

Joint Anatomy and Basic Biomechanics

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MODELS OF SPINE FUNCTION

This chapter provides an academic picture of the applied anatomy and biomechanics of the musculoskeletal system. The human body may be viewed as a machine formed of many different parts that allow motion. These motions occur at the many joints formed by the specific parts that compose the body's musculoskeletal system. Although there is some controversy and speculation among those who study these complex activities, the information presented here is considered essential for understanding clinical correlations and applications. Biomechanical discussions require specific nomenclature, which enables people

working in a wide variety of disciplines to communicate (see Appendix 3). Biomechanics is often overwhelming because of its mathematical and engineering emphasis. This chapter will present a nonmathematical approach to defining clinically useful biomechanical concepts necessary for the ability to describe and interpret changes in joint function. Thorough explanations of biomechanical concepts are discussed in other works.¹⁻³

FUNDAMENTAL CONCEPTS, PRINCIPLES, AND TERMS

Mechanics is the study of forces and their effects. *Biomechanics* is the application of mechanical laws to living structures, specifically to the locomotor system of the human body. Therefore biomechanics concerns the interrelations of the skeleton, muscles, and joints. The bones form the levers, the ligaments surrounding the joints form hinges, and the muscles provide the forces for moving the levers about the joints.

Kinematics is a branch of mechanics that deals with the geometry of the motion of objects, including displacement, velocity, and acceleration, without taking into account the forces that produce the motion. *Kinetics*, however, is the study of the relationships between the force system acting on a body and the changes it produces in body motion.

Knowledge of joint mechanics and structure, as well as the effects that forces produce on the body, has important implications for the use of manipulative procedures and, specifically, chiropractic adjustments. Forces have vector characteristics whereby specific directions are delineated at the points of application. Moreover, forces can vary in magnitude, which will affect the acceleration of the object to which the force is applied.

Levers

A lever is a rigid bar that pivots about a fixed point, called the *axis* or *fulcrum*, when a force is applied to it. Force is

applied by muscles at some point along the lever to move the body part (resistance). The lever is one of the simplest of all mechanical devices that can be called a *machine*. The relationship of fulcrum to force to resistance distinguishes the different classes of levers.

In a first-class lever, the axis (fulcrum) is located between the force and the resistance; in a second-class lever, the resistance is between the axis and the force; and in a third-class lever, the force is between the axis and the resistance (Figure 2-1). Every movable bone in the body

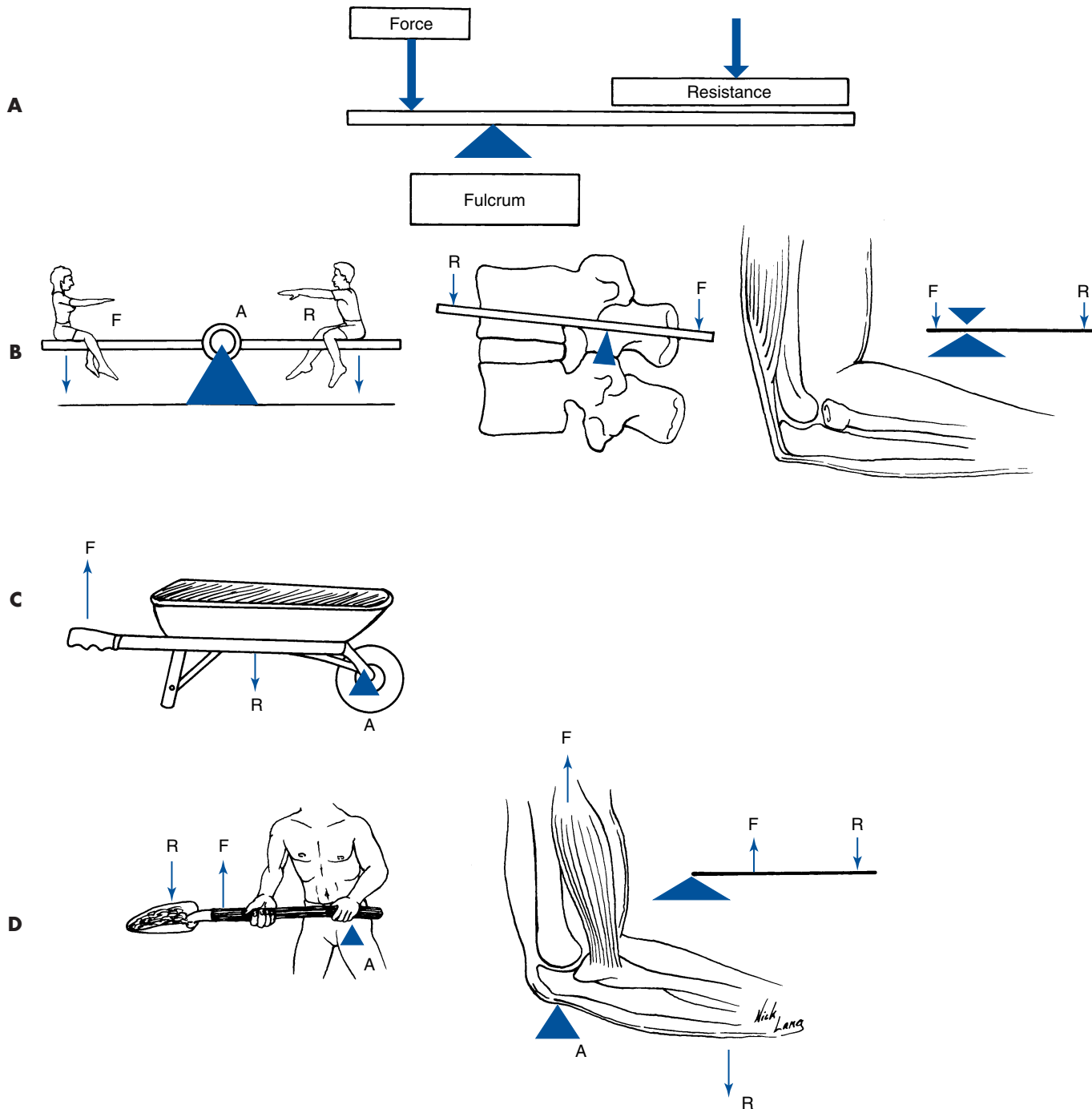


Figure 2-1

A, Lever system showing components. B, First-class lever system. C, Second-class lever system. D, Third-class lever system. A, Axis (fulcrum); F, force; R, resistance.

acts alone or in combination, forcing a network of lever systems characteristic of the first- and third-class levers. There are virtually no second-class levers in the body, although opening the mouth against resistance is an example.

With a first-class lever, the longer the lever arm is, the less force is required to overcome the resistance. The force arm may be longer, shorter, or equal to the resistance arm, but the axis will always be between these two points. An example of a first-class lever in the human body is the forearm moving from a position of flexion into extension at the elbow through contraction of the triceps muscle.

Third-class levers are the most common types in the body because they allow the muscle to be inserted near the joint and can thereby produce increased speed of movement, although at a sacrifice of force. The force arm must be smaller than the resistance arm, and the applied force lies closer to the axis than the resistance force. An example of a third-class lever is flexion of the elbow joint through contraction of the biceps muscle.

Body Planes

It is also necessary to delineate the specific body planes of reference, since they will be used to describe structural position and directions of functional movement. The stan-

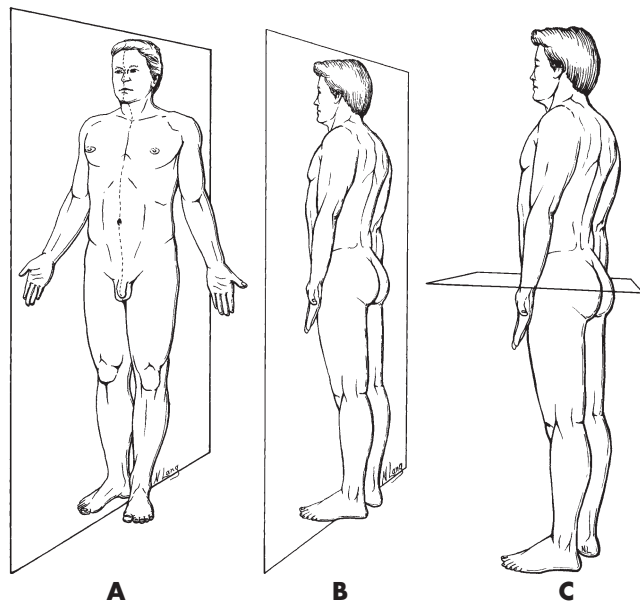


Figure 2-2
A, Midsagittal plane. Movements of flexion and extension take place in the sagittal plane. **B**, Coronal plane. Movements of abduction and adduction (lateral flexion) take place in the coronal plane. **C**, Transverse plane. Movements of medial and lateral rotation take place in the transverse plane.

dard position of reference, or anatomic position, has the body facing forward, the hands at the sides of the body, with the palms facing forward, and the feet pointing straight ahead. The body planes are derived from dimensions in space and are oriented at right angles to one another. The *sagittal plane* is vertical and extends from front to back, or from anterior to posterior. Its name is derived from the direction of the human sagittal suture in the cranium. The *median sagittal plane*, also called the *midsagittal plane*, divides the body into right and left halves (Figure 2-2, *A*, Table 2-1). The *coronal plane* is vertical and extends from side to side. Its name is derived from the orientation of the human coronal suture of the cranium. It may also be referred to as the *frontal plane*, and it divides the body into anterior and posterior components (Figure 2-2, *B*). The transverse plane is a horizontal plane and divides a structure into upper and lower components (Figure 2-2, *C*).

Axes of Movement

An axis is a line around which motion occurs. Axes are related to planes of reference, and the cardinal axes are oriented at right angles to one another. This is expressed as a three-dimensional coordinate system with *x*, *y*, and *z* used to mark the axes (Figure 2-3). The significance of this coordinate system is in defining or locating the extent of the types of movement possible at each joint—rotation, translation, and curvilinear motion. All movements that occur about an axis are considered *rotational*, whereas linear movements along an axis and through a plane are called *translational*. *Curvilinear* motion occurs when a translational movement accompanies rotational movements. The load that produces a rotational movement is called *torsion*; a force that produces a translational movement is called an *axial* or *shear force*.

Joint Motion

Motion can be defined as a continuous change in position of an object. The axis around which movement takes

TABLE 2-1

Body Planes of Movement

Plane of Movement	Axis	Joint Movement
Sagittal	Coronal [<i>x</i>]	Flexion and extension
Coronal	Sagittal (antero-posterior) [<i>z</i>]	Abduction and adduction (lateral flexion)
Transverse	Longitudinal (vertical) [<i>y</i>]	Medial and lateral rotation (axial rotation)

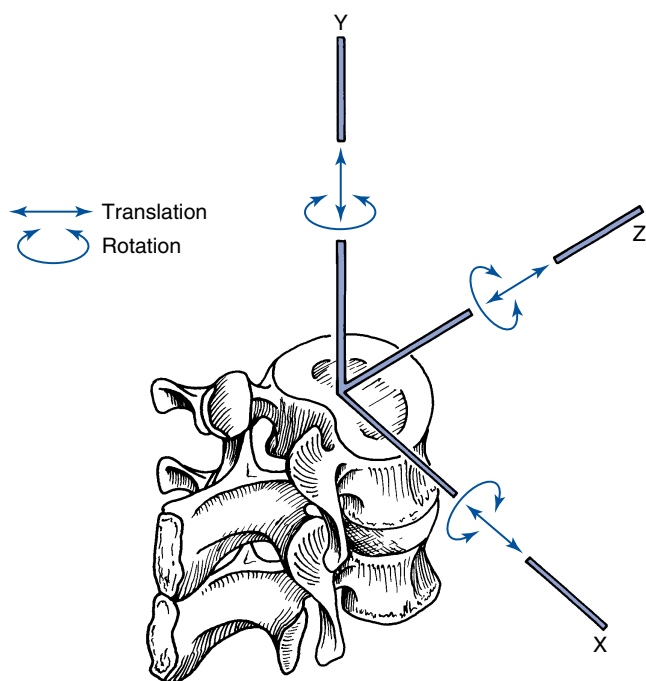


Figure 2-3

Three-dimensional coordinate system identifying the translational and rotational movements along or around the three axes to produce 6 degrees of freedom.

place and the plane through which movement occurs define specific motions or resultant positions. The coronal axis (x-axis) lies in the coronal plane and extends from one side of the body to the other. The motions of flexion and extension occur about this axis and through the sagittal plane. Flexion is motion in the anterior direction for joints of the head, neck, trunk, upper extremity, and hips (Figure 2-4, *A*). Flexion of the knee, ankle, foot, and toes is movement in the posterior direction. Extension is the motion opposite of flexion.

The sagittal axis (z-axis) lies in the sagittal plane and extends horizontally from anterior to posterior. Movements of abduction and adduction of the extremities, as well as lateral flexion of the spine, occur around this axis and through the coronal plane. Lateral flexion is a rotational movement and is used to denote lateral movements of the head, neck, and trunk in the coronal plane (Figure 2-4, *B*). In the human, lateral flexion is usually combined with some element of rotation. Abduction and adduction are also motions in a coronal plane. Abduction is movement away from the body, and adduction is movement toward the body; the reference here is to the midsagittal plane of the body. This would be true for all parts of the extremities, excluding the thumb, fingers, and toes. For these structures, reference points are to be found within that particular extremity.

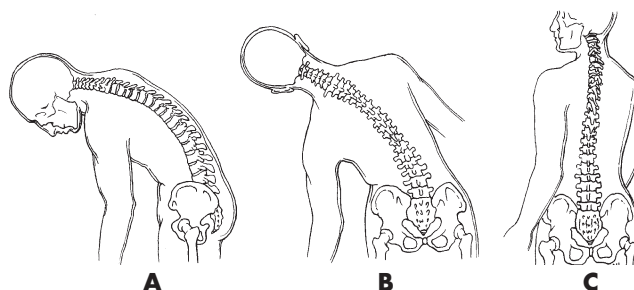


Figure 2-4

A, Sagittal plane movement of flexion. *B*, Coronal plane movement of lateral flexion. *C*, Transverse plane movement of axial rotation.

The longitudinal axis (y-axis) is vertical, extending in a head-to-toe direction. Movements of medial (internal) and lateral (external) rotation in the extremities, as well as axial rotation in the spine, occur around it and through the transverse plane (Figure 2-4, *C*). Axial rotation is used to describe this type of movement for all areas of the body except the scapula and clavicle. Rotation occurs about an anatomic axis, except in the case of the femur, which rotates around a mechanical axis.⁴ In the human extremity, the anterior surface of the extremity is used as a reference area. Rotation of the anterior surface toward the midsagittal plane of the body is medial (internal) rotation, and rotation away from the midsagittal plane is lateral (external) rotation. Supination and pronation are rotation movements of the forearm.

Because the head, neck, thorax, and pelvis rotate about longitudinal axes in the midsagittal area, rotation cannot be named in reference to the midsagittal plane. Rotation of the head, spine, and pelvis is described as rotation of the anterior surface posteriorly toward the right or left. Rotation of the scapula is movement about a sagittal axis, rather than about a longitudinal axis. The terms *clockwise* or *counterclockwise* are used.

Translational movements are linear movements or, simply, movements in a straight line. Gliding movements of the joint are translational in character. The term *slide* has also been used in referring to translational movements between joint surfaces. Posterior-to-anterior (P-A) glide (anterolisthesis) and anterior-to-posterior (A-P) glide (retrolisthesis) are translational movements along the z axis. Lateral-to-medial (L-M) glide and medial-to-lateral (M-L) glide (laterolisthesis) translate along the x axis. Distraction and compression (altered interosseous spacing) translate along the y axis. Curvilinear motion combines both rotational and translational movements and is the most common motion produced by the joints of the body (Figure 2-5).

Moreover, the potential exists for each joint to exhibit three translational movements and three rotational movements, constituting 6 degrees of freedom. The ex-

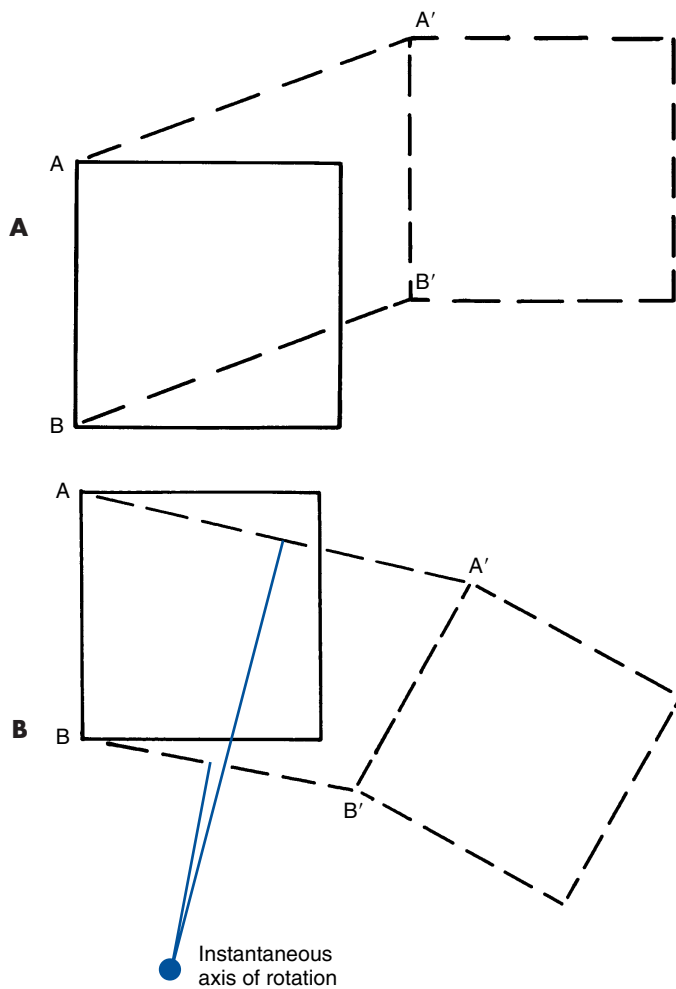


Figure 2-5
A, Translational movement. **B**, Curvilinear movement: a combination of translation and rotation movements.

ment of each movement is based more or less on the joint anatomy and, specifically, the plane of the joint surface. Each articulation in the body has the potential to exhibit, to some degree, flexion, extension, right and left lateral flexion, right and left axial rotation, A-P glide, P-A glide, L-M glide, M-L glide, compression, and distraction.

Joints are classified first by their functional capabilities and then are subdivided by their structural characteristics. Synarthroses allow very little, if any, movement; diarthroses, or true synovial joints, allow significant movement. The structural characteristics of these joints are detailed in Table 2-2.

Synovial Joints

Synovial joints are the most common joints of the human appendicular skeleton, representing highly evolved, movable joints. Although these joints are considered freely movable, the degree of possible motion varies ac-

ording to the individual structural design, facet planes, and primary function (motion vs. stability). The components of a typical synovial joint include the bony elements, subchondral bone, articular cartilage, synovial membrane, fibroligamentous joint capsule, and articular joint receptors. An understanding of the basic anatomy of a synovial joint forms the foundation for appreciation of clinically significant changes in the joint that lead to joint dysfunction.

Bony Elements

The bony elements provide the supporting structure that gives the joint its capabilities and individual characteristics by forming lever arms to which intrinsic and extrinsic forces are applied. Bone is actually a form of connective tissue that has an inorganic constituent (lime salts). A hard outer shell of cortical bone provides structural support and surrounds the cancellous bone, which contains marrow and blood vessels that provide nutrition. Trabecular patterns develop in the cancellous bone, corresponding to mechanical stress applied to and required by the bone (Figure 2-6). Bone also has the important role of hemopoiesis (formation of blood cells). Furthermore, bone stores calcium and phosphorus, which it exchanges with blood and tissue fluids. Finally, bone has the unique characteristic of repairing itself with its own tissue as opposed to fibrous scar tissue, which all other body tissues use.

Articular Cartilage

Articular cartilage covers the articulating bones in synovial joints and helps to transmit loads and reduce friction. It is bonded tightly to the subchondral bone through the zone of calcification, which is the end of bone visible on x-ray film. The joint space visible on x-ray film is composed of the synovial cavity and noncalcified articular cartilage. In its normal composition, articular cartilage has four histologic areas or zones (Figure 2-7). These zones have been further studied and refined so that a wealth of newer information regarding cartilage has developed.

The outermost layer of cartilage is known as the *gliding zone*, which itself contains a superficial layer (outer) and a tangential layer (inner). The outer segment is made up solely of collagen randomly oriented into flat bundles. The tangential layer consists of densely packed layers of collagen, which are oriented parallel to the surface of the joint.⁵ This orientation is along the lines of the joint motion, which implies that the outer layers of collagen are stronger when forces are applied parallel to the joint motion rather than perpendicular to it.⁶ This particular orientation of fibers provides a great deal of strength to the joint in normal motion. The gliding zone also has a role in protecting the deeper elastic cartilage.

TABLE 2-2

Joint Classification

Joint Type	Structure	Example
Synarthrotic		
Fibrous	Suture—nearly no movement	Cranial sutures
Cartilaginous	Syndesmosis—some movement	Distal tibia-fibula
	Synchondrosis—temporary	Epiphyseal plates
	Symphysis—fibrocartilage	Pubes
		Intervertebral discs
Diarthrotic		
Uniaxial	Ginglymus (hinge)	Elbow
	Trochoid (pivot)	Atlantoaxial joint
	Condylar	Metacarpophalangeal joint
Biaxial	Ellipsoid	Radiocarpal joint
	Sellar (saddle)	Carpometacarpal joint of the thumb
Multiaxial	Triaxial	Shoulder
	Spheroid (ball and socket)	Hip
Plane (nonaxial)		Intercarpal joints
		Posterior facet joints in the spine

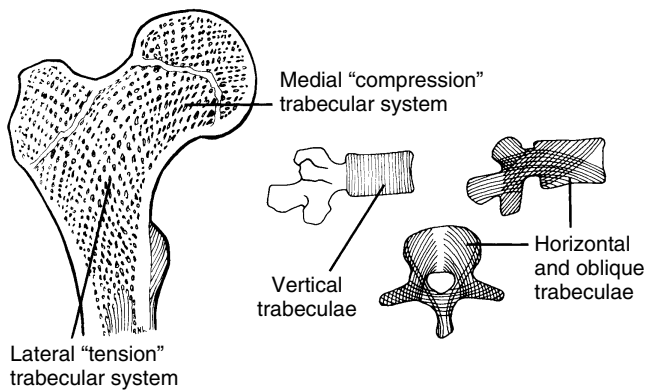


Figure 2-6

Trabecular patterns corresponding to mechanical stresses in the hip joint and vertebra. (Modified from Hertling D, Kessler RM: *Management of common musculoskeletal disorders: Physical therapy principles and methods*, ed 2, Philadelphia, 1990, JB Lippincott.)

The *transitional zone* lies beneath the gliding zone. It represents an area where the orientation of the fibers begins to change from the parallel orientation of the gliding zone to the more perpendicular orientation of the radial zone. Therefore fiber orientation is more or less oblique and, in varying angles, formed from glucuronic acid and *N*-acetylgalactosamine with a sulfate on either the fourth or sixth position. The keratin compound is formed with galactose and *N*-acetylgalactosamine. All of this occurs in linked, repeating units (Figure 2-8).

Articular cartilage is considered mostly avascular. Articular cartilage must rely on other sources for nutrition,

removal of waste products, and the process of repair. Therefore intermittent compression (loading) and distraction (unloading) are necessary for adequate exchange of nutrients and waste products. The highly vascularized synovium is believed to be a critical source of nutrition for the articular cartilage it covers. The avascular nature of articular cartilage limits the potential for cartilage repair by limiting the availability of the repair products on which healing depends. Chondrocytes, the basic cells of cartilage that maintain and synthesize the matrix, are contained within a mesh of collagen and proteoglycan that does not allow them to migrate to the injury site from adjacent healthy cartilage.⁷ Moreover, the articular cartilage matrix may contain substances that inhibit vascular and macrophage invasion and clot formation that are also necessary for healing.⁸ After an injury to the articular cartilage, the joint can return to an asymptomatic state after the transient synovitis subsides. Degeneration of the articular cartilage depends on the size and depth of the lesion, the integrity of the surrounding articular surface, the age and weight of the patient, associated meniscal and ligamentous lesions, and a variety of other biomechanical factors.⁷ Continuous passive motion has increased the ability of full-thickness defects in articular cartilage to heal, producing tissue that closely resembles hyaline cartilage.⁹

Ligamentous Elements

The primary ligamentous structure of a synovial joint is the joint capsule. Throughout the vertebral column, the joint capsules are thin and loose. The capsules are attached to the opposed superior and inferior articular

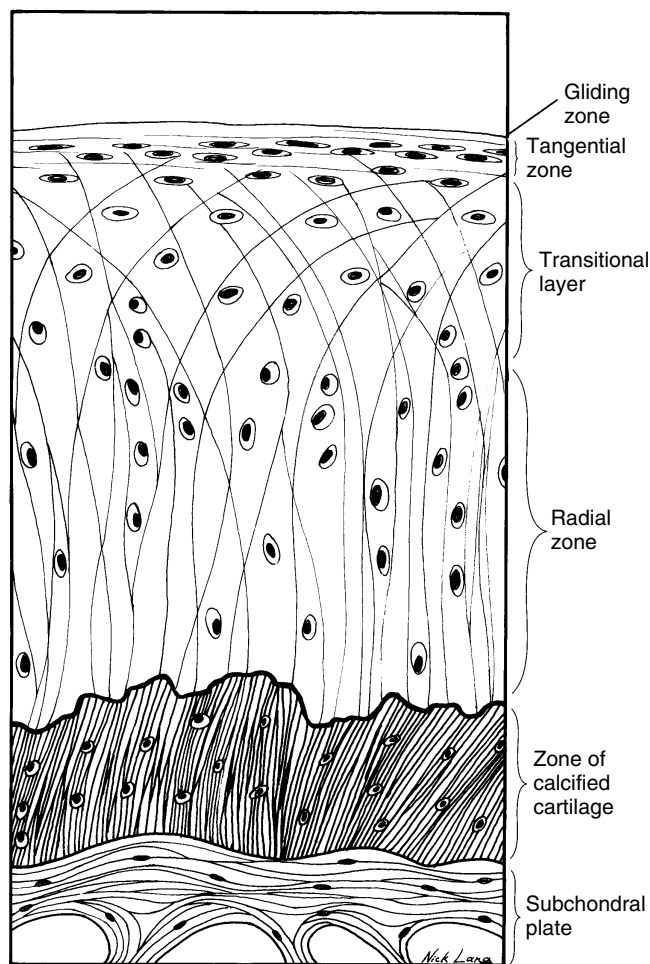


Figure 2-7 Microscopic anatomy of articular cartilage. (Modified from Albright JA, Brand RA: *The scientific basis of orthopaedics*, East Norwalk, Conn, 1979, Appleton-Century-Crofts.)

facets of adjacent vertebrae. Joint capsules in the spine have three layers.¹⁰ The outer layer is composed of dense fibroelastic connective tissue made up of parallel bundles of collagen fibers. The middle layer is composed of loose connective tissue and areolar tissue containing vascular structures. The inner layer consists of the synovial membrane. This joint capsules covers the posterior and lateral aspects of the zygapophyseal joint. The ligamentum flavum covers the joint capsules anteriorly and medially.

Synovial Fluid

Although the exact role of synovial fluid is still unknown, it is thought to serve as a joint lubricant or at least to interact with the articular cartilage to decrease friction between joint surfaces. This is of clinical relevance because immobilized joints have been shown to undergo degeneration of the articular cartilage.¹¹ Synovial fluid is similar in composition to plasma, with the addition of mucin

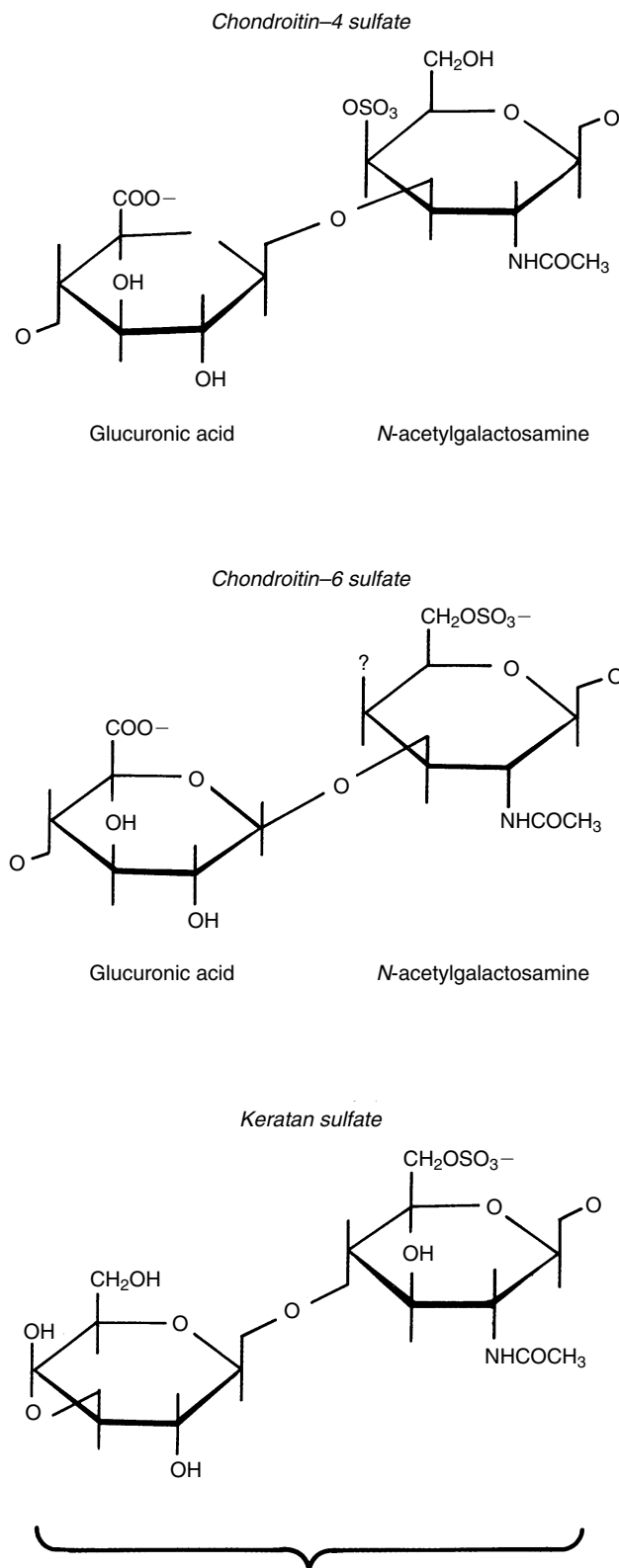


Figure 2-8 Structure of chondroitin and keratin compounds.

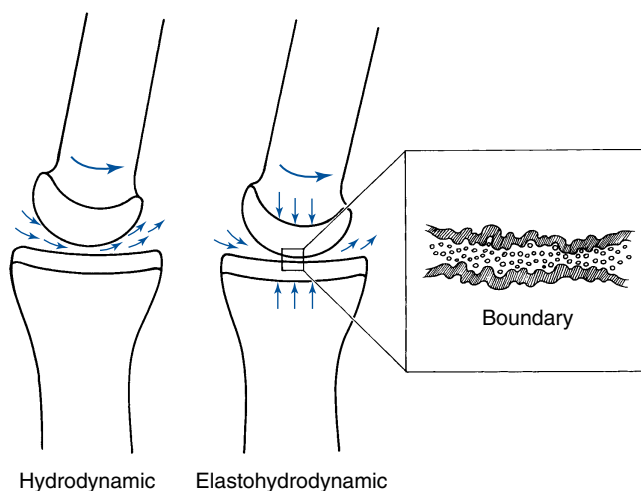


Figure 2-9

Lubrication models for synovial joints. (Modified from Hertling D, Kessler RM: *Management of common musculoskeletal disorders: Physical therapy principles and methods*, ed 2, Philadelphia, 1990, JB Lippincott.)

(hyaluronic acid), which gives it a high molecular weight and its characteristic viscosity. Three models of joint lubrication exist. The controversy lies in the fact that no one model of joint lubrication applies to all joints under all circumstances.

According to the hydrodynamic model, synovial fluid fills in spaces left by the incongruent joint surfaces. During joint movement, synovial fluid is attracted to the area of contact between the joint surfaces, resulting in the maintenance of a fluid film between moving surfaces. This model was the first to be described and works well with quick movement, but it would not provide adequate lubrication for slow movements and movement under increased loads.

The elastohydrodynamic model is a modification of the hydrodynamic model that considers the viscoelastic properties of articular cartilage whereby deformation of joint surfaces occurs with loading, creating increased contact between surfaces. This would effectively reduce the compression stress to the lubrication fluid. Although this model allows for loading forces, it does not explain lubrication at the initiation of movement or the period of relative zero velocity during reciprocating movements.¹²

In the boundary lubrication model, the lubricant is adsorbed on the joint surface, which would reduce the roughness of the surface by filling the irregularities and effectively coating the joint surface. This model allows for initial movement and zero velocity movements. Moreover, boundary lubrication combined with the elastohydrodynamic model, creating a mixed model, meets the demands of the human synovial joint (Figure 2-9).

Articular Neurology

Articular neurology gives invaluable information on the nature of joint pain, the relationship of joint pain to joint dysfunction, and the role of manipulative procedures in affecting joint pain. Synovial joints are innervated by three or four varieties of neuroreceptors, each with a wide variety of parent neurons. The axons differ in diameter and conduction velocity, representing a continuum from the largest heavily myelinated A α -fibers to the smallest unmyelinated C fibers. All are derived from the dorsal and ventral rami, as well as the recurrent meningeal nerve of each segmental spinal nerve (Figure 2-10). Information from these receptors spreads among many segmental levels because of multilevel ascending and descending primary afferents. The receptors are divided into the four groups according to their neurohistologic properties, which include three corpuscular mechanoreceptors and one nociceptor.¹³

Type I receptors are confined to the outer layers of the joint capsule and are stimulated by active or passive joint motions. Their firing rate is inhibited with joint approximation, and they have a low threshold, making them very sensitive to movement. Some are considered static receptors because they fire continually, even with no joint movement. Because they are slow adapting, the effects of movement are long lasting. Stimulation of type I receptors is involved with the following:

1. Reflex modulation of posture, as well as movement (kinesthetic sensations), through constant monitoring of outer joint tension
2. Perception of posture and movement
3. Inhibition of flow from pain receptors via an enkephalin synaptic interneuron transmitter
4. Tonic effects on lower motor neuron pools involved in the neck, limbs, jaw, and eye muscles

Type II mechanoreceptors are found within the deeper layers of the joint capsule. They are also low threshold and again are stimulated with even minor changes in tension within the inner joint. Unlike type I receptors, however, type II receptors adapt very rapidly and quickly cease firing when the joint stops moving. Type II receptors are completely inactive in immobilized joints. Functions of the type II receptors are likely to include the following:

1. Movement monitoring for reflex actions and perhaps perceptual sensations
2. Inhibition of flow from pain receptors via an enkephalin synaptic interneuron neural transmitter
3. Phasic effects on lower motor neuron pools involved in the neck, limbs, jaw, and eye muscles

Type III mechanoreceptors are found in the intrinsic and extrinsic ligaments of the peripheral joints, but they had been previously thought to be absent from all of the synovial spinal joints. However, McLain¹⁴ examined 21 cervical facet capsules from three normal human subjects

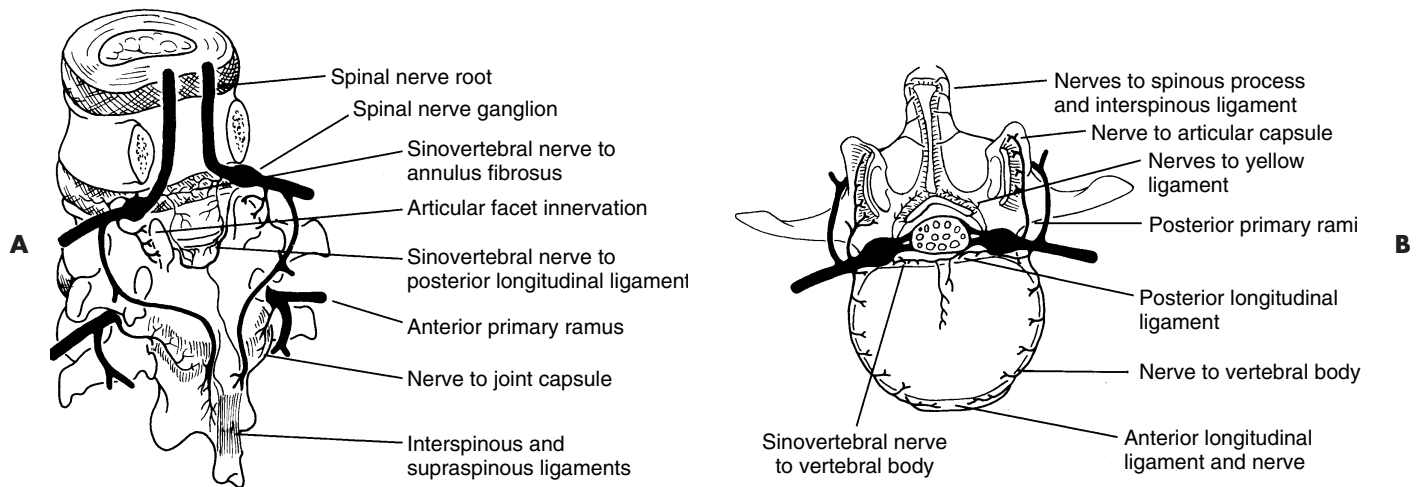


Figure 2-10

Innervation of the outer fibers of the disc and facet joint capsule by the sinuvertebral nerve.

A, Oblique posterior view. **B**, Top view. (Modified from White AA, Panjabi MM: *Clinical biomechanics of the spine*, Philadelphia, 1978, JB Lippincott.)

and found type III receptors, although they were less abundant than either type I or type II. These receptors are very slow adapters with a very high threshold because they are innervated by large myelinated fibers. They seem to be the joint version of the Golgi tendon organ in that they impose an inhibitory effect on motoneurons. Although the functions of type III receptors are not completely understood, it is likely that they achieve the following:

1. Monitor direction of movement
2. Create a reflex effect on segmental muscle tone, providing a “braking mechanism” against movement that overdisplaces the joint
3. Recognize potentially harmful movements

Type IV receptors are composed of a network of free nerve endings, as well as unmyelinated fibers. They are associated with pain perception and include many different varieties with large ranges of sensations, including itch and tickle. They possess an intimate physical relationship to the mechanoreceptors and are present throughout the fibrous portions of the joint capsule and ligaments. They are absent from articular cartilage and synovial linings, although they have been found in synovial folds.^{15,16} They are very high-threshold receptors and are completely inactive in the physiologic joint. Joint capsule pressure, narrowing of the intervertebral disc, fracture of a vertebral body, dislocation of the zygapophyseal joints, chemical irritation, and interstitial edema associated with acute or chronic inflammation may all activate the nociceptive system. The basic functions of the nociceptors include the following:

1. Evocation of pain
2. Tonic effects on neck, limb, jaw, and eye muscles
3. Central reflex connections for pain inhibition

4. Central reflex connections for a myriad of autonomic effects

A relationship exists between mechanoreceptors and nociceptors such that when the mechanoreceptors function correctly, an inhibition of nociceptor activity occurs.¹³ The converse also holds true; when the mechanoreceptors fail to function correctly, inhibition of nociceptors will occur less, and pain will be perceived.¹³

Discharges from the articular mechanoreceptors are polysynaptic and produce coordinated facilitatory and inhibitory reflex changes in the spinal musculature. This provides a significant contribution to the reflex control of these muscles.¹³ Gillette¹⁵ suggests that a chiropractic adjustment produces sufficient force to coactivate a wide variety of mechanically sensitive receptor types in the paraspinal tissues. The A- δ -mechanoreceptors and C-polymodal nociceptors, which can generate impulses during and after stimulation, may well be the most physiologically interesting component of the afferent bombardment initiated by high-velocity, low-amplitude manipulations. For normal function of the joint structures, an integration of proprioception, kinesthetic perception, and reflex regulation is absolutely essential.

Pain-sensitive fibers also exist within the annulus fibrosus of the disc. Malinsky¹⁶ demonstrated the presence of a variety of free and complex nerve endings in the outer one third of the annulus. The disc is innervated posteriorly by the recurrent meningeal nerve (sinuvertebral nerve) and laterally by branches of the gray rami communicantes. During evaluation of disc material surgically removed before spinal fusion, Bogduk¹⁷ found abundant nerve endings with various morphologies. The varieties of nerve endings included free terminals,

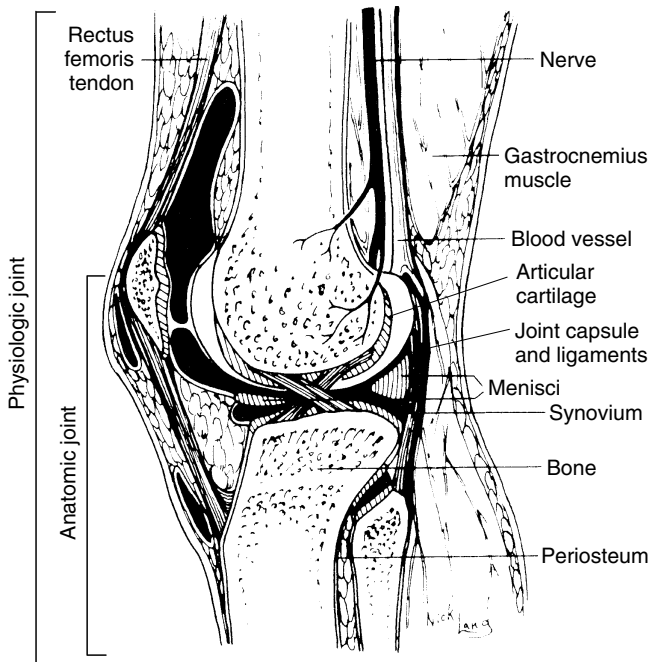


Figure 2-11 Structures that make up the anatomic joint and the physiologic joint in the knee.

complex sprays, and convoluted tangles. Furthermore, many of these endings contained substance P, a putative transmitter substance involved in nociception.

Shinohara¹⁸ reported the presence of such nerve fibers accompanying granulation tissue as deep as the nucleus in degenerated discs. Freemont et al¹⁹ examined discs from individuals free of back pain and from those with back pain. They identified nerve fibers in the outer one third of the annulus in pain-free disc samples, but they found nerve fibers extending into the inner one third of the annulus and into the nucleus pulposus of the discs from the pain sample. They suggest that their findings of isolated nerve fibers that express substance P deep within diseased intervertebral discs may play an important role in the pathogenesis of chronic low back pain. Abundant evidence shows that the disc can be painful, supporting the ascribed nociceptive function of the free nerve endings.¹⁶⁻²⁷

Because structure and function are interdependent, the study of joint characteristics should not isolate structure from function. The structural attributes of a joint are defined as the *anatomic joint*, consisting of the articular surfaces with the surrounding joint capsule and ligaments, as well as any intraarticular structures. The functional attributes are defined as the *physiologic joint*, consisting of

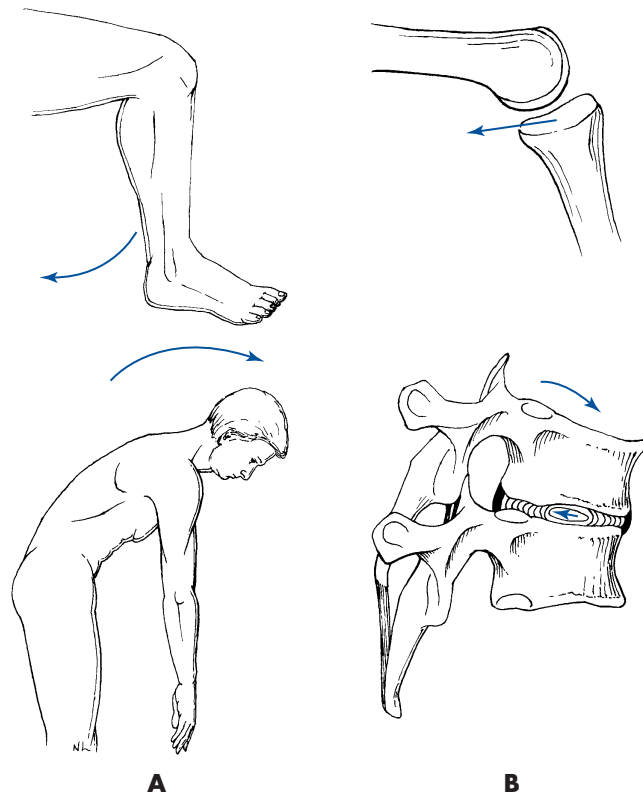


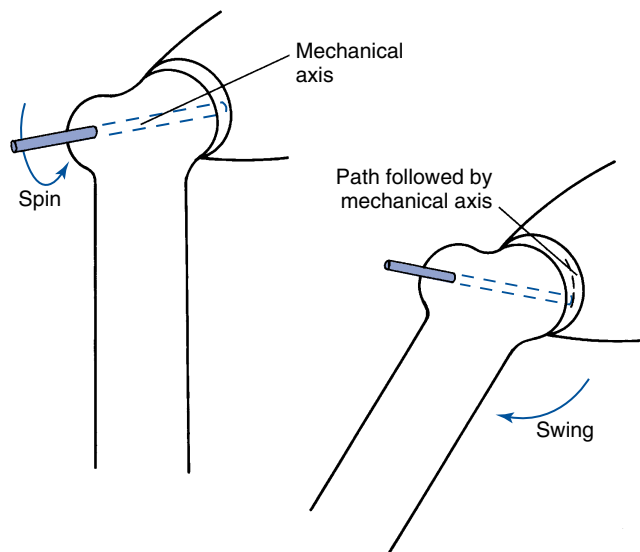
Figure 2-12 A, Osteokinematic movement of knee and trunk flexion. B, Arthrokinematic movements of tibiofemoral and T6-T7 joint flexion.

the anatomic joint plus the surrounding soft tissues, including the muscles, connective tissue, nerves, and blood vessels (Figure 2-11).

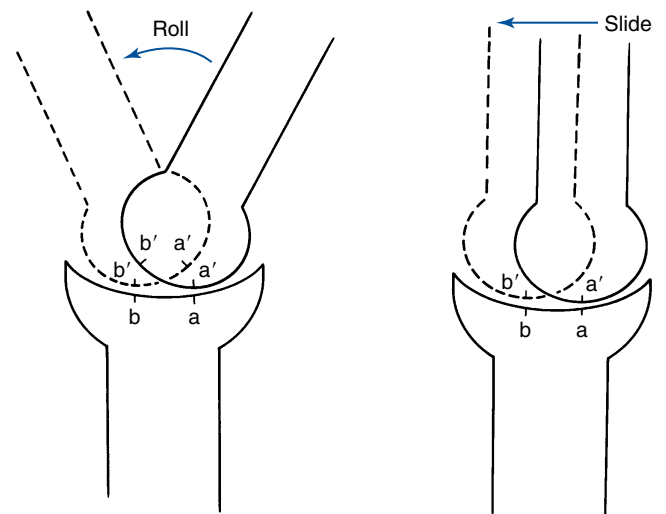
JOINT FUNCTION

The physiologic movement possible at each joint occurs when muscles contract or when gravity acts on bone to move it. This motion is termed *osteokinematic movement*. Osteokinematic movement describes how each bony joint partner moves relative to the other. The specific movements that occur at the articulating joint surfaces are referred to as *arthrokinematic movement*. Consideration of the motion between bones alone or osteokinematic movement is insufficient, because no concern is given to what occurs at the joint and because movement commonly involves coupling of motion around different axes. Furthermore, arthrokinematic movements consider the forces applied to the joint and include the accessory motion present in a particular articulation.

It is therefore important to relate osteokinematic movement to arthrokinematic movement when evaluating joint motion (Figure 2-12). This involves determining the movement of the mechanical axis of the moving bone

**Figure 2-13**

Mechanical axis of a joint and MacConail and Basmajian's concept of spin and swing. (Modified from Hertling D, Kessler RM: *Management of common musculoskeletal disorders: Physical therapy principles and methods*, ed 2, Philadelphia, 1990, JB Lippincott.)

**Figure 2-14**

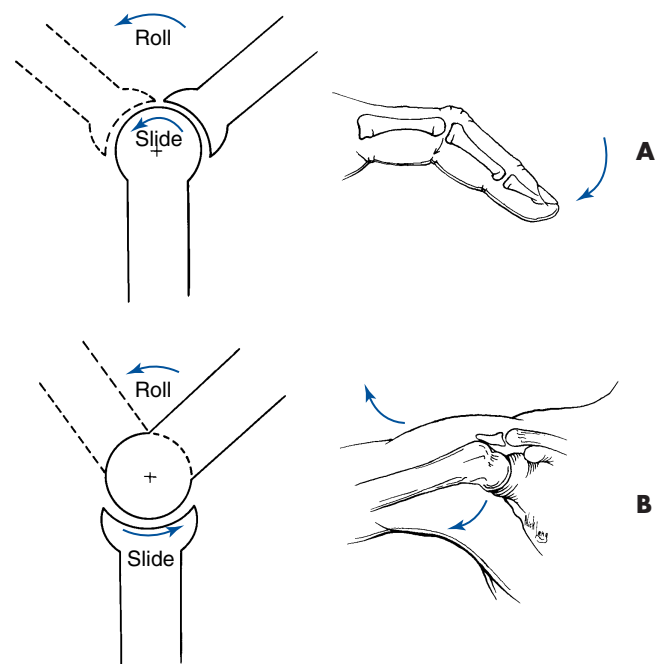
Arthrokinematic movements of roll and slide. (Modified from Hertling D, Kessler RM: *Management of common musculoskeletal disorders: Physical therapy principles and methods*, ed 2, Philadelphia, 1990, JB Lippincott.)

relative to the stationary joint surface. The *mechanical axis of a joint* is defined as a line passing through the moving bone, oriented perpendicular to the center of the stationary joint surface (Figure 2-13).

When one joint surface moves relative to the other, spin, roll, slide, or combinations occur. MacConail and Basmajian²⁸ use the term *spin* to describe rotational movement around the mechanical axis, which is possible as a pure movement only in the hip, shoulder, and proximal radius. *Roll* occurs when points on the surface of one bone contact points at the same interval of the other bone. *Slide* occurs when only one point on the moving joint surface contacts various points on the opposing joint surface (Figure 2-14).

In most joints of the human body, these motions occur simultaneously. The concave-convex rule relates to this expected coupling of rotational (roll) and translational (slide) movements. When a concave surface moves on a convex surface, roll and slide movements should occur in the same direction. When a convex surface moves on a concave surface, however, roll and slide should occur in opposite directions (Figure 2-15). Pure roll movement tends to result in joint dislocation, whereas pure slide movement causes joint surface impingement (Figure 2-16). Moreover, coupling of roll and slide is important anatomically because less articular cartilage is necessary in a joint to allow for movement and may decrease wear on the joint.

These concepts are instrumental in clinical decision-making regarding the restoration of restricted joint motion. Roll and spin can be restored with passive range-

**Figure 2-15**

Concave-convex rule. **A**, Movement of concave surface on a convex surface. **B**, Movement of a convex surface on a concave surface.

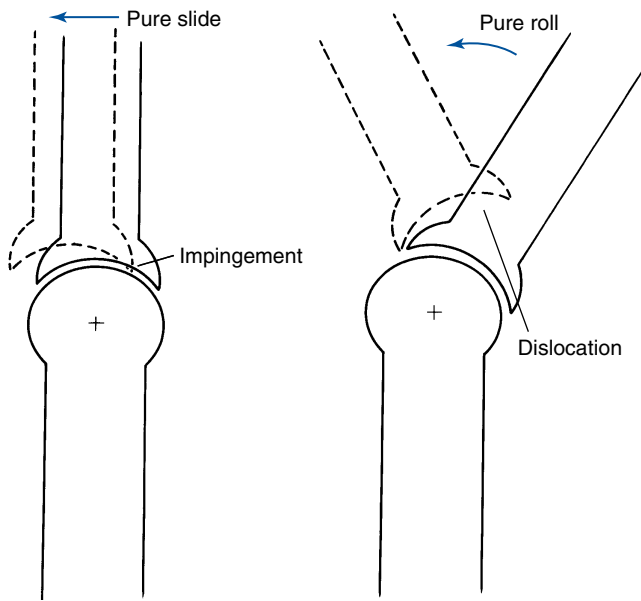


Figure 2-16
 Consequences of pure roll or pure slide movements. (Modified from Hertling D, Kessler RM: *Management of common musculoskeletal disorders: Physical therapy principles and methods*, ed 2, Philadelphia, 1990, JB Lippincott.)

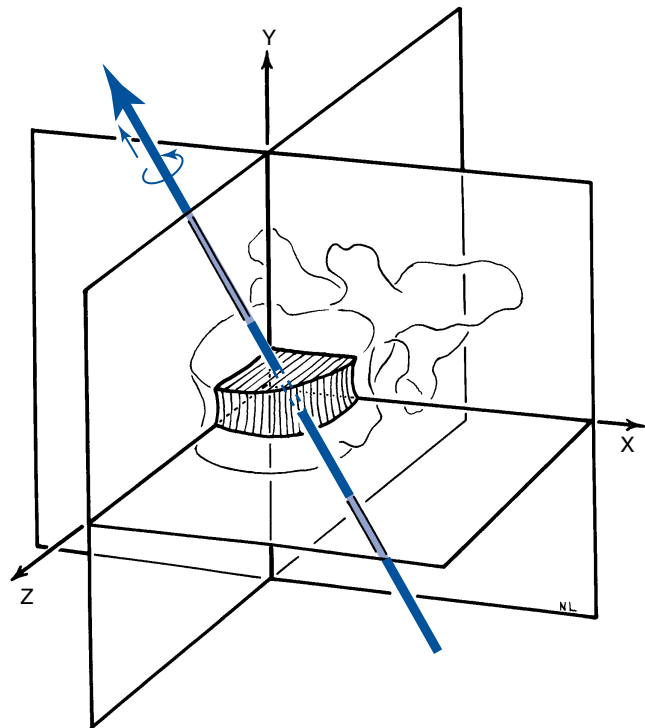


Figure 2-18
 Helical axis of motion. (Modified from White AA, Panjabi MM: *Clinical biomechanics of the spine*, Philadelphia, 1978, JB Lippincott.)

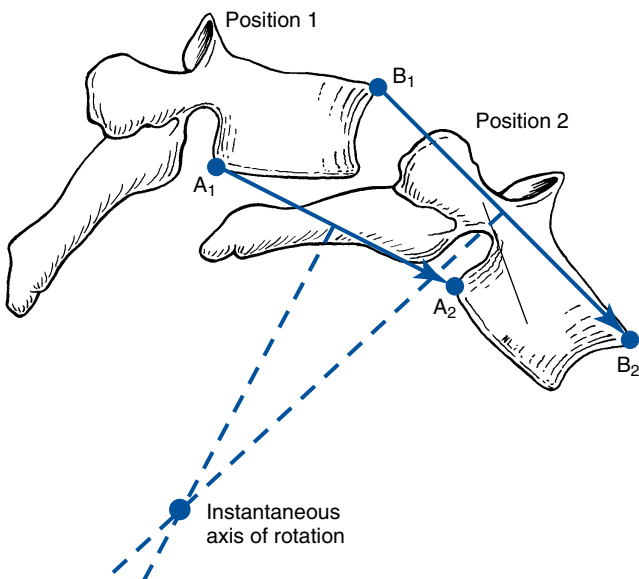


Figure 2-17
 Instantaneous axis of rotation. (Modified from White AA, Panjabi MM: *Clinical biomechanics of the spine*, Philadelphia, 1978, JB Lippincott.)

of-motion procedures that induce the arthrokinematic movements of the dysfunctional joint. Manipulative (thrust) techniques are needed to restore slide movements and can also be used for roll and spin problems.²⁹

In addition, when an object moves, the axis around which the movement occurs can vary in placement from one instant to another. The term *instantaneous axis of rotation (IAR)* is used to denote this location point. Asymmetric forces applied to the joint can cause a shift in the normal IAR. Furthermore, vertebral movement may be more easily analyzed as the IAR becomes more completely understood (Figure 2-17). White and Panjabi¹ point out that the value of this concept is that any kind of plane motion can be described relative to the IAR. Complex motions are simply regarded as many very small movements with many changing IARs.¹ This concept is designed to describe plane movement, or movement in two dimensions.

When three-dimensional motion occurs between objects, a unique axis in space is defined called the *helical axis of motion (HAM)*, or screw axis of motion (Figure 2-18). HAM is the most precise way to describe motion occurring between irregularly shaped objects, such as anatomic structures, because it is difficult to consistently and accurately identify reference points for such objects.

Clearly, most movements occur around and through several axes simultaneously, so pure movements in the

TABLE 2-3

Close-Packed Positions for Each Joint

Region	Specific Joint	Close-Packed Position
Fingers	Distal interphalangeal joints	Maximal extension
	Proximal interphalangeal joints	Maximal extension
	Metacarpophalangeal joints	Maximal flexion
Hand	Intermetacarpal joints	Maximal opposition
Wrist	Intercarpal joints	Maximal dorsiflexion
Forearm	Radioulnar joints	5 degrees of supination
Elbow	Ulnohumeral joint	Extension in supination
	Radiohumeral joint	Flexion in supination
Shoulder	Glenohumeral joint	Abduction and external rotation
	Acromioclavicular joint	90 degrees of abduction
	Sternoclavicular joint	Maximal elevation
Toes	Distal interphalangeal joints	Maximal extension
	Proximal interphalangeal joints	Maximal extension
	Metatarsophalangeal joints	Maximal extension
Foot	Intermetatarsal joints	Maximal opposition
Ankle	Tarsometatarsal joints	Maximal inversion
	Tibiotalar joint	Maximal dorsiflexion
Knee	Tibiofemoral joint	Maximal extension and external rotation
Hip	Coxofemoral joint	Maximal extension, internal rotation, and abduction
Spine	Three-joint complex	Maximal extension

human frame rarely occur. The nature and extent of individual joint motion are determined by the joint structure and, specifically, by the shape and direction of the joint surfaces. No two opposing joint surfaces are perfectly matched, nor are they perfectly geometric. All joint surfaces have some degree of curvature that is not constant but changing from point to point. Because of the incongruence between joint surfaces, some joint space and “play” must be present to allow free movement. This joint play is an accessory movement of the joint that is essential for normal functioning of the joint.

The resting position of a joint, or its neutral position, occurs when the joint capsule is most relaxed and the greatest amount of play is possible. When injured, a joint often seeks this maximum loose-packed position to allow for swelling.

The close-packed position occurs when the joint capsule and ligaments are maximally tightened. Moreover, there is maximal contact between the articular surfaces, making the joint very stable and difficult to move or separate.

Joint surfaces will approximate or separate as the joint goes through a range of motion. This is the motion of compression and distraction. A joint moving toward its close-packed position is undergoing *compression*, and a joint moving toward its open-packed position is undergoing *distraction*²⁸ (Table 2-3).

Joint motion consists of five qualities of movement that must be present for normal joint function. These five qualities are joint play, active range of motion, pas-

sive range of motion, end feel or play, and paraphysiologic movement. From the neutral close-packed position, joint play should be present. This is followed by a range of active movement under the control of the musculature. The passive range of motion is produced by the examiner and includes the active range, plus a small degree of movement into the elastic range. The elastic barrier of resistance is then encountered, which exhibits the characteristic movement of end feel. The small amount of movement available past the elastic barrier typically occurs postcavitation and has been classified as paraphysiologic movement. Movement of the joint beyond the paraphysiologic barrier takes the joint beyond its limit of anatomic integrity and into a pathologic zone of movement. Should a joint enter the pathologic zone, there will be damage to the joint structures, including the osseous and soft tissue components (see Figures 3-22 and 3-23).

Both joint play and end-feel movements are thought to be necessary for the normal functioning of the joint. A loss of either movement can result in a restriction of motion, pain, and most likely, both. Active movements can be influenced by exercise and mobilization, and passive movements can be influenced by traction and some forms of mobilization, but end-feel movements are affected when the joint is taken through the elastic barrier, creating a sudden yielding of the joint and a characteristic cracking noise (cavitation). This action can be accomplished with deep mobilization and a high-velocity, low-amplitude manipulative thrust.

MECHANICAL FORCES ACTING ON CONNECTIVE TISSUE

Whereas an understanding of structure is needed to form a foundation, an understanding of the dynamics of the various forces affecting joints will aid in the explanation of joint injury and repair. Functionally, the most important properties of bone are its strength and stiffness, which become significant qualities when loads are applied (Figure 2-19). Living tissue is subjected to many different combinations of loading force throughout the requirements of daily living. Although each type of loading force is described individually, most activities produce varying amounts and combinations of all of them.

Tension Forces

The force known as *tension* occurs when a structure is stretched longitudinally. Tensile loading is a stretching action that creates equal and opposite loads outward from the surface and tensile stress and strain inward. Therefore a tension force tends to pull a structure apart,

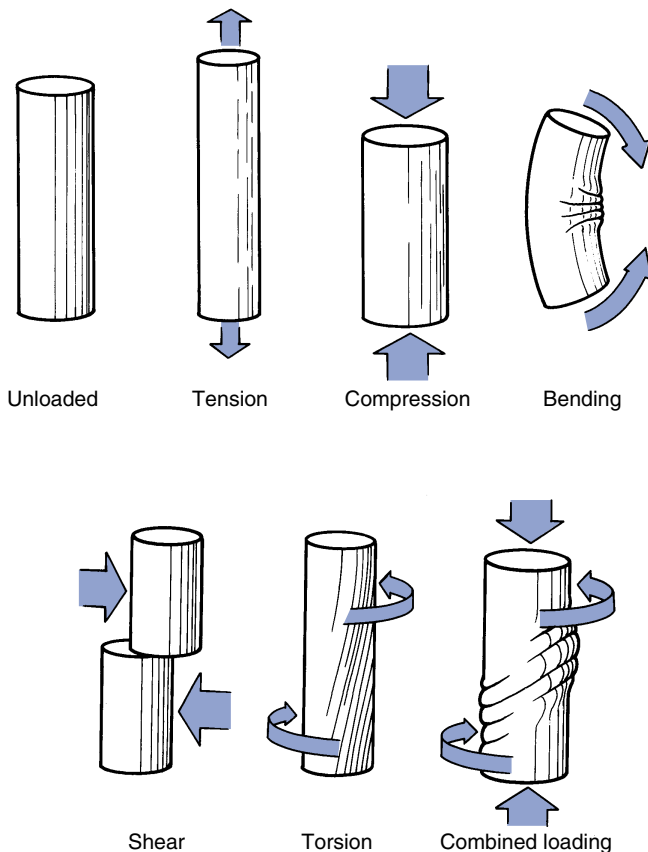


Figure 2-19

Loads to which bone may be subject. (Modified from Soderberg GL: *Kinesiology: Application to pathological motion*, Baltimore, 1986, Williams & Wilkins.)

causing the cross-sectional area of the structure to decrease. When a material is stretched in the direction of the pull, it contracts in the other two directions. If the primary stress is tensile, there will be secondary stresses that are compressive and vice versa.

The tension elements of the body are the soft tissues (fascia, muscles, ligaments, and connective tissue) and have largely been ignored as construction members of the body frame. The tension elements are an integral part of the construction and not just a secondary support. In the spine, the ligaments are loaded in tension.³⁰ Tensile forces also occur in the intervertebral disc during the rotational movements of flexion, extension, axial rotation, and lateral flexion. The nucleus tends to bear the compressive load, and the annular fibers tend to bear the tensile loads.

Compression Forces

Compression occurs when a load produces forces that push the material together, creating a deforming stress. The behavior of a structure in compression depends a great deal on its length and how far or long the load is applied.

Compressive forces are transmitted to the vertebral body and intervertebral disc in the spine. The nucleus pulposus is a semiliquid or gel that has the characteristics of a fluid or hydraulic structure. It is incompressible and must therefore distort under compressive loads. The nucleus pulposus dissipates the compressive force by redirecting it radially.

It is important clinically to note that mechanical failure occurs first in the cartilaginous endplate when compressive forces applied alone are too great. The result is nuclear herniation into the vertebral body, called a *Schmorl's node*. However, failure may be modified when the spine is loaded in either flexion or extension. Compressive loads applied in flexion tend to cause anterior collapse of the endplate or vertebral body, where the bony structure is weaker. With compressive loads applied in extension, a significant percentage of the compressive load is transmitted through the facets, leading to capsular injuries.

Compressive loads applied with torque around the long axis can produce circumferential tears in the disc annulus. Compression loading (axial loading) on bone creates equal and opposite loads toward the surface and compressive stress and strain inward, causing the structure to become shorter and wider. Compression fractures of the vertebral bodies are examples of failure to withstand compressive forces.

Bending loads are a combination of tensile and compressive loads. The magnitude depends on the distance of the forces from the neutral axis. Fractures to long bones frequently occur through this mechanism.

Shear Forces

The biomechanical effects on living things would be a great deal easier to understand if the loads, stresses, and strains were all either tensile or compressive ones. However, living things are also subjected to shear forces. A *shear* force creates sliding or, more specifically, resistance to sliding. Shear loading causes the structure to deform internally in an angular manner as a result of loads applied parallel to the surface of the structure.

Primarily, the facet joints and the fibers of the annulus fibrosus resist shear forces in the spinal motion segment. Under normal physiologic conditions, the facets can resist shear forces when they are in contact. If, however, the disc space is narrowed by degeneration with subsequent thinning of the disc, abnormally high stresses may be placed on the facet joints, and the limit of resistance to such forces is not well documented.^{31,32}

Since there is no significant provision for resisting shear stress, the risk of disc failure is greater with tensile loading than with compression loading.¹ However, the studies available demonstrating the effects of shear forces have been performed mostly on cadavers in which the posterior elements have been removed. The lumbar facets are aligned mostly in the sagittal plane with an interlocking mechanism that only allows a few degrees of rotation. Therefore, at least in the lower lumbar segments, the facet joints do provide resistance to shear stress. Cancellous bone is most prone to fracture from shear loading, with the femoral condyles and tibial plateaus often falling victim.

Torque Forces

Torsion occurs when an object twists, and the force that causes the twisting is referred to as *torque*. Torque is a load produced by parallel forces in opposite directions about the long axis of a structure. In a curved structure, such as the spine, bending also occurs when a torque load is applied.

Farfan et al³³ estimates that about 90% of the resistance to torque of a motion segment is provided by its disc. They further state that the annulus provides the majority of the torsional resistance in the lumbar spine and speculate that with torsional injury, annular layers will tear, leading to disc degeneration.³³ This concept is developed around the idea that when torsional forces are created in the spine, the annular fibers oriented in one direction will stretch while those oriented in the other direction will relax. The result is that only half of the fibers are available to resist the force.

However, Adams and Hutton³⁴ disagreed with Farfan et al and demonstrated that primarily the facets resist the torsion of the lumbar spine and that the compressed facet was the first structure to yield at the limit of torsion. Others have performed experiments that further suggest

and support that the posterior elements of the spine, including the facet joints and ligaments, play a significant role in resisting torsion.^{35,36} In deference to Farfan et al's conclusions, these authors suggest that torsion alone is unimportant in the etiology of disc degeneration and prolapse, since rotation is produced by voluntary muscle activity and the intervertebral disc experiences relatively small stresses and strains. Bogduk and Twomey³⁷ state that axial rotation can strain the annulus in torsion, but ordinarily the zygapophyseal joints protect it. Normal rotation in the lumbar spine produces impaction of the facet joints, preventing no more than 3% strain to the annulus. With further rotation force, the impacted facet joint can serve as a new axis of rotation, allowing some additional lateral shear exerted on the annulus. Excessive rotational force can result in failure of any of the elements that resist rotation.³⁷ Fracture can occur in the impacted facet joint; the pars interarticularis can also fracture; capsular tears can occur in the nonimpacted facet joint; and circumferential tears can occur in the annulus (Figure 2-20). Spiral fractures are another example of the results of torsional loads applied to long bones.

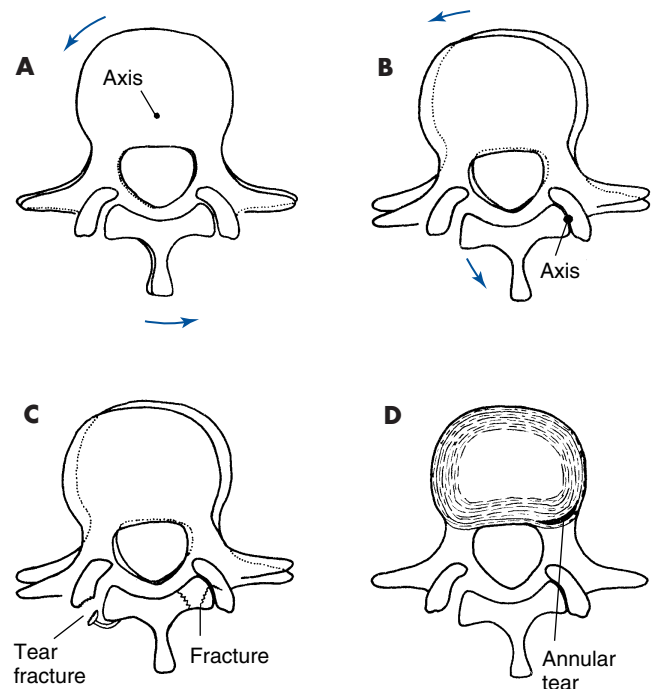


Figure 2-20

Effects of rotation on lumbar segments. **A**, Rotation is limited by impaction of facet joint. **B**, Further rotation causes a shift in the axis of rotation. **C**, The impacted facet is exposed to fracture, and the distracted facet is exposed to avulsion or capsular tear. **D**, The disc is exposed to lateral shear that can lead to circumferential tears in the annulus. (Modified from Bogduk N, Twomey LT: *Clinical anatomy of the lumbar spine*, ed 2, Melbourne, 1991, Churchill Livingstone.)

PROPERTIES OF CONNECTIVE TISSUE

The response of connective tissue to various stress loads contributes significantly to the soft tissue component of joint dysfunction. Within the past several decades, a great deal of scientific investigation has been directed to defining the physical properties of connective tissue.

Connective tissue contributes to kinetic joint stability and integrity by resisting rotatory moments of force. When these rotatory moments of force are large, considerable connective tissue power is required to produce the needed joint stability and integrity. Connective tissue is made up of various densities and spatial arrangements of collagen fibers embedded in a protein-polysaccharide matrix, which is commonly called *ground substance*. Collagen is a fibrous protein that has a very high tensile strength. Collagenous tissue is organized into many different higher-order structures, including tendons, ligaments, joint capsules, aponeuroses, and fascial sheaths. The principal sources of passive resistance at the normal extremes of joint motion include ligaments, tendons, and muscles. Therefore, under normal and pathologic conditions, the range of motion in most body joints is predominantly limited by one or more connective tissue structures. The relative contribution of each to the total resistance varies with the specific area of the body.

All connective tissue has a combination of two qualities—elastic stretch and plastic (viscous) stretch (Figure 2-21). The term *stretch* refers to elongation in a linear direction and increase in length. Stretching, then, is the process of elongation. *Elastic stretch* represents springlike behavior, with the elongation produced by tensile loading being recovered after the load is removed. It is therefore also described as temporary, or recoverable, elongation. *Plastic (viscous) stretch* refers to putty-like behavior; the linear deformation produced by tensile stress remains even after the stress is removed. This is described as permanent, or nonrecoverable, elongation.

The term *viscoelastic* is used to describe tissue that represents both viscous and elastic properties. The viscous properties permit time-dependent plastic or permanent deformation. Elastic properties, on the other hand, result in elastic or recoverable deformation. This allows it to rebound to the previous size, shape, and length.

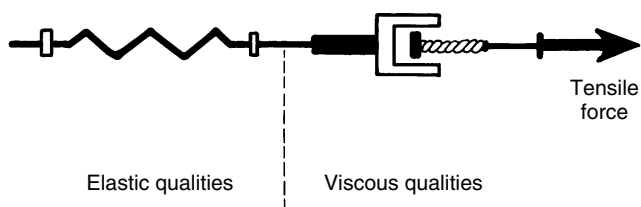


Figure 2-21

Model of connective tissue properties.

Different factors influence whether the plastic or elastic component of connective tissue is predominantly affected. These include the amount of applied force and the duration of the applied force. Therefore the major factors affecting connective tissue deformation are force and time. When a force great enough to overcome joint resistance is applied over a short period of time, elastic deformation occurs. However when the same force is applied over a long period of time, plastic deformation occurs.

When connective tissue is stretched, the relative proportion of elastic and plastic deformation can vary widely, depending on how and under what conditions the stretching is performed. When tensile forces are continuously applied to connective tissue, the time required to stretch the tissue a specific amount varies inversely with the force used. Therefore a low-force stretching method requires more time to produce the same amount of elongation as a higher-force method. However, the proportion of tissue lengthening that remains after the tensile stress is removed is greater for the low-force, long-duration method. Of course, high force and long duration will also cause stretch and possibly rupture of the connective tissue.

When connective tissue structures are permanently elongated, some degree of mechanical weakening occurs, even though outright rupture has not occurred. The amount of weakening depends on the way the tissue is stretched, as well as how much it is stretched. For the same amount of tissue elongation, however, a high-force stretching method produces more structural weakening than a slower, lower-force method.

Because plastic deformation involves permanent changes in connective tissue, it is important to know when plastic deformity is most likely to occur. The greatest impact will occur when positions of stress are maintained for long periods. Awkward sleep postures, poor seated posture, and stationary standing for extended periods can create plastic changes that have the potential for skeletal misalignment, joint dysfunction, and instability.

After trauma or surgery, the connective tissue involved in the body's reparative process frequently impedes function; it may abnormally limit the joint's range of motion as a result of fibrotic tissue replacing elastic tissue. Scar tissue, adhesions, and fibrotic contractures are common types of pathologic connective tissue that must be dealt with during chiropractic manipulative procedures.

Connective tissue elements can lose their extensibility when their related joints are immobilized.³⁸ With immobilization, water is released from the proteoglycan molecule, allowing connective tissue fibers to contact one another, encouraging abnormal cross-linking, and resulting in a loss of extensibility.³⁹ It is hypothesized that manual therapy can break the cross-linking and any intraarticular capsular fiber fatty adhesions, thereby providing free motion and allowing water inhibition to occur. Furthermore, pro-

cedures can stretch segmental muscles, stimulating spindle reflexes that may decrease the state of hypertonicity.⁴⁰

Muscle

The role of muscles is to move bone and allow the human body to perform work. In the normal man, muscle accounts for about 40% to 50% of body weight. For the woman, this falls to approximately 30% of total body weight. Three types of muscle are found in the body: striated skeletal muscle, nonstriated smooth involuntary muscle, and cardiac muscle. Only the skeletal muscle is under voluntary control.

There are three gross morphologic muscle types in striated muscle (Figure 2-22). Parallel muscles have fibers that run parallel throughout the length of the muscle and end in a tendon. This type of muscle is essentially designed to rapidly contract, although it typically cannot generate a great deal of power. Pennate muscles are those in which the fibers converge onto a central tendon. A muscle of this type is unipennate if the fibers attach to only one side of a central tendon, and it is bipennate if the muscle attaches to both sides of a central tendon. Finally, there is a multipennate muscle in which the muscle fibers insert on the tendon from a variety of differing directions. This form of muscle can generate large amounts of power, although it will perform work more slowly than a parallel muscle.

Muscle has three layers of connective tissue (Figure 2-23). An epimysium formed of connective tissue surrounds the muscle; a perimysium separates the muscle

cells into various bundles; and an endomysium surrounds the individual muscle cells. The muscle fibers also have three layers. The outermost layer is formed of collagen fibers. A basement membrane layer comprises polysaccharides and protein and is approximately 500 Å thick. The innermost layer, the sarcolemma, forms the excitable membrane of a muscle.

Muscle fibers contain columns of filaments of contractile proteins. In striated muscle, these molecules are interrelated layers of actin and myosin molecules. These myofibrils are suspended in a matrix called *sarcoplasm*, composed of the usual intracellular components. The fluid of the sarcoplasm is rich with potassium, magnesium, phosphate, and protein enzymes. Numerous mitochondria lie close to the actin filaments of the I bands, suggesting that the actin filaments play a major role in using adenosine triphosphate (ATP) formed by the mitochondria.⁴¹ The sarcoplasmic reticulum functions in a calcium ion equilibrium. A transverse tubular system transmits membrane depolarization from the muscle cell to the protein. Also located within the sarcoplasm is the protein myoglobin that is necessary for oxygen binding and oxygen transfer.

Skeletal muscle occurs in two forms, originally known as *white* and *red muscle*. The white muscle is a fast-twitch, or phasic, muscle. It has a rapid contraction time and contains a large amount of glycolytic enzyme. Essentially, this muscle allows for rapid function necessary for quick contractions for short periods. Red muscle is a slow-twitch, or tonic, muscle. It contracts much more slowly than does white muscle and contains a great deal more myoglobin and oxidative enzymes. Red muscle is more important in static activities that require sustained effort over longer periods. Standing is a good example of this.

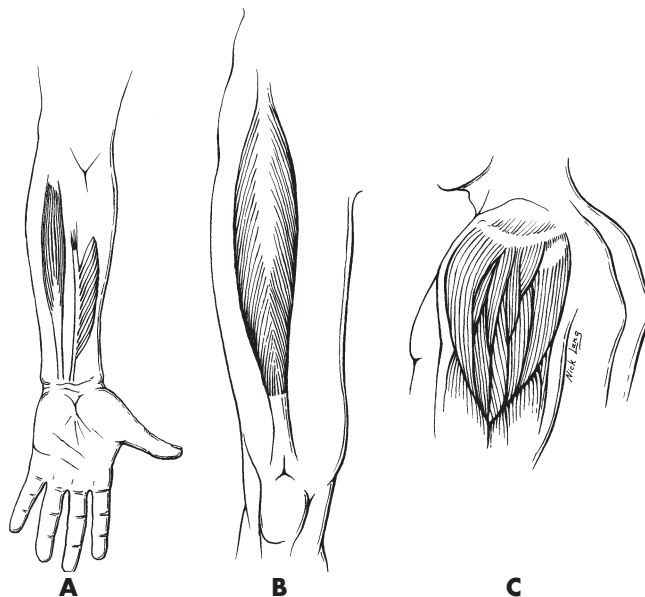


Figure 2-22

Morphologic muscle types. **A**, Unipennate. **B**, Bipennate. **C**, Multipennate.

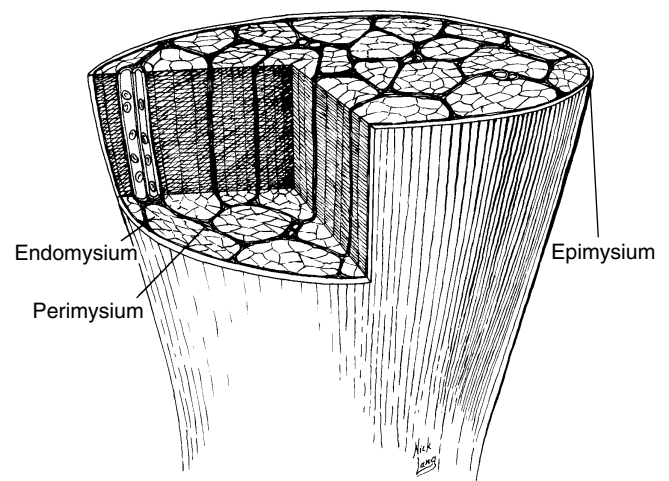


Figure 2-23

Connective tissue layers.

In the human body, each individual muscle is composed of a mix of both types of muscle.

When a stimulus is delivered to a muscle from a motor nerve, all fibers in the muscle contract at once.⁴² Two types of muscle contractions have been defined. During an *isotonic* contraction, a muscle shortens its fibers under a constant load. This allows work to occur. During an *isometric* contraction, the length of the muscle does not change. This produces tension, but no work. No muscle can perform a purely isotonic contraction, because each isotonic contraction must be initiated by an isometric contraction.

Muscle contraction refers to the development of tension within the muscle, not necessarily creating a shortening of the muscle. When a muscle develops enough tension to overcome a resistance so that the muscle visibly shortens and moves the body part, *concentric contraction* is said to occur. Acceleration is thus the ability of a muscle to exert a force (concentric contraction) on the bony lever to produce movement around the fulcrum to the extent intended.

When a given resistance overcomes the muscle tension so that the muscle actually lengthens, the movement is termed an *eccentric contraction*. Deceleration is the property of a muscle being able to relax (eccentric contraction) at a controlled rate. There are numerous clinical applications of the eccentric contraction of muscles, particularly in posture.

Muscles can perform various functions because of their ability to contract and relax. One property is that of shock absorption, another is acceleration, and a third is deceleration. Each is very important to the overall understanding of the biomechanics of the body and will be discussed separately. The predominant responsibility for the dissipation of axial compression shocks rests with the musculotendon system. As a result, shock causes many musculoskeletal complaints. Shin splints, plantar fasciitis, Achilles tendinitis, lateral epicondylitis, as well as some forms of back pain, can result from the body's inability to absorb and dissipate shock adequately.

Although the muscular system is the primary stabilizer of the joint, if the muscle breaks down, the ligaments take up the stress. This is often seen in an ankle sprain, when the muscles cannot respond quickly enough to protect the joint and the ligaments become sprained or torn. If the ligaments are stretched but not torn completely through, this can lead to a chronic instability of the joint, especially if the surrounding musculature is not adequately rehabilitated. When the muscles fail and the ligaments do not maintain adequate joint stability, the stress cannot be fully absorbed by those tissues, and the bone and its architecture take up the stress.

Forces applied to joints in any position may cause damage to the bony structure, ligaments, and muscles. Tensile forces generated by muscle contractions can pull apart the cement from the osteons, resulting in fractures

(the most common of which is at the base of the fifth metatarsal from the pull of the peroneus brevis). Calcaneal fractures from the pull of the Achilles tendon also occur through this mechanism. Because the closed-packed position has the joint surfaces approximated and capsular structures tight, an improperly applied force may cause fracture of the bone, dislocation of the joint, or tearing of the ligaments. Kaltenborn⁴³ states that it is important to know the closed-packed position for each joint because testing of joint movements and manipulative procedures should not be done to the joint in its closed-packed position (Table 2-3). When an improperly applied force is used in the open-packed position, the joint laxity and loss of stability may allow damage to the ligaments and supporting musculature.

One of the signs of segmental dysfunction is the presence of muscle hypertonicity. Localized increased paraspinal muscle tone can be detected with palpation, and in some cases with electromyography. Janda⁴⁴ recognizes five different types of increased muscle tone: limbic dysfunction, segmental spasm, reflex spasm, trigger points, and muscle tightness. Liebenson⁴⁵ has discussed the treatment of these five types using active muscle contraction and relaxation procedures.

Acute traumatic injury to muscle is generally considered to result from a large force of short duration, influencing primarily the elastic deformation of the connective tissue. If the force is beyond the elastic range of the connective tissue, it enters the plastic range. If the force is beyond the plastic range, tissue rupture occurs. More commonly encountered by the chiropractor is the microtrauma seen in postural distortions, repetitive minor trauma occurring in occupational and daily living activities, and joint dysfunction as a result of low gravitational forces occurring over a long period, thus creating plastic deformation.

Muscle immobilized in a shortened position develops less force with contraction and will tear at a shorter length than nonimmobilized muscle with a normal resting length.⁴⁶ For this reason, vigorous muscle stretching has been recommended for muscle tightness.⁴⁴ However, for the stretch to be effective, the underlying joints should be freely mobile. Patients therefore often require manipulation that specifically moves associated joints before muscle stretching.

Ligaments

Ligaments are usually cordlike or bandlike structures made of dense collagenous connective tissue similar to that of a tendon. Ligaments are composed of type I and type III collagen, with intervening rows of fibrocytes. Also interwoven with the collagen bundles are elastin fibers that provide extensibility. The amount of elastin varies from ligament to ligament. Ligaments exhibit a mechanical property called

crimping that provides a shock-absorbing mechanism and contributes to the flexibility of the ligament.

Large loads are capable of overcoming the tensile resistance of ligaments, resulting in complete or partial tear injuries. Ligament healing occurs through the basic mechanisms of inflammation, repair, and remodeling. Immobilization of ligamentous tissue results in a diminished number of small diameter fibers⁴⁷ that presumably lead to joint stiffness. However, the precise mechanism by which immobilization leads to joint stiffness has not been determined. It likely results from a combination of intraarticular adhesion formation and contracture of ligaments by fibroblasts.⁴⁸⁻⁵⁰

Facet Joints

The common factor in all of the spinal segments from the atlantooccipital joint to the pelvis is the fact that each has two posterior spinal articulations. These paired components have been referred to as the *zygapophyseal* (meaning an “oval offshoot”) *joints* and are enveloped in a somewhat baggy capsule, which has some degree of elasticity. Each of the facet facings is lined with articular cartilage, as is the case with all contact-bearing joint surfaces, with the exception of the temporomandibular joint and the sternoclavicular joint. These joints have intracapsular fibrocartilaginous discs that separate the joint surfaces.

Compared to intervertebral discs, facet joints have been the focus of very little biomechanical research. Yet, these structures must control patterns of motion, protect discs from shear forces, and provide support of the spinal column. The orientation of the joint surface varies with each spinal region, largely governing the degree of freedom each region can accomplish (Figure 2-24).

Because these joints are true diarthrodial (synovial) articulations, each has a synovial membrane that supplies the joint surfaces with synovial fluid. The exact role of synovial fluid is still unknown, although it is thought to serve as a joint lubricant or, at least, to interact with the articular cartilage to decrease friction between joint surfaces. In addition, the synovium may be a source of nutrition for the avascular articular cartilage. Intermittent compression and distraction of the joint surfaces must occur for an adequate exchange of nutrients and waste products to occur.² Furthermore, as mentioned, immobilized joints have been shown to undergo degeneration of the articular cartilage.¹¹ Certainly, the nature of synovial joint function and lubrication is of interest because there is evidence that the facet joints sustain considerable stress and undergo degenerative changes.

The capsule is richly innervated with nociceptors (pain) and mechanoreceptors (proprioception), allowing the supporting structures to react to many combinations of tension and compression moments imposed by different postures and physical activity. Each movement of the joint

must first overcome the resistance of the capsule but must then be able to return to its original position maintaining joint apposition. The lateral portions of the capsule are much more lax and contain fewer elastic fibers.⁵¹

Although the posterior joints were not designed to bear much weight, they can share up to about one third of this function with the intervertebral disc. Moreover, as a part of the three-joint complex, if the disc undergoes degeneration and loses height, more weight-bearing function will fall on the facets. During long periods of axial loading, the disc loses height through fluid loss, thereby creating more weight bearing on the facets on a daily basis.

The posterior joints also have been found to contain fibroadipose meniscoids that apparently function to adapt to the incongruity of the articular surfaces but whose clin-

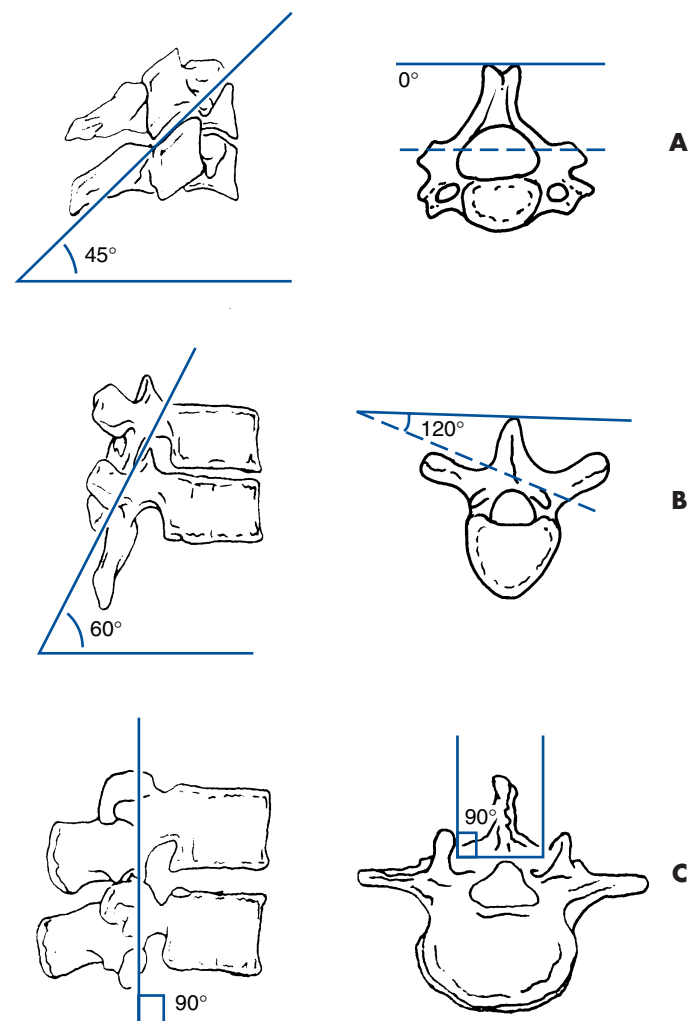


Figure 2-24

Facet planes in each spinal region viewed from the side and above. **A**, Cervical (C3-C7). **B**, Thoracic. **C**, Lumbar. (Modified from White AA, Panjabi MM: *Clinical biomechanics of the spine*, Philadelphia, 1978, JB Lippincott.)

ical significance remains controversial. Bogduk and Engel⁵² provide an excellent review of the meniscoids of the lumbar zygapophyseal joints. Although the genesis of their article was as a literature review to support the contention that the meniscoids could be a cause of an acute locking of the low back because of entrapment, the article also provided a comprehensive review of the anatomic consideration of lumbar meniscoids.

The meniscoids appear to be synovial folds continuous with the periarticular tissues and with both intracapsular and extracapsular components. Microscopically, the tissue consisted of loose connective and adipose tissue, mixed with many blood vessels (Figure 2-25). The meniscoids could present in various shapes, including annular menisci found in the thoracic region, with linguiform menisci and filiform menisci commonly found in the lumbar region.⁵³

These meniscoid structures can project into the joint space when the joint surfaces of articular cartilage are not in contact. Bogduk and Engel⁵² noted two groups of menisci: one located along the dorsal and ventral margins of the joint and one located at the superior and inferior aspects of the joint. In their view, only the ones located along the dorsal and ventral borders of the joint represented true meniscoids. Functionally, Bogduk and Engel feel these structures may help to provide greater stability to a lumbar zygapophyseal joint by helping to distribute the load over a wider area. In their words, meniscoids play a space-filling role.⁵²

Clinically and theoretically, these meniscoids may become entrapped or extrapped.⁵⁴ Entrapment of the meniscoid between the joint surfaces itself is not believed to be painful, although pain can be created by traction on the joint capsule through the base of the meniscoid. This could,

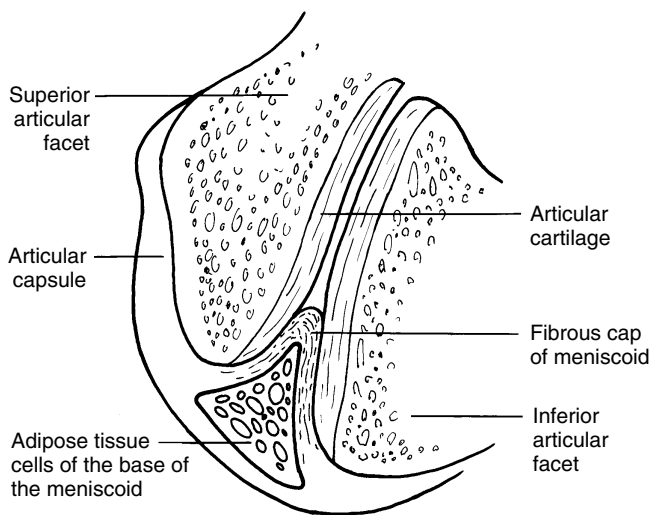


Figure 2-25

Fibroadipose meniscoid in a lumbar facet joint. (Modified from Bogduk N, Engel R: *Spine* 9:454, 1984.)

through a cascade of events, lead to more pain and reflex muscle spasm, known as *acute locked low back*, which is amenable to manipulative therapy. Extrusion of the meniscoid may occur when the joint is in flexed position and the meniscoid is drawn out of the joint but fails to reenter the joint space on attempted extension. It gets stuck against the edge of the bony lip or articular cartilage, causing a buckling of the capsule that serves as a space-occupying lesion. Pain is produced through capsular distention.⁵⁵

Giles and Taylor^{51,56} examined the innervation of meniscoids (synovial folds) in the lumbar zygapophyseal joints, using both light microscopy and transmission electron microscopy. The authors removed part of the posteromedial joint capsule along with the adjacent ligamentum flavum and synovial folds after a laminectomy, fixed these specimens in various solutions, and prepared them for microscopy. They demonstrated that neurologic structures were located in the areas studied. Nerves seen in the synovial fold were 0.6 to 12 μm in diameter. These neurologic structures may give rise to pain.

Taylor and Twomey⁵⁷ suggest that because of their rich blood supply, spinal joint meniscoids do not undergo degeneration with age as do the intervertebral disc and articular cartilage. However, with degenerative changes to disc and especially articular cartilage, the meniscoid inclusions are exposed to abnormal biomechanical forces that may result in their demise.

Adams and Hutton⁵⁸ examined the mechanical function of the lumbar apophyseal joints on spines taken from cadavers. The authors wanted to examine various loading regimens on the function of these joints. They found that the lumbar zygapophyseal joints can resist most of the intervertebral shear force only when the spine is in a lordotic posture. These joints also can aid in resisting the intervertebral compressive force and can prevent excessive movement from damaging the intervertebral discs. The facet surfaces protect the posterior annulus, whereas the capsular ligament helps to resist the motion of flexion. The authors noted that in full flexion the capsular ligaments provide nearly 40% of the joint's resistance. They conclude that "the function of the lumbar apophyseal joints is to allow limited movement between vertebrae and to protect the discs from shear forces, excessive flexion and axial rotation."⁵⁸

Taylor and Twomey⁵⁷ studied how age affected the structure and function of the zygapophyseal joints. They took transverse sections of the lumbar spine from cadavers ranging in age from fetus to 84 years and prepared them in staining media. They noted that fetal and infant lumbar zygapophyseal joints are coronally oriented, and only later (in early childhood) become curved or biplanar joints. In the adult, the joint has a coronal component in the anterior third of the joint and a sagittal component in the posterior two thirds of the joint. The joint is generally hemicylindrical.

The structures located in the anterior third of the joint, primarily articular cartilage and subchondral bone, tend to show changes that are related to loading the joint in flexion. The posterior part of the joint shows a variety of different changes related to age. There may be changes from shearing forces. The subchondral bone will thicken as it ages and is wedge shaped. These changes occur because of loading stresses from flexion.⁵⁷

Taylor and Twomey⁵⁷ are careful to note that they could make no clinical correlation with their findings, which is one of the problems with cadaveric studies of this sort. They believe that this work has biomechanical implications; they feel that the lumbar zygapophyseal joints limit the forward translational component of flexion to only a very small displacement. Indeed, they feel this fact may be the most important component limiting forward flexion. Although the lumbar facet joints are oriented in the sagittal plane, they are not purely sagittal, and flexion with anterior translation will result in impaction of the facets limiting this movement.³⁷

Intervertebral Discs

The intervertebral discs are fibrocartilaginous mucopolysaccharide structures that lie between adjoining vertebral bodies. In the adult, there are 23 discs, each given a numeric name based on the segment above. Thus the L5 disc lies between the fifth lumbar segment and the sacrum, and the L4 disc lies between the fourth and fifth lumbar segments. In the early years of life, the discs between the sacral segments are replaced with osseous tissue but remain as rudimentary structures, generally regarded as having no clinical significance.

The unique and resilient structure of the disc allows for its function in weight bearing and motion. The anterior junction of two vertebrae is an amphiarthrodial symphysis articulation formed by the two vertebral endplates and the intervertebral disc. The discs are responsible for approximately one fourth of the entire height of the vertebral column. The greater the height of the intervertebral disc as compared to the height of the vertebral body, the greater the disc to vertebral body ratio and the greater the spinal segmental mobility. The ratio is greatest in the cervical spine (2/5) and least in the thoracic spine (1/5), with the lumbar region (1/3) in between. A disc has three distinct components: the annulus fibrosus, the nucleus pulposus, and the cartilaginous endplates.

The cartilaginous endplates are composed of hyaline cartilage that separates but also helps attach the disc to the vertebral bodies. There is no closure of cortical bone between the hyaline cartilage and the vascular cancellous bone of the vertebral body. The functions of the endplates are to anchor the disc, to form a growth zone for the immature vertebral body, and to provide a permeable barrier between the disc and the body. This role allows

the avascular disc material to receive nutrients and repair products.

The annulus fibrosus is a fibrocartilaginous ring that encloses and retains the nucleus pulposus, although the transition is gradual, with no clear distinction between the innermost layers of the annulus and the outer aspect of the nucleus. The fibrous tissue of the annulus is arranged in concentric, laminated bands, which appear to cross one another obliquely, each forming an angle of about 30 degrees to the vertebral body (Figure 2-26). The annular fibers of the inner layers are attached to the cartilaginous endplates, and the outer layers are attached directly to the osseous tissue of the vertebral body by means of Sharpey's fibers.⁵⁹

Superficially, the anterior longitudinal ligament and the posterior longitudinal ligament (PLL) reinforce the fibers. The PLL is clinically significant in that as it courses caudally, its width narrows until covering only about 50% of the central portion of the lower lumbar discs. The weakest area of the annulus, and hence the area most likely to be injured, is the posterolateral aspect. This is the most likely spot for a disc herniation in the lumbar spine.⁶⁰

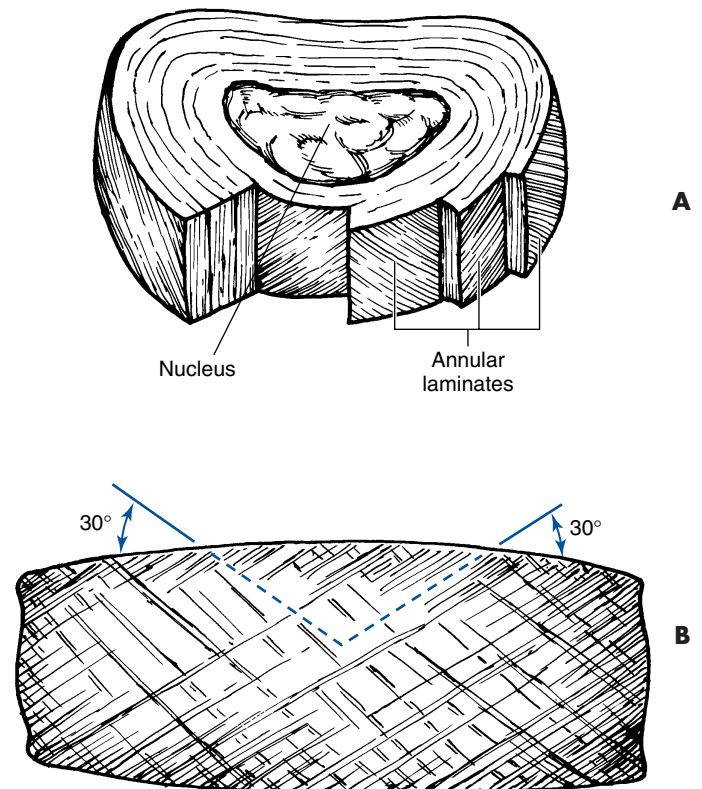


Figure 2-26

Intervertebral disc. **A**, Nucleus pulposus and annulus fibrosus. **B**, Orientation of annular fibers. (Modified from White AA, Panjabi MM: *Clinical biomechanics of the spine*, Philadelphia, 1978, JB Lippincott.)

The annulus fibrosus contains little elastic tissue, and the amount of stretch is limited to only 1.04 times its original length, with further stretch resulting in a tearing of fibers. The functions of the annulus fibrosus include enclosing and retaining the nucleus pulposus, absorbing compressive shocks, forming a structural unit between vertebral bodies, and allowing and restricting motion.

The nucleus pulposus is the central portion of the disc and is the embryologic derivative of the notochord. It accounts for about 40% of the disc and is a semifluid gel that will deform easily but is considered incompressible. The nucleus is composed of a loose network of fine fibrous strands that lie in a mucoprotein matrix containing mucopolysaccharides, chondroitin sulphate, hyaluronic acid, and keratan sulfate. These large molecules are strongly hydrophilic, capable of binding nearly nine times their volume of water, and are therefore responsible for the high water content of the disc. In young adults, the water content of a disc approaches 90% and maintains an internal pressure of about 30 pounds per square inch.¹ The water content, however, steadily decreases with age. The composition of the nucleus produces a resilient spacer that allows motion between segments, and although it does not truly function as a shock absorber, it does serve as a means to distribute compressive forces.

The image of the nucleus as a round ball between two hard surfaces must be abandoned. This gives the impression that the nucleus can roll around between the two endplates. The only means for significant nuclear migration is through a tear in the annular fibers, allowing the nucleus to change shape but not actually shift position. The result of nuclear migration will be a potential change in the instantaneous axis of movement and potential aberrant segmental motion.

The intervertebral disc is a vital component for the optimal, efficient functioning of the spinal column. In conjunction with the vertebral bodies, the discs form the anterior portion of the functional unit responsible for bearing weight and dissipating shock. In so doing, it distributes loads, acts as a flexible buffer between the rigid vertebrae, and permits adequate motion at low loads while providing stability at higher loads.

The simple compression test of the disc has been one of the most popular experiments because of the importance of the disc as a major load-carrying element of the spine. Axial compression forces continually affect the disc during upright posture. The nucleus bears 75% of this force initially but redistributes some to the annulus.

Furthermore, the ability of the disc to imbibe water causes it to “swell” within its inextensible casing. Thus the pressure in the nucleus is never zero in a healthy disc. This is termed a *preloaded state*. The preloaded state gives the disc a greater resistance to forces of compression.

With age and exposure to biomechanical stresses, the chemical nature of the disc changes and becomes more

fibrous. This reduces the imbibition effect and, in turn, the preloaded state. As a result, flexibility is diminished, and more pressure is exerted on the annulus and peripheral areas of the endplate. A disc that has been injured will deform more than a healthy one.

The preloaded state also explains the elastic properties of the disc. When the disc is subjected to a force, the disc exhibits dampened oscillations over time. If the force is too great, however, the intensity of the oscillations can destroy the annulus, thus accounting for the deterioration of intervertebral discs that have been exposed to repeated stresses.

Compressive forces are transmitted from endplate to endplate by both the annulus and the nucleus. When compressed, the disc bulges in the horizontal plane. A diseased disc will compress more, and as this occurs, stress is distributed differently to other parts of the functional unit, notably the apophyseal articulations. Because the disc is prepared for axial compression, it should be noted that under large loads, the endplate will fracture (Schmorl's node) (Figure 2-27) or the anterior vertebral body will collapse.

Axial tensile stresses are also produced in the annulus during the movements of flexion, extension, and lateral flexion. The motions create compression stresses ipsilaterally and tensile stresses contralaterally. This causes a bulging (buckling) on the concave side and a contraction on the convex side of the disc (Figure 2-28).

Axial rotation of the spine also produces tensile stresses in the disc. Studies have shown that the greatest tensile capabilities of the disc are in the anterior and posterior regions; the center portion of the disc is the weakest. When the disc is subjected to torsion, shear stresses are produced in the horizontal and axial planes. Shear stresses act in the horizontal plane, perpendicular to the long axis of the spine. It has been found that torsional forces, and hence shear forces, can be the injury-causing load factors. During normal movements, the disc is pro-

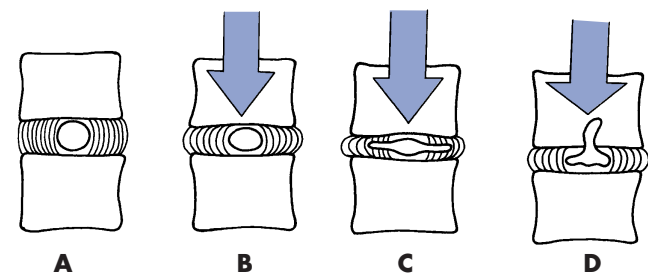


Figure 2-27

Effects of axial loads on vertebral body and disc. **A**, Normal disc height. **B**, Normal disc under mild to moderate axial load, showing slight approximation of bodies. **C**, Diseased disc under same axial load, showing significant loss of disc height. **D**, Endplate fracture from significant axial load causing a Schmorl's node.

tected from excessive torsion and shear forces by the lumbar facet joints.

All viscoelastic structures, which include the disc, exhibit hysteresis and creep. Cadaveric studies allowed Twomey and Taylor⁶¹ to study creep and hysteresis in the lumbar spine. *Hysteresis* refers to the loss of energy when the disc or other viscoelastic structures are subjected to repetitive cycles of loading and unloading. It is the absorption or dissipation of energy by a distorted structure. For example, when a person jumps up and down, the shock energy is absorbed by the discs on its way from the feet to the head. The larger the load is, the greater the hysteresis will be.¹ When the load is applied a second time, the hysteresis decreases, meaning there is less capacity to absorb the shock energy (load). This implies that the discs are less protected against repetitive loads.

Creep is the progressive deformation of a structure under constant load. When a load is applied to a viscoelastic structure, it immediately deforms under the

load. If the load is maintained, there will be continued deformation over time. As might be expected, the creep and hysteresis created in differing types of load forces (e.g., flexion loading vs. extension loading) may differ, but this has not been quantified for the lumbar spine.

Because the disc is under the influence of the preloaded state of the nucleus, movements will have specific effects on the behavior of the nucleus and annular fibers. When a distraction force is applied, the tension on the annular fibers increases, and the internal pressure of the nucleus decreases. When an axial compression force is applied symmetrically, the internal pressure of the nucleus increases and transmits this force to the annular fibers. The vertical force is transformed into a lateral force, applying pressure outward.

During the asymmetric movements of flexion, extension, and lateral flexion, a compressive force is applied to the side of movement, and a tensile force occurs on the opposite side. The tension transmitted from the nucleus to the annular fibers helps to restore the functional unit to its original position by producing a “bowstringlike” tension on the annular fibers.

During axial rotation, some layers of the annulus are stretched while others are compressed (slackened). Tension forces reach a maximum within the internal layers of the annulus. This has a strong compressive force on the nucleus and causes an increased internal pressure proportional to the degree of rotation.

Kurowski and Kubo⁶² investigated how degeneration of the intervertebral disc influences the loading conditions on the lumbar spine. Because disc degeneration is common, almost inevitably it will contribute to low back dysfunction by influencing motion and load bearing at each individual level. Kurowski and Kubo⁶² examined load transmission through the lumbar spine with differing amounts of disc degeneration and used fine element analysis to study stress transmission. In a healthy disc, they found the highest effective stresses in the center of the endplate of the vertebra, but in an unhealthy and degenerated disc, they found these stresses in the lateral aspects of the endplates, as well as in the cortical wall and vertebral body rims.

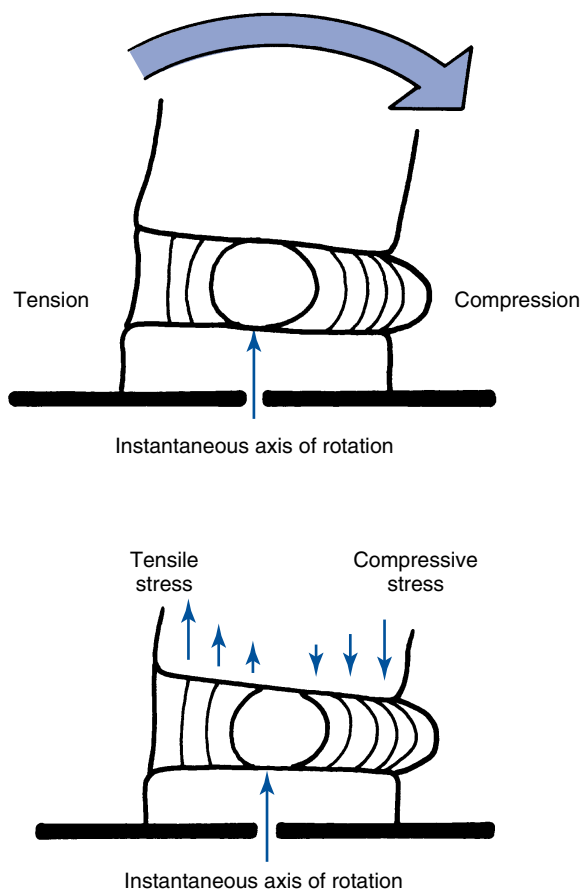


Figure 2-28

Disc stresses with bending movements of flexion, extension, and lateral flexion. Tension is produced on the convex side, whereas compression and buckling occur on the concave side.

MODELS OF SPINE FUNCTION

Understanding the overall function of the human spine has proved to be difficult and frustrating. It is important to view the spine as an integrated functioning unit. It must be remembered, however, that the spine is also a part of the larger locomotor system. If consideration is not given to the whole locomotor system, the potential for clinical failures results.

The vertebral column is a flexible axis composed of the articulated vertebrae. The spine must be rigid for it to maintain upright bipedal posture, yet it has to deform its shape to allow for mobility. In addition, it houses and

protects the spinal cord while providing a means for neurologic transmission to and from the periphery.

Many models of spine function have been developed, each attempting to define spine function according to new and different parameters. Gracovetsky⁶³ proposed a model of the spine based on the concept that spinal joints contain stress sensors that drive a feedback mechanism. He believes that this mechanism creates an arrangement that can react to loads by modifying muscular action to decrease or minimize stress at those joints and cut the risk of injury. This model depicts the spine in terms of *stresses*, *forces*, and *moments* acting at the intervertebral joints.

As Gracovetsky⁶³ notes, mathematical models of erector spinae muscles demonstrate that these muscles cannot support more than 50 kg of weight, so other or additional mechanisms must explain the human ability to carry loads greater than that. To explain this feature of the human spine, Gracovetsky⁶³ theorizes that the interaction between the erector spinae group and the abdominal muscles is of “fundamental importance” in understanding spinal function. He later uses this theory to show how posture and behavior may produce spinal injury.

One of the major problems with this model is that no such monitoring system of stress sensors has been delineated by neurophysiologic research. Gracovetsky shows how the system would have to work if such sensors did exist, and thus this model of the spine is based on the demarcation of stress, loads, and moments. With such a mathematical model in place, it is possible to determine spinal disability.

Aspden⁶⁴ notes that many theories of the spine tend to fall into two broad categories: those that treat the spine as a cantilever and those that perform an elastic analysis of the system. When the spine is treated as a cantilever system that is connected to a series of free bodies, the movement created by the spinal muscles acting about the sacrum balances forward-bending moments. However, in using such a model to make mathematical calculations, the forces generated are extremely high and may be dangerous. Furthermore, they probably do not exist.

Aspden's model to explain the static behavior of the human spine looks at the spine as an arch rather than as the more accepted cantilever system. According to Aspden,⁶⁴ if the spine is considered an arch, its mechanical stability can be described and the forces developed along the spinal axis for any given posture or load can be calculated.

Aspden⁶⁴ notes that the human spine shares many characteristics with a masonry arch and that a masonry arch can be analyzed using plasticity theory. The plasticity theory describes the behavior of a structure once it has been loaded beyond its limits, and it describes how these materials flow in response to stress. To reduce stress, the structure deforms. Also, the theory helps provide the limits of elastic behavior.

In normal erect posture, the lumbar lordosis forms an arch, which is convex anteriorly, and this brings the vertebral bodies almost directly into the center of the body. With spinal flexion, this arch will flatten and even reverse so that it is concave anteriorly, and a single arch is formed with the thoracic and lower cervical vertebrae. Body weight is transmitted along the spinal axis. The forces generated can then be calculated. Muscle forces can be overlaid on this, and then forces can be recalculated.

Aspden shows how this can be calculated for a spine placed in certain configurations.⁶⁴ When a practitioner has this information, it is then possible to predict failure when these criteria are not met. Using these procedures, Aspden demonstrates that compressive forces developed in the spine may not be as high as was previously believed. He also demonstrated that normal spinal curvatures are necessary for proper load-bearing function. The presence of the normal lumbar lordosis, coupled with intraabdominal pressure, helps to provide the spine with strength and to protect the spine from injury during heavy load lifting.

The human spine, with its musculature removed, cannot carry normal physiologic loads. This fact led Panjabi et al⁶⁵ to devise a model of spinal stability and intersegmental muscle force. They note that muscles are necessary to stabilize the spine and to allow the spine to carry out its other physiologic functions.

This stabilization feature is in addition to the obvious need for a muscle to move body parts. Their experiment simulated intersegmental muscle forces on spinal instability, subjecting cadaveric lumbar functional spinal units (FSUs) to biomechanical tests of increasing muscle forces. Compressive preload and six physiologic movements were applied to a series of FSUs to determine three-dimensional motion of the spine. The FSUs were also then given a series of injuries, and incremental intersegmental muscle forces were applied to the upper vertebra of the FSUs. The same tests were then repeated on the injured segments. The injuries included division of the supraspinous and interspinous ligaments,¹ left medial facetectomy,² and bilateral medial facetectomy.³ Some biomechanical parameters, including range of motion and neutral zone, were then calculated.

When the forces produced by muscle were applied, range of motion and neutral zone increased in flexion loading, although both decreased in extension loading.⁶⁵ With lateral bending, neither of these parameters was affected by applying the muscle forces. With rotation, the range of motion was significantly decreased. Panjabi et al⁶⁵ concluded that an action of the intersegmental muscle forces is to maintain or decrease intervertebral motions after injury.

Louis⁶⁶ examined spinal stability from an entirely different perspective—that of the three-column spine. He notes an axial stability and a transverse stability in the

spine. The axial stability is maintained along a vertical column system consisting of two columns at the C1 to C2 level and three columns from C2 to the sacrum (Figure 2-29). These three columns consist of one anterior column (formed by the vertebral bodies and the disc) and two posterior columns (formed by the posterior joints). The transverse stability is the result of the coupling of bony buttresses and ligamentous brakes.

Louis sees the C1 vertebra as two lateral masses joined by two arches. He sees the C2 vertebra as three pillars: “a vertical conical pillar lying medially and anteriorly (dens and body) and two lateral oblique pillars.”⁶⁶ These three pillars are fused above in the body of C2 and then diverge below that area. The three resultant pillars run down to the sacrum, where three points of contact support the pillars at the sacral base and at the two sacral facets. Of the three, the anterior pillar (as compared to the two posterior pillars) is by far the largest. It takes on the characteristics of a quadrangular pyramid that is formed by alternating vertebral bodies and intervertebral discs down to the sacral base. In this model, the spinous processes and transverse processes do not contribute to spinal stability. Louis⁶⁶ believes this three-column model of the spine provides the simplest and most efficient system of stability (Figure 2-29).

Gracovetsky and Farfan⁶⁷ use system theory to describe a model of the human spine. After a great deal of discussion of the evolutionary considerations of the human spine, they make the point that intervertebral joints are essential for our survival as a species. They describe the mechanical behavior of the intervertebral joint and then use that information to calculate spinal motion and muscular action. This allows the authors to ultimately devise a new theory of human locomotion, which also allows for the calculation of safe loads for the spine. Theirs is one of the most detailed and important papers concerning mathematical modeling of the human spine.

Another model of the spine considers the structural integrity of the spine as a whole, providing an interesting look at how adaptation to upright biped posture places specific demands on the spinal components. A *structure* is defined as any assemblage of materials that is intended to sustain loads. Each life form needs to be contained by a structure. Even the most primitive unicellular organism has to be enclosed and protected by cell membranes that are both flexible and strong, yet capable of accommodating cell division during reproduction. With advancement of and competition in evolving life forms, the structure requirements need to become more sophisticated. The majority of living tissues have to carry mechanical loads of one kind or another. Muscles also have to apply loads, changing shape as they do so. By making use of contractile muscles as tension members and strong bones as compression members, highly developed vertebrate animals have been able to withstand necessary loads and still allow for mobility, growth, and evolution.

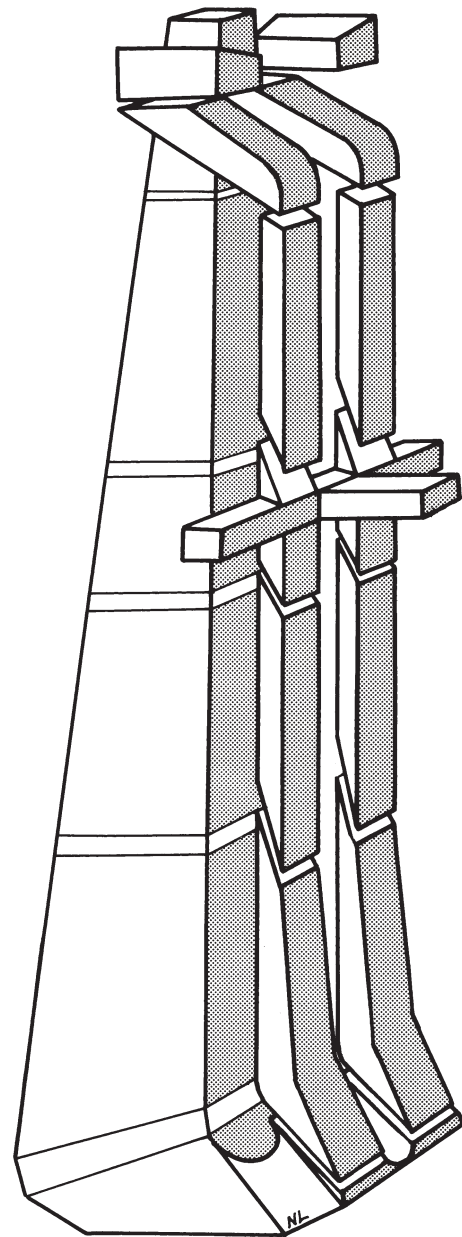


Figure 2-29

Three-column spine model, representing vertebral bodies and articular pillars. (Modified from Louis R: *Anat Clin* 7:33, 1985.)

Parallels have been drawn between the spine and the mast of a ship. Compressive loads are concentrated in the vertebrae of the spine and the wooden mast of the ship. Tension loads are diffused into tendons, skin, and other soft tissues of the body and into the ropes and sails of the ship to maintain an upright position. However, a ship mast is immobile, rigidly hinged, vertically oriented, and dependent on gravity. These rigid columns require a heavy base to support the incumbent load. The biologic structure of the spine, however, must

be a mobile, flexibly hinged, low-energy-consuming, omnidirectional structure that can function in a gravity-free environment.⁶⁸

Comparisons have also been made between the spine and a bridge (or truss). The musculoskeletal configuration of a large four-legged animal (e.g., horse) has a large body, is capable of bearing a substantial load in addition to its own weight, rests on four slender compression members (leg bones), and is supported efficiently by an assortment of tension members (tendons, muscles, and skin). Trusses have flexible, even, frictionless hinges, with no bending moments about the joint. The support elements are either in tension or compression only. Loads applied at any point are distributed about the truss as tension or compression.⁶⁸

Although this model sounds quite plausible for the spine, it is not a complete explanation. Most trusses are constructed with tension members oriented in one direction. This means that they will function in only one direction and can therefore not function as the mobile, omnidirectional structure necessary for describing the spinal functions. Moreover, bridges do not have to move, whereas vertebrate animals do. Furthermore, the comparison cannot be directly applied to the human skeleton, since it is upright and the forces are applied in the long axis rather than along it.

Levin⁶⁸ identifies another class of truss called *tensegrity structures* that are omnidirectional so that the tension elements always function in tension regardless of

the direction of the applied force. The structure that fits the requirements of an integrated tensegrity model has been described and constructed as the tensegrity icosahedron. In this structure, the outer shell is under tension, and the vertices are held apart by internal compression struts that seem to float in the tension network (Figure 2-30). In architecture, stable form is generated through an equilibrium between many interdependent structures, each of which is independently in a state of disequilibrium. Complex architecture cannot be broken up into isolated pieces without losing qualities that are inherent to the structural whole. This is extremely important in biologic systems in which every functional unit is literally more than the sum of its constituent parts.⁶⁹

Many architectural structures are dependent on compressive forces for structural integrity. Compression-dependent structures are inherently rigid and poorly adapted for a rapidly changing environment. Most naturally occurring structures depend on natural forces for their integrity.⁷⁰ The human body can be described as a tensile structure in which tensile integrity (tensegrity) is maintained by muscles suspended across compression-resistant bones.

Fuller⁷¹ spoke for many years of a universal system of structural organization of the highest efficiency based on a continuum of tensegrity. Fuller's theory of tensegrity developed out of the discovery of the geodesic dome, the most efficient of architectural forms, and through study of the distribution of stress forces over its structural elements. A *tensegrity system* is defined as an architectural construction that is composed of an array of compression-resistant struts (bones) that do not physically touch one another but are interconnected by a continuous series of tension elements (muscles and ligaments).⁶⁹ Because action and reaction are equal and opposite, the tension forces have to be compensated by equal and opposite compressive forces and vice versa.

Gravitational force is a constant and greatly underestimated stressor to the somatic system. The most obvious effect of gravitational stress can be evaluated by careful observation of posture, which is both static and dynamic. The static alignment of body mass with respect to gravity is constantly adjusted by dynamic neuromuscular coordination as the individual changes position. Over time, individual static postural alignment conforms to inherent connective tissue structure, as well as the cumulative functional demands of both static and dynamic postural conditions.

Musculoligamentous function is also significantly influenced by, as well as responsible for, static and dynamic postural alignment.⁷² The development of asymmetric functional barriers in the spine likely has more than one cause. A unifying factor, however, is the transfer of forces within the soft tissues, creating altered and asymmetric tension, namely the *tensegrity mechanism*.

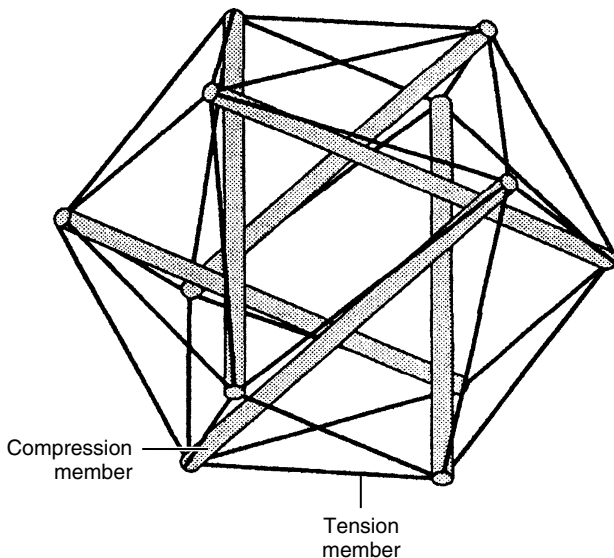


Figure 2-30

Tensegrity icosahedron with rigid compression members and elastic tension members. Multiple units sharing a compression member form a structural model of the spine. (Modified from Bergmann TF, Davis PT: *Mechanically assisted manual techniques: Distraction procedures*, St Louis, 1998, Mosby.)

When the various principles and research noted here are combined, a more complete picture of spinal biomechanics is developed, one in which pathologic changes may ultimately be better studied as well.

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