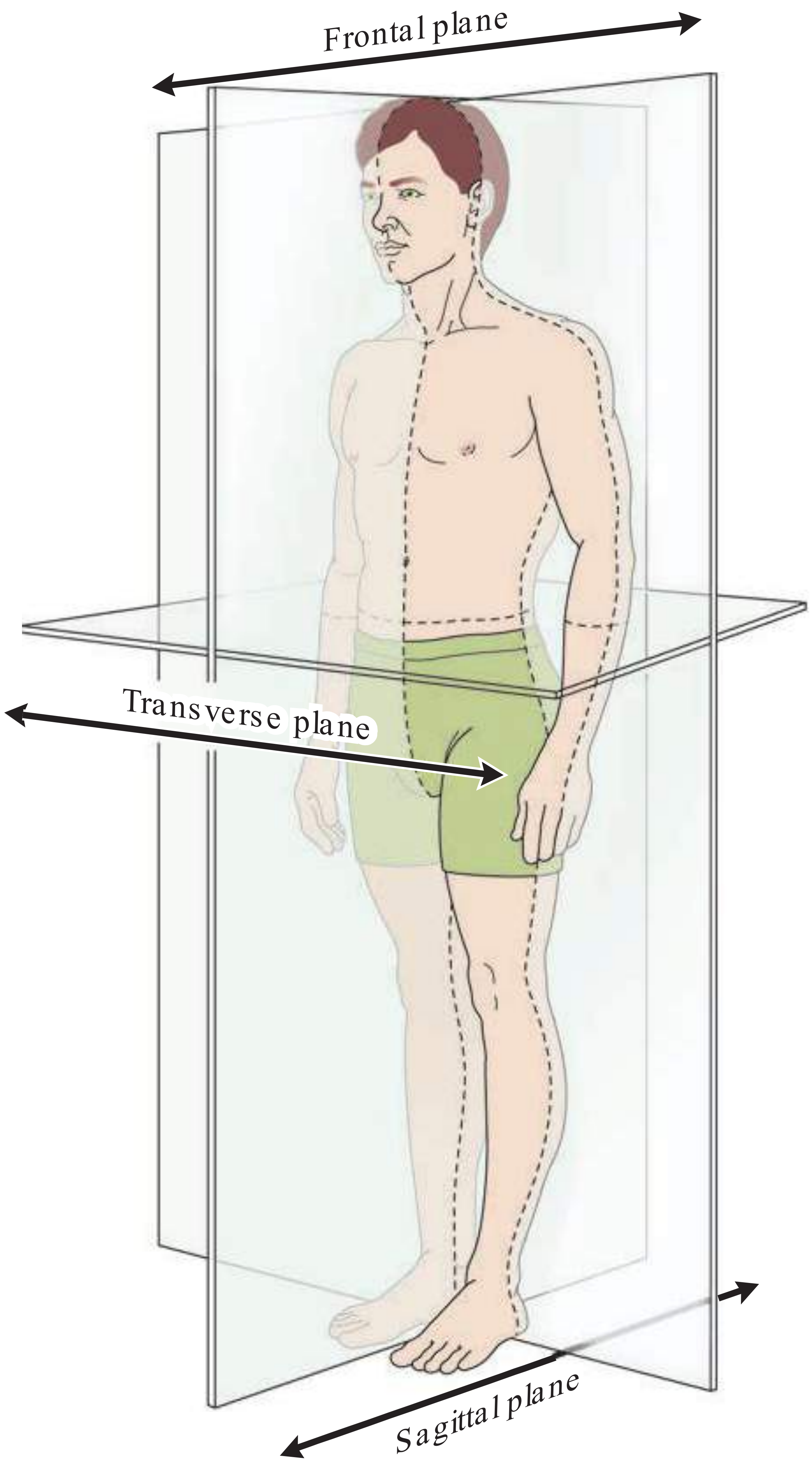

FIGURE 1-5 Planes of the body.

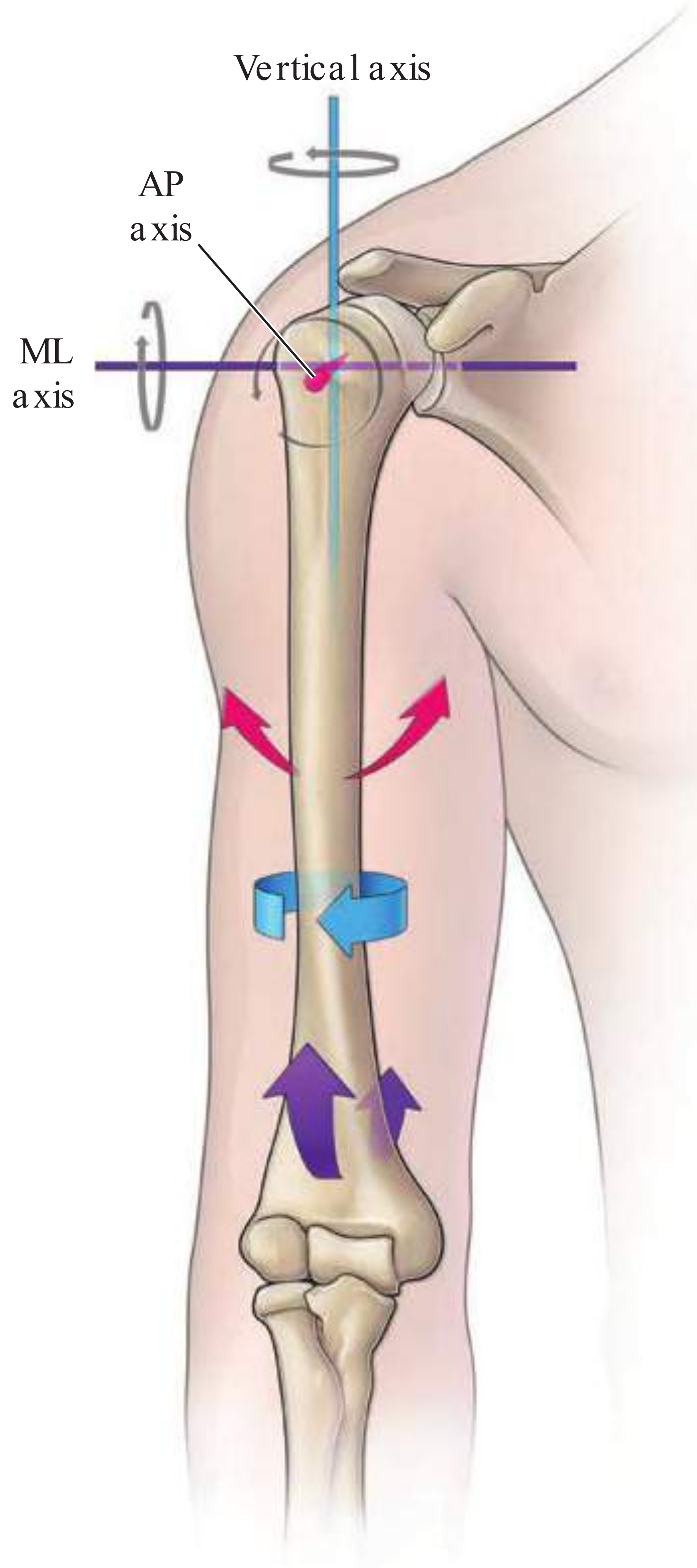

FIGURE 1-6 Axes of the body.

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 (see later). 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.[107] 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 (lateral plane).[107]

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 (see the discussion that follows).

Axes of the Body

Three reference axes are used to describe human motion (Fig. 1-6). 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. The 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

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*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.

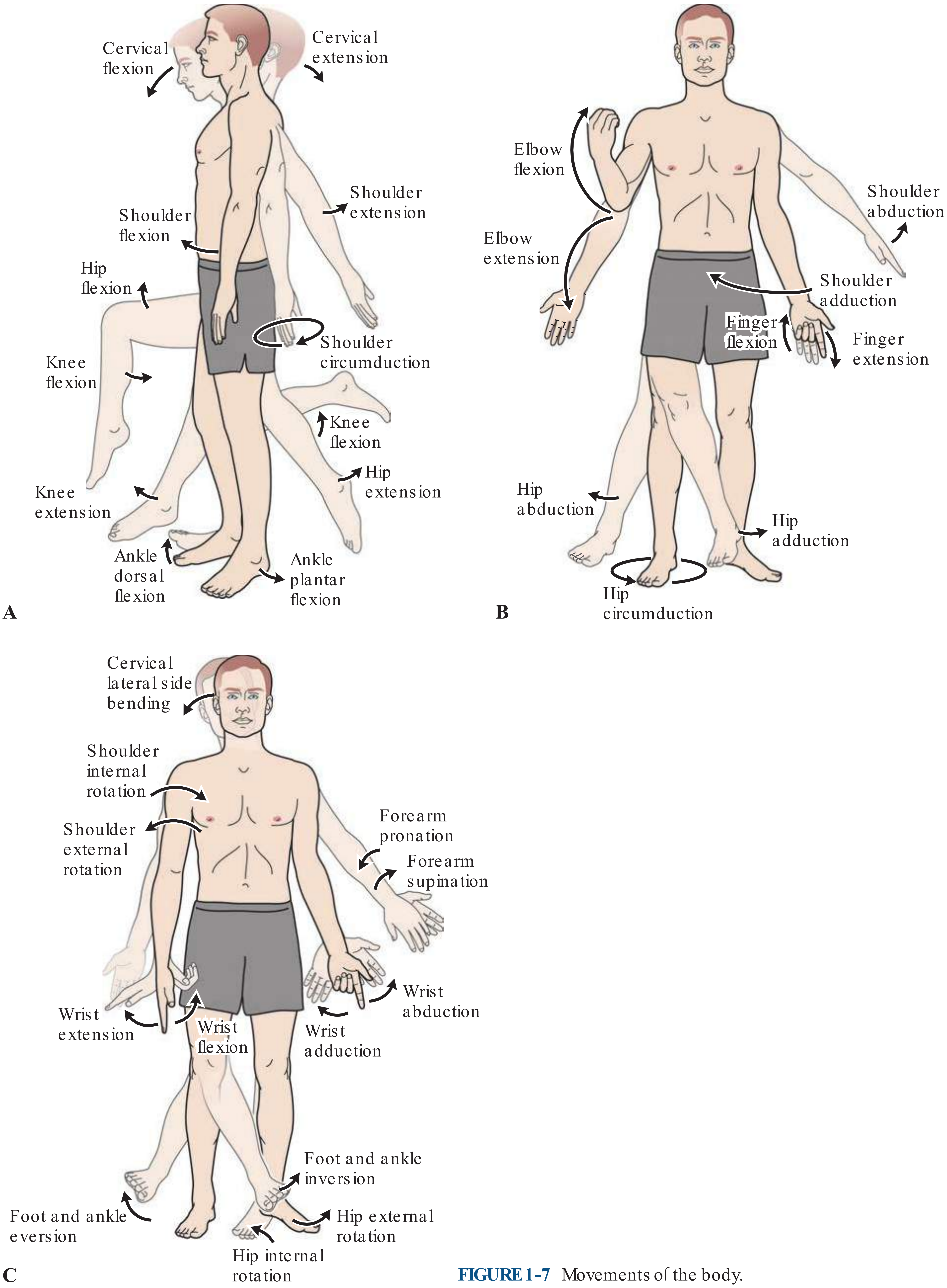

FIGURE 1-7 Movements of the body.

concave member. The planes and axes for the more common planar movements (Fig. 1-7) 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 (see Moment Arm).

- 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 of 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 plumbline), with a string attached to the COG of an object.[108] 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.[108] 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.[109] 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.[108]

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.[110] If a joint can swing in one direction or can only spin, it is said to have 1 DOF.[111–114] 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.[111–114] 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.[111–114] 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 facing 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 fact, 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 (see Chapter 10).

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 (see Chapter 2). 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 for osteokinematic motions is oriented perpendicular to the plane in which the rotation occurs.[106] 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[115]—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 (see Chapter 2).[90]

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 for a full-range of physiologic motion to occur. Mennell[116,117] 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,

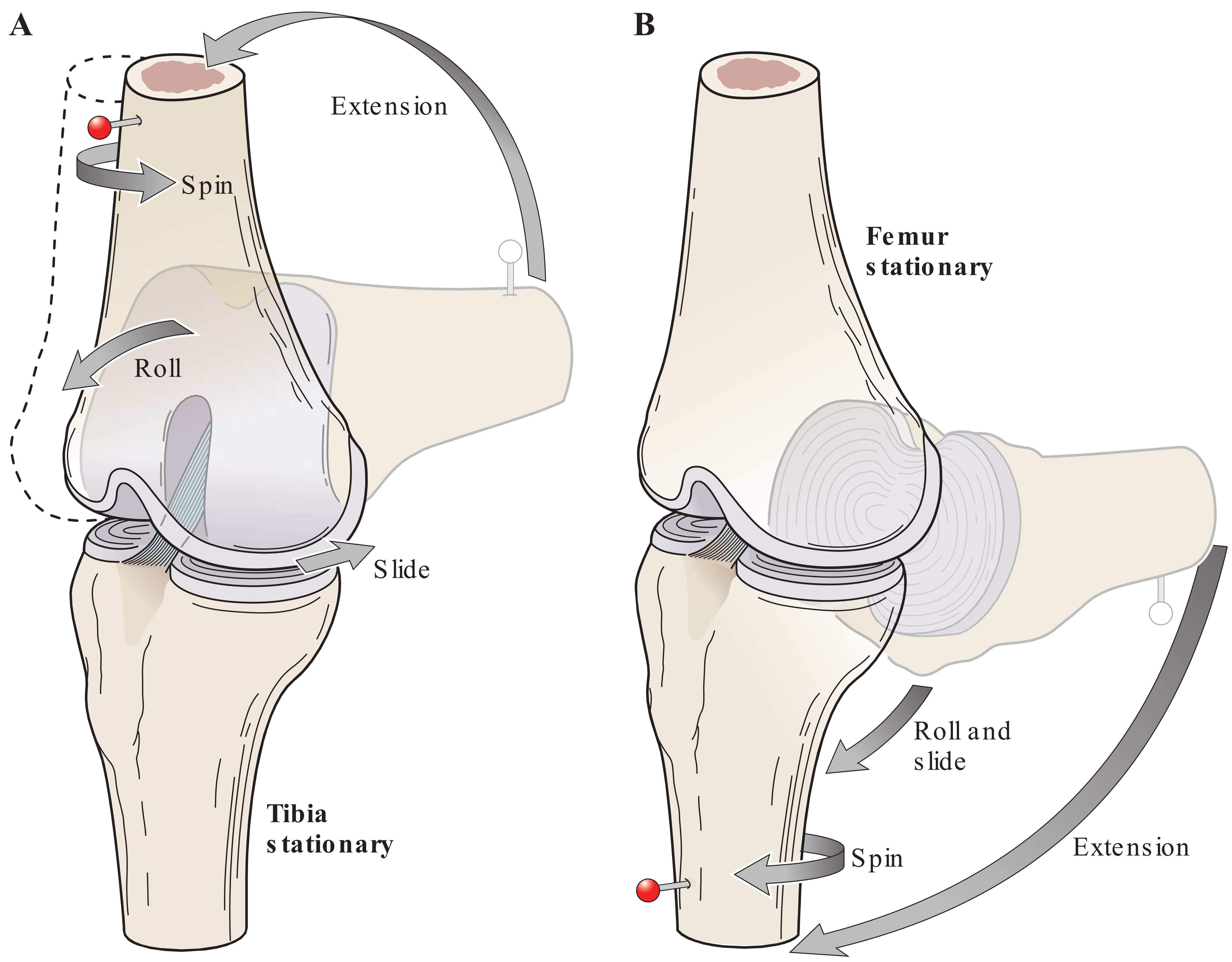

FIGURE 1-8 Arthrokinematics of motion.

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 (Fig. 1-8):[118]

- 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 (see Fig. 1-8). 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 often 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 (Fig. 1-8). 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 flat or curved. It occurs if only one point on the moving surface makes contact with new points on the opposing surface (see Fig. 1-8). 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 (Fig. 1-9). This rule is

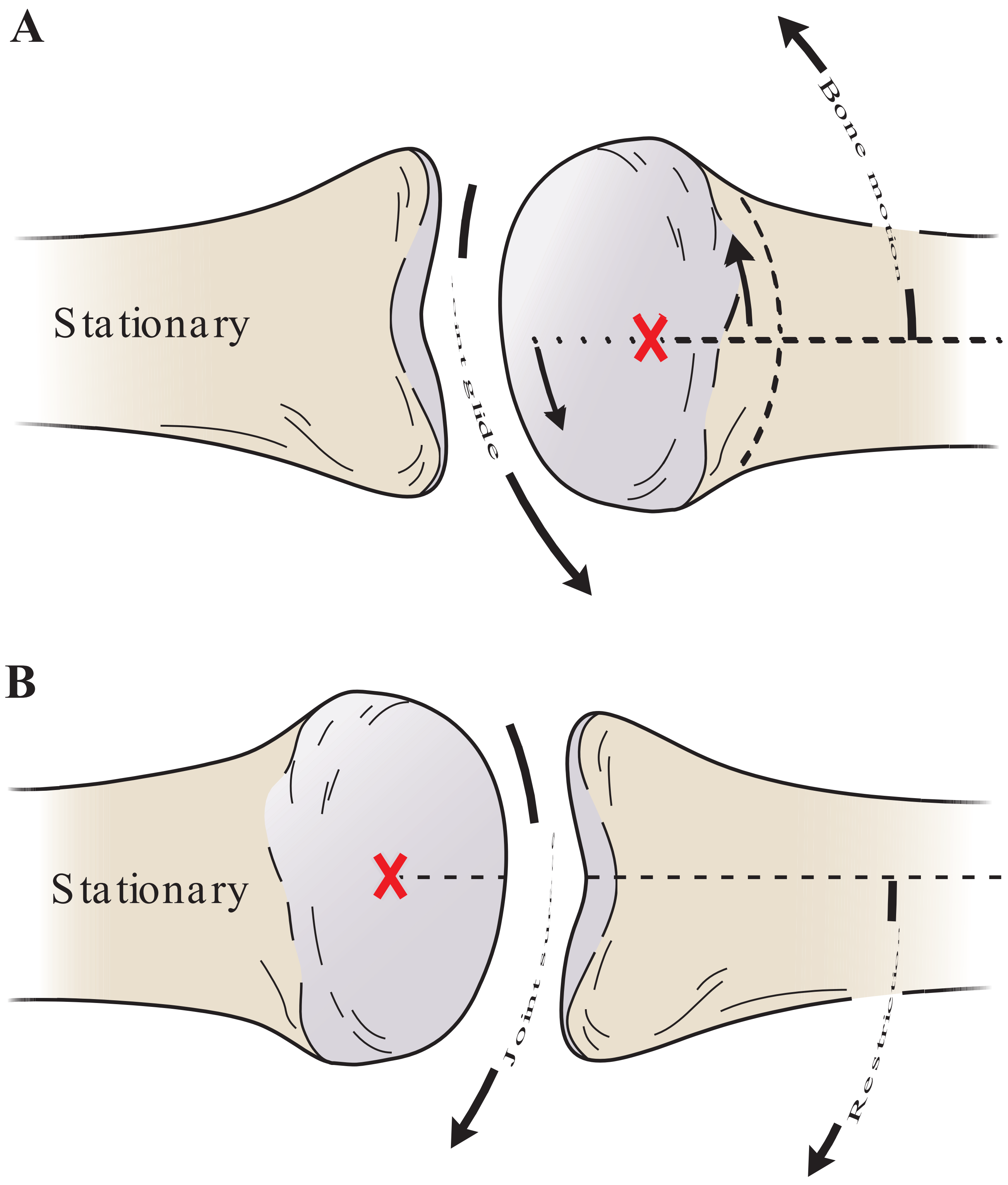

FIGURE 1-9 Gliding motions according to joint surfaces.

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 (see Fig. 1-9). If, on the other hand, the joint surface is concave, the slide occurs in the same direction as the osteokinematic motion (see Fig. 1-9). The clinical significance of the concave–convex rule is described in Chapter 10.

- **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 (see Fig. 1-8). 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 soft 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 (see Chapter 20).

In contrast, in the spine, the osteokinematic motion is controlled by both the flexibility of the surrounding soft 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 (see Chapter 23).

The examination of these motions and their clinical implications are described in Chapters 4 and 10.

Levers

A lever is a rigid object that is used to either multiply the mechanical force (effort) or resistance force (load) applied to it around an axis. The effort force attempts to cause movement of the load. For simplicity sake, levers are usually described using a straight bar that is the lever, and the fulcrum, which is the point on which the bar is resting, and around which the lever rotates. That part of the lever between the fulcrum and the load is referred to as the load arm. Three types of levers are commonly cited:

- First class: occurs when two forces are applied on either side of the axis, and the fulcrum lies between the effort and the load (Fig. 1-10), like a seesaw. Examples in the human body include the contraction of the triceps at the elbow joint, or tipping of the head forward and backward.
- Second class: occurs when the load (resistance) is applied between the fulcrum and the point where the effort is exerted (Fig. 1-10). The magnifying effects of the effort require less force to move the resistance. Examples of second-class levers in everyday life include the nutcracker, and the wheelbarrow—with the wheel acting as the fulcrum. Examples of second-class levers in the human body include weight-bearing plantarflexion (rising up on the toes) (Fig. 1-10). Another would be an isolated contraction of the brachioradialis to flex the elbow, which could only occur if the other elbow flexors are paralyzed.
- Third class: occurs when the load is located at the end of the lever (Fig. 1-10), and the effort lies between the fulcrum and the load, like a drawbridge or a crane. The effort is exerted between the load and the fulcrum. The effort expended is greater than the load, but the load is moved a greater distance. Most movable joints in the human body function as third-class levers—flexion at the elbow.

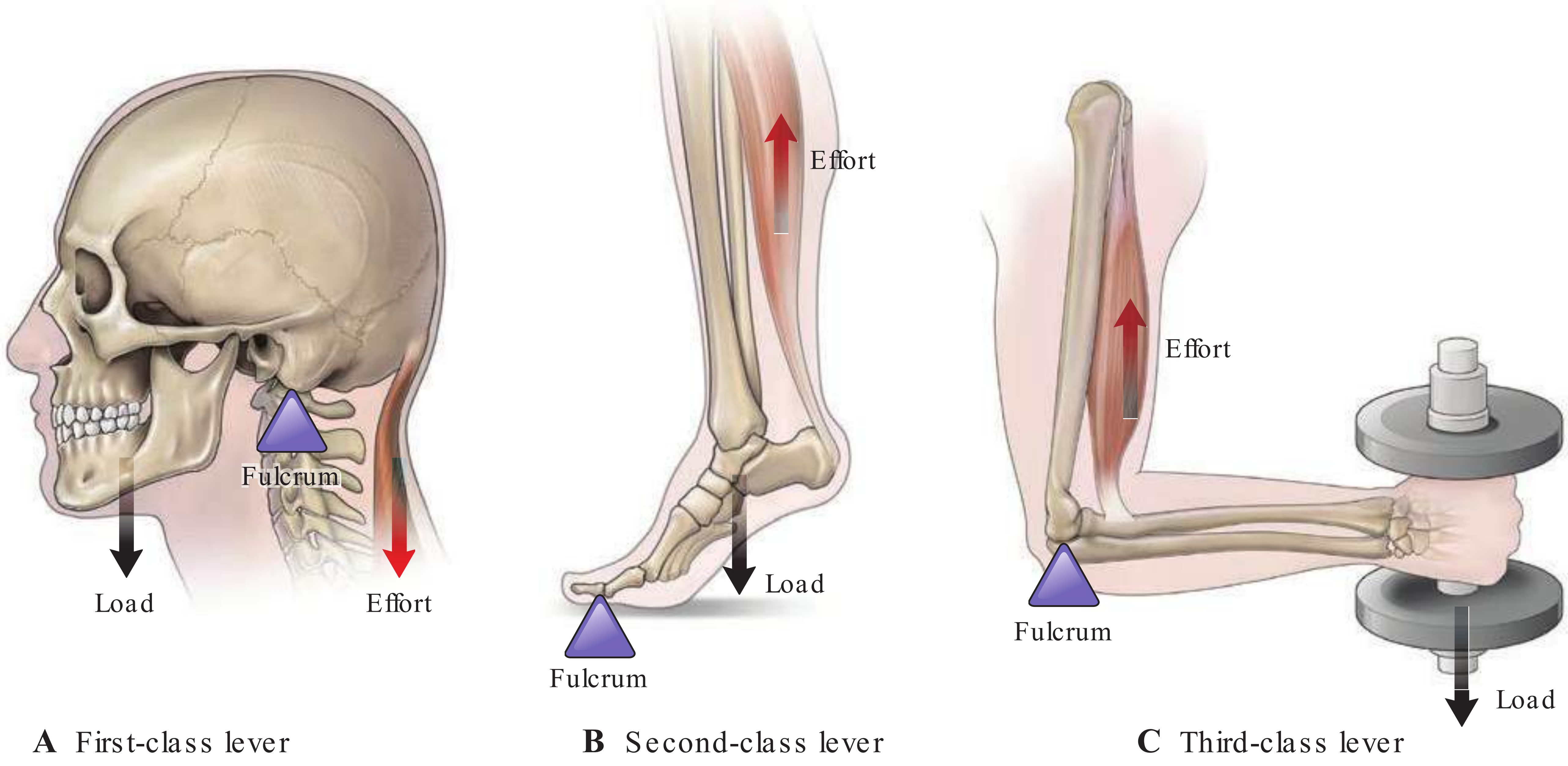

FIGURE 1-10 Classes of levers.

When a machine puts out more force than is put in, the machine is said to have a mechanical advantage (MA). The MA of the musculoskeletal lever is defined as the ratio of the internal moment arm to the external moment arm. Depending on the location of the axis of rotation, the first-class lever can have an MA equal to, less than, or greater than 1.[110] Second-class levers always have an MA greater than 1. Third-class levers always have an MA less than 1. The majority of muscles throughout the musculoskeletal system function with an MA of much less than 1. Therefore, the muscles and underlying joints must "pay the price" by generating and dispersing relative large forces, respectively, even for seemingly low-load activities.[110]

KINEMATIC CHAINS

When a body moves, it does so by its kinematics, which in the human body take place through arthrokinematic and osteokinematic movements. The expression kinematic chain is used in rehabilitation to describe the function or activity of an extremity or trunk in terms of a series of linked chains (see Chapter 12). A kinematic chain refers to a series of articulated, segmented links, such as the connected pelvis, thigh, leg, and foot of the lower extremity.[110] According to kinematic chain theory, each of the joint segments of the body involved in a particular movement constitutes a link in the kinematic chain. Because each motion of a joint is often a function of other joint motions, the efficiency of an activity can be dependent on how well these chain-links work together.[119]

CLINICAL PEARL

The number of links within a particular kinematic chain varies, depending on the activity. In general, longer kinematic chains are involved with more strenuous activities.

Two types of kinematic chain systems are recognized: closed kinematic chain (CKC) systems and the open kinematic chain (OKC) systems (Table 1-5).[120]

Closed Kinematic Chain

A variety of definitions for a CKC activity have been proposed:

1. Palmitier et al.[121] define an activity as closed if both ends of the kinetic chain are connected to an immovable framework, thus preventing translation of either the proximal, or distal joint center, and creating a situation whereby movement at one joint produces a predictable movement at all other joints.
2. Gray[122] considers a closed-chain activity to involve fixation of the distal segment so that joint motion takes place in multiple planes, and the limb is supporting the weight.
3. Dillman et al.[123] describe the characteristics of closed-chain activities to include relatively small joint movements, low joint accelerations, greater joint compressive forces, greater joint congruity, decreased shear, stimulation of joint proprioception, and enhanced dynamic stabilization through muscle coactivation.[124]
4. Kibler[124] defines a closed-chain activity as a sequential combination of joint motions that have the following characteristics:
   a. The distal segment of the kinetic chain meets considerable resistance.
   b. The movement of the individual joints, and translation of their instant centers of rotation occurs in a predictable manner that is secondary to the distribution of forces from each end of the chain.

Examples of closed kinematic chain exercises (CKCEs) involving the lower extremities include the squat and the leg

TABLE 1-5 Differential Features of OKC and CKC Exercises

Exercise Mode	Characteristics	Advantages	Disadvantages
Open kinematic chain	1. Single muscle group 2. Single axis and plane 3. Emphasizes concentric contraction 4. Nonweight bearing	1. Isolated recruitment 2. Simple movement pattern 3. Minimal joint compression	1. Limited function 2. Limited eccentrics 3. Less proprioception and joint stability with increased joint shear forces
Closed kinematic	1. Multiple muscle groups 2. Multiple axes and planes 3. Balance of concentric and eccentric contractions 4. Weight-bearing exercise	1. Functional recruitment 2. Functional movement patterns 3. Functional contractions 4. Increased proprioception and joint stability	1. Difficult to isolate 2. More complex 3. Loss of control of target joint 4. Compressive forces on articular surfaces

Data from Greenfield BH, Tovin BJ. The application of open and closed kinematic chain exercises in rehabilitation of the lower extremity. J Back Musculoskel Rehabil. 1992;2:38–51.

press. The activities of walking, running, jumping, climbing, and rising from the floor all incorporate closed kinetic chain components. An example of a CKCE for the upper extremities is the push-up, or when using the arms to push down on the armrests to rise out of a chair.

CLINICAL PEARL

In most activities of daily living, the activation sequence of the links involves a closed chain whereby the activity is initiated from a firm base of support and transferred to a more mobile distal segment.

Open Kinematic Chain

It is accepted that the difference between OKC and CKC activities is determined by the movement of the end segment. The traditional definition for an open-chain activity included all activities that involved the end segment of an extremity moving freely through space, resulting in isolated movement of a joint.

Examples of an open-chain activity include lifting a drinking glass and kicking a soccer ball. Open kinematic chain exercises (OKCEs) involving the lower extremity include the seated knee extension and prone knee flexion. Upper extremity examples of OKCE include the biceps curl and the military press.

Many activities, such as swimming and cycling, traditionally viewed as OKC activities, include a load on the end segment; yet the end segment is not "fixed" and restricted from movement. This ambiguity of definitions for CKC and OKC activities has allowed some activities to be classified in opposing categories.[123] Thus, there has been a growing need for clarification of OKC and CKC terminology, especially when related to functional activities.

The works of Dillman et al.[123] and then Lephart and Henry[125] have attempted to address the confusion. Dillman et al.[123] proposed three classifications of activity to help clarify the gray area between the CKC and the OKC activity. These classifications were based on the boundary condition, either movable or fixed, and the presence or absence of a load on the end segment. An activity with a fixed boundary and no load does not exist, resulting in three classifications:

1. Movable no load. These activities involve a movable end with no load and closely resemble the extreme of an open-chain activity. An example of this type of activity is hitting a ball with a tennis racket.
2. Movable external load. These activities involve a movable end with an external load and include a combination of open- and closed-chain actions because they are characterized by cocontractions of the muscles around the joints. An example of this type of activity is the overhead shoulder (military) press.
3. Fixed external load. These activities involve a fixed end with an external load, and closely resemble the extreme of a closed-chain activity. An example of this type of activity is the push-up.

Lephart and Henry suggested that a further definition could be made by analyzing the following characteristics of an activity:

- The direction of force.
- The magnitude of the load.
- Muscle action.
- Joint motion.
- Neuromuscular function.

Under Lephart and Henry's classification, activities could be subdivided into four groups:

1. Activities that involve a fixed boundary with an external and axial load. An example of this type of activity is the use of a slide board.
2. Activities that involve a movable boundary with an external and axial load. An example of this type of activity is the bench press.
3. Activities that involve a movable boundary with an external and rotary load. An example of this type of activity is a

resisted proprioceptive neuromuscular facilitation (PNF) motion pattern (see Chapter 10).

4. Activities that involve a movable boundary with no load. An example of this type of activity is position training.

Although both the Dillman and Lephart and Henry models appear to be describing the same concept, the Lephart and Henry model is distinct in that it incorporates diagonal or rotary components to the movements. These diagonal and rotary movements feature in the vast majority of functional activities.

CLOSE-PACKED AND OPEN-PACKED POSITIONS OF THE JOINT

Joint movements usually are accompanied by a relative compression (approximation) or distraction (separation) of the opposing joint surfaces. These relative compressions or distractions affect the level of congruity of the opposing surfaces. The position of maximum congruity of the opposing joint surfaces is termed the close-packed position of the joint. The position of least congruity is termed the open-packed position. Thus, movements toward the close-packed position of a joint involve an element of compression, whereas movements out of this position involve an element of distraction.

Close-Packed Position

The close-packed position of a joint is the joint position that results in:

- The maximal tautness of the major ligaments.
- Maximal surface congruity.
- Minimal joint volume.
- Maximal stability of the joint.

Once the close-packed position is achieved, no further motion in that direction is possible. This is the often-cited reason most fractures and dislocations occur when an external force is applied to a joint that is in its close-packed position. Also, many of the traumatic injuries of the upper extremities result from falling on a shoulder, elbow or wrist, which are in their close-packed position. This type of injury, a *f*all on an outstretched hand is often referred to as a FOOSH injury. The close-packed positions for the various joints are depicted in Table 1-6.

TABLE 1-6 Close-Packed Position of the Joints

Joint	Position
Zygapophyseal (spine)	Extension
Temporomandibular	Teeth clenched
Glenohumeral	Abduction and external rotation
Acromioclavicular	Arm abducted to 90 degrees
Sternoclavicular	Maximum shoulder elevation
Ulnohumeral	Extension
Radiohumeral	Elbow flexed 90 degrees; forearm supinated 5 degrees
Proximal radioulnar	5 degrees of supination
Distal radioulnar	5 degrees of supination
Radiocarpal (wrist)	Extension with radial deviation
Metacarpophalangeal	Full flexion
Carpometacarpal	Full opposition
Interphalangeal	Full extension
Hip	Full extension, internal rotation, and abduction
Tibiofemoral	Full extension and external rotation of tibia
Talocrural (ankle)	Maximum dorsiflexion
Subtalar	Supination
Midtarsal	Supination
Tarsometatarsal	Supination
Metatarsophalangeal	Full extension
Interphalangeal	Full extension

Open-Packed Position

In essence, any position of the joint, other than the close-packed position, could be considered as an open-packed position. The open-packed position, also referred to as the loose-packed position of a joint, is the joint position that results in:

- Slackening of the major ligaments of the joint.
- Minimal surface congruity.
- Minimal joint surface contact.
- Maximal joint volume.
- Minimal stability of the joint.

The open-packed position permits maximal distraction of the joint surfaces. Because the open-packed position causes the brunt of any external force to be borne by the joint capsule or surrounding ligaments, most capsular or ligamentous sprains occur when a joint is in its open-packed position. The open-packed positions for the various joints are depicted in Table 1-7.

CLINICAL PEARL

The open-packed position is commonly used during joint mobilization techniques (see Chapter 10).

TABLE 1-7 Open-Packed (Resting) Position of the Joints

Joint	Position
Zygapophyseal (spine)	Midway between flexion and extension
Temporomandibular	Mouth slightly open (freeway space)
Glenohumeral	55 degrees of abduction; 30 degrees of horizontal adduction
Acromioclavicular	Arm resting by side
Sternoclavicular	Arm resting by side
Ulnohumeral	70 degrees of flexion; 10 degrees of supination
Radiohumeral	Full extension; full supination
Proximal radioulnar	70 degrees of flexion; 35 degrees of supination
Distal radioulnar	10 degrees of supination
Radiocarpal (wrist)	Neutral with slight ulnar deviation
Carpometacarpal	Midway between abduction–adduction and flexion–extension
Metacarpophalangeal	Slight flexion
Interphalangeal	Slight flexion
Hip	10–30 degrees of flexion; 10–30 degrees of abduction; and 0–5 degrees of external rotation
Tibiofemoral	25 degrees of flexion
Talocrural (ankle)	10 degrees of plantar flexion; midway between maximum inversion and eversion
Subtalar	Midway between extremes of range of movement
Midtarsal	Midway between extremes of range of movement
Tarsometatarsal	Midway between extremes of range of movement
Metatarsophalangeal	Neutral
Interphalangeal	Slight flexion

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CHAPTER 2

Tissue Behavior, Injury, Healing, and Treatment

CHAPTER OBJECTIVES

At the completion of this chapter, the reader will be able to:

1. Describe the various types of stress that are applied to the body.
2. Describe the various physiological processes by which the body adapts to stress.
3. Define the various common mechanisms of injury.
4. Describe the etiology and pathophysiology of musculoskeletal injuries associated with various types of body tissue.
5. Outline the pathophysiology of the healing process and the various stages of healing of the various connective tissues.
6. Describe the factors that can impede the healing process.
7. Outline the more common surgical procedures available for musculoskeletal injuries.
8. Outline the principles behind postsurgical rehabilitation.
9. Describe the detrimental effects of immobilization.

OVERVIEW

Tissues in the body are designed to function while undergoing the stresses of everyday living. Body weight, friction, and air or water resistance are all types of stresses that commonly act on the body. The ability of the tissues to respond to stress is due to the differing viscoelastic properties of the tissue, with each tissue responding to stress in an individual manner based on design. Maintaining the health of the various tissues is a delicate balance because insufficient, excessive, or repetitive stresses can prove deleterious. Fortunately, most tissues have an inherent ability to self-heal—a process that is an intricate phenomenon.

THE RESPONSE OF TISSUE TO STRESS

Kinetics is the term applied to define the forces acting on the body. Posture and movement are both governed by the body's ability to control these forces. The same forces that move and stabilize the body also have the potential to deform and injure the body.[1] A wide range of external and internal forces are either generated or resisted by the human body during daily activities. Examples of these external forces include ground reaction force, gravity, and applied force through contact. Examples of internal forces include structural tension, joint compression, and joint shear forces (Fig. 2-1). Under the right circumstances, the body can respond and adapt to these stresses. The terms stress and strain have specific mechanical meanings. Stress, or load, is defined in units of force per area, and is used to describe the type of force applied. Stress is independent of the amount of material, but is directly related to the magnitude of force and inversely related to the unit area.[2] Strain is defined as the change in length of a material due to an imposed load, divided by the original length.[2] The two basic types of strain are a linear strain, which causes a change in the length of a structure, and shear strain, which causes a change in the angular relationships within a structure. It is the concentration of proteoglycans in solution (see Chapter 1) that is responsible for influencing the mechanical properties of the tissue, including compressive stiffness, sheer stiffness, osmotic pressure, and the regulation of hydration.[3]

CLINICAL PEARL

Strain is the amount of elongation divided by the length of the structure.

Stress is the force in a structure divided by the cross-sectional area.

The inherent ability of a tissue to tolerate load can be observed experimentally in graphic form. When any stress is plotted on a graph against the resulting strain for a given material, the shape of the resulting load–deformation curve depends on the kind of material involved. The load–deformation curve, or stress–strain curve, of a structure (Fig. 2-2) depicts the relationship between the amount of force applied to a structure and the

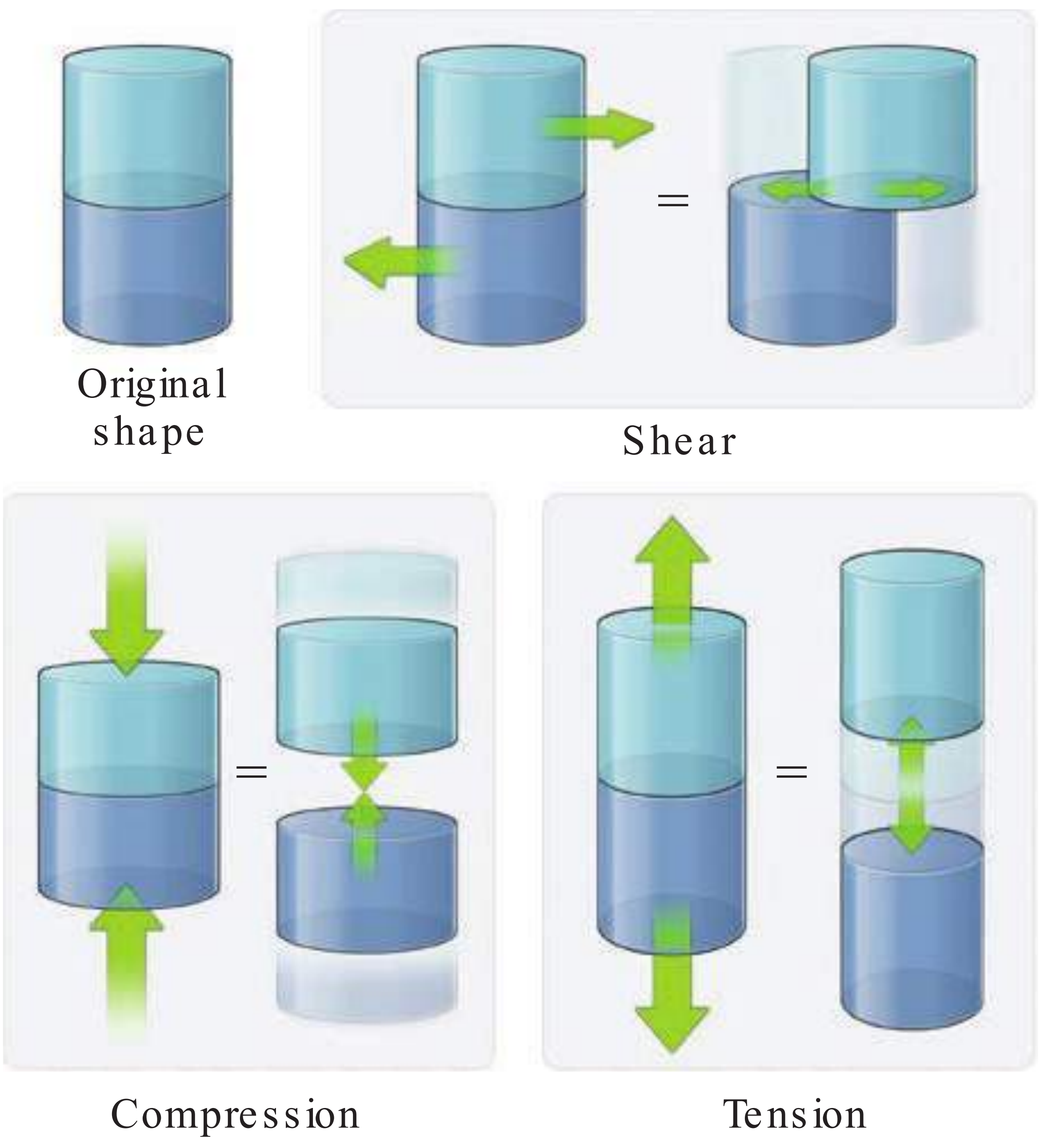

FIGURE 2-1 Internal forces acting on the body.

structure's response in terms of deformation or acceleration. The horizontal axis (deformation or strain) represents the ratio of the tissue's deformed length to its original length. The vertical axis of the graph (load or stress) denotes the internal resistance generated as a tissue resists its deformation, divided by its cross-sectional area. The load–deformation curve can be divided into four regions, each region representing a biomechanical property of the tissue (Fig. 2-2):

- Toe region. Collagen fibers have a wavy, or folded, appearance at rest or on slack. When a force that lengthens the collagen fibers is initially applied to connective tissue, this slack range is affected first, and the fibers unfold as the slack is taken up (see Crimp later). The toe region is an artifact caused by this take-up of slack, alignment, and/or seating of the test specimen. The length of the toe region depends on the type of material and the waviness of the collagen pattern.
- Elastic region. Within the elastic deformation region, the structure imitates a spring—the geometric deformation in the structure increases linearly with increasing load, and after the load is released the structure returns to its original shape. The slope of the elastic region of the load–deformation curve from one point in the curve to another, which corresponds to the physiological range of a structure, is called the modulus of elasticity or Young's modulus, and represents the extrinsic stiffness or rigidity of the structure—the stiffer the tissue, the steeper the slope. A key characteristic of passive tendon loading is its stiffness—the force in the tendon divided by the amount of lengthening of the tendon.[4] Young's modulus is a numerical description of the relationship between the amount of stress a tissue undergoes and the deformation that results—stress divided by the strain. The ratio of stress to strain in an elastic material is a measure of its stiffness. Young's modulus is independent of specimen size and is, therefore, a measure of the intrinsic stiffness of the material. The greater the Young's modulus for a material, the better it can withstand greater forces. Mathematically, the value for stiffness is found by dividing the load by the deformation at any point in the selected range. All normal tissues within the musculoskeletal system exhibit some degree of stiffness. Larger structures will have greater rigidity than smaller structures of similar composition. Stiffness is not necessarily a negative characteristic—tendons transmit force more effectively and efficiently when they are stiffer.[4]
- Plastic region. The end of the elastic deformation range, and the beginning of the plastic deformation range, represents the point where an increasing level of stress on

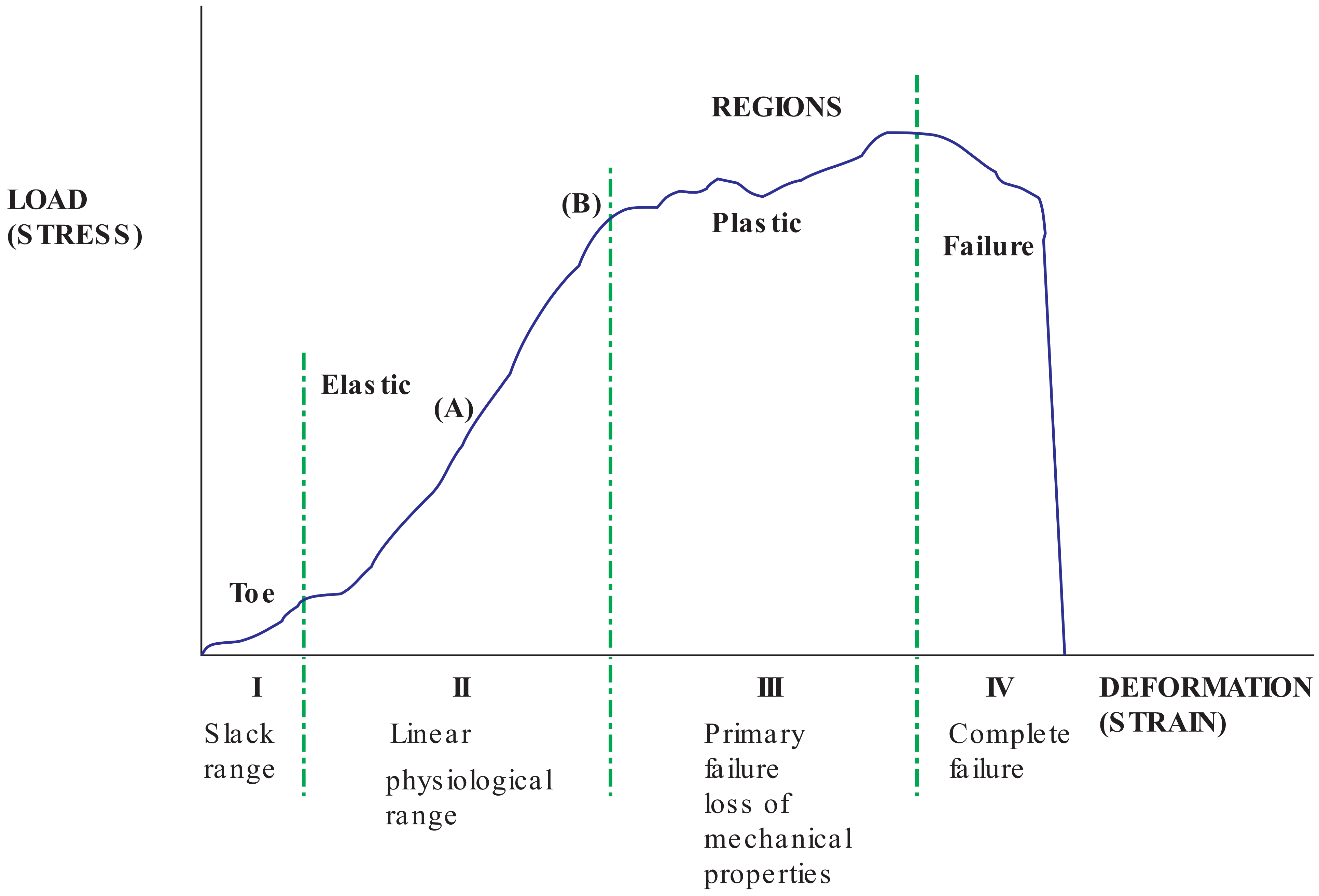

FIGURE 2-2 The stress–strain curve.

the tissue results in progressive failure and microscopic tearing of the collagen fibers. Further increases in strain result in microscopic damage and permanent deformation. The permanent change results from the breaking of bonds and their subsequent inability to contribute to the recovery of the tissue. Unlike the elastic region, removal of the load in this region will not result in a return of the tissue to its original length.

- Failure region. Deformations exceeding the ultimate failure point (Fig. 2-2) produce mechanical failure of the structure, which in the human body may be represented by the fracturing of bone or the rupturing of a soft tissue.

CLINICAL PEARL

Stiffness = force/deformation. The gradient in the linear portion of the load-deformation graph immediately after the toe region of the load–displacement curve represents the stiffness value. The load–deformation curve does not indicate the variable of time.

Elastic modulus = stress/strain. The larger the Young's modulus for a material, the greater stress needed for a given strain.

Biological tissues are anisotropic, which means they can demonstrate differing mechanical behavior as a function of test direction. The properties of extensibility and elasticity are common to many biologic tissues. Extensibility is the ability to be stretched, and elasticity is the ability to return to normal length after lengthening or shortening.[5]

CLINICAL PEARL

Unloading a tendon significantly influences the mechanical properties. For example, one study that looked at the effects of 4 weeks of unilateral lower limb suspension followed by 6 weeks of rehabilitation found that there was a 17% decrease in the elastic modulus (lower stiffness) after suspension, and the restoration of normal stiffness after rehabilitation.[6]

Some protective mechanisms exist in connective tissue to help respond to stress and strain, including crimp, viscoelasticity, creep and stress relaxation, plastic deformation, and stress response.

CLINICAL PEARL

Protective tissue mechanisms include:

- Crimp
- Viscoelasticity
- Creep and stress relaxation
- Plastic deformation
- Stress response

Crimp

The crimp of collagen is one of the major factors behind the viscoelastic properties of connective tissue. Crimp, a collagen tissue's first line of response to stress, is different for each type of connective tissue, providing each with different viscoelastic properties. Collagen fibers are oriented obliquely when relaxed. However, when a load is applied, the fibers line up in the direction of the applied force as they uncrimp. Crimping is seen primarily in ligaments, tendons, and joint capsules, and occurs in the toe phase of the stress–strain curve (Fig. 2-2).

CLINICAL PEARL

If a load is applied to the connective tissue and then removed immediately, the material recoils to its original size. If, however, the load is allowed to remain, the material continues to stretch. After a period of a sustained stretch, the stretching tends to reach a steady-state value. Realignment of the collagen fibers in the direction of the stress occurs, and water and proteoglycans are displaced from the fibers.

Viscoelasticity

Viscoelasticity is the time-dependent mechanical property of a material to stretch or compress over time, and to return to its original shape when a force is removed. The mechanical qualities of a tissue can be separated into categories based on whether the tissue acts primarily as a solid, fluid, or a mixture of the two. Solids are described according to their elasticity, strength, hardness, and stiffness. Bone, ligaments, tendons, and skeletal muscle are all examples of elastic solids. Biological tissues that demonstrate attributes of both solids and fluids are viscoelastic. The viscoelastic properties of a structure determine its response to loading. For example, a ligament demonstrates more viscous behavior at lower loads whereas, at higher loads, elastic behaviors dominate.[7]

Creep and Stress Relaxation

Creep and stress relaxation are two characteristics of viscoelastic materials that are used to document their behavior quantitatively.[5]

Creep is the gradual rearrangement of collagen fibers, proteoglycans, and water that occurs because of a constantly applied force after the initial lengthening caused by crimp has ceased. Creep is a time-dependent and transient biomechanical phenomenon. Short duration stresses (<15 minutes) do not have sufficient time to produce this displacement; however, longer times can produce it. Once creep occurs, the tissue has difficulty returning to its initial length (see below).

Stress relaxation is a phenomenon in which stress or force in a deformed structure decreases with time while the deformation is held constant.[5] Unlike creep, stress relaxation responds with a high initial stress that decreases over time until equilibrium is reached and the stress equals zero, hence the label "relaxation." As a result, no change in length is produced.