SPINE BIOMECHANICS

INTRODUCTION

The spine is a complex, and remarkable, mechanical structure. It serves to protect the spinal cord and nerve roots and provides an incredible amount of flexibility to the trunk. It transmits the weight of the upper body to the pelvis and is subjected to internal forces exceeding many times the entire body weight. A disturbing trait of the spine is that it is also the bane of many people's existence. Back pain episodes and injuries exceed the common cold for the number of missed days of work. The vast majority of us will have at least one bout of debilitating back pain in our lives, and many of us live with chronic symptoms. A confounding trait of the spine is that a clinical finding does not necessarily correlate with symptoms (Figure 1). This individual was not radiographed for any symptoms associated with the obvious finding (a spondylolopsis, a complete displacement of one vertebra off of another; here, the lopsis was laterally). In fact, some asymptomatic anomaly could be found in nearly everyone's spine on radiograph; conversely, many symptomatic conditions show up as normal. The clinical challenges presented by the spine, its catastrophic injury potential, and its complex mechanical behavior makes it, arguably, the most interesting musculoskeletal structure.
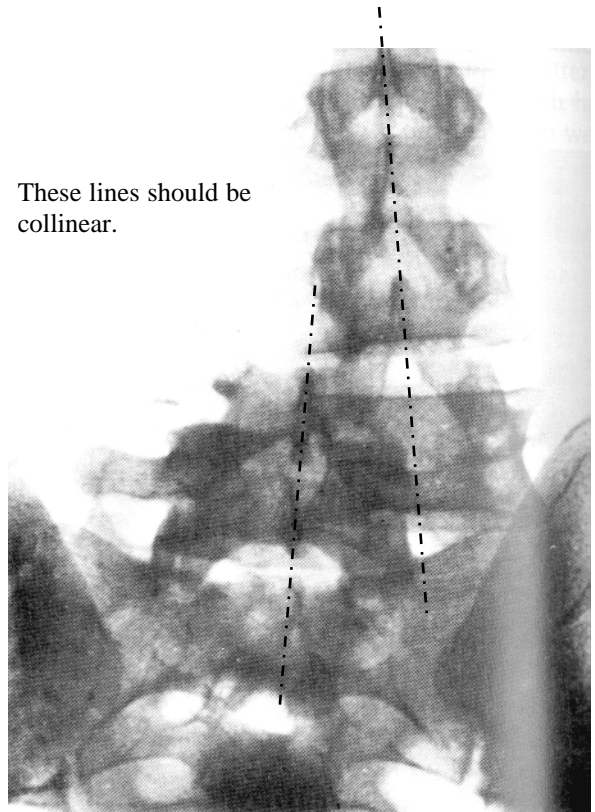
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Figure 1. Spondylolopsis of lumbar L4 vertebra. Person was neurologically intact. Radiograph from White & Panjabi *Clinical Biomechanics of the Spine*.

MACROSCOPIC ANATOMY

The spine consists of discrete bony elements (vertebrae) joined by passive ligamentous restraints, kept separated by intervertebral discs and articulating joints, and dynamically controlled by muscular activation. The spine is broadly divided into 5 regions: the cervical spine, the thoracic spine, the lumbar spine, the sacrum, and the coccyx (Figure 2). Each has it's own unique set of kinematic functions, pathologies, and treatments. In fact, the cervical, thoracic, and lumbar regions (the cervicothoracolumbar (C-T-L) spine) are further divided based on kinematic and clinical considerations.

The cervical spine (C-spine) consists of 7 vertebrae (C1-C7) in all mammals and the base of the skull, the occiput (C0) and is divided into upper (C0-C2), middle (C2-C5), and lower (C5-T1) regions. A natural, slight lordotic curve exists in the C-spine, meaning that the middle lies farther anterior than the ends. The thoracic spine (T-spine) consists of 12 vertebrae (T1-T12) and is divided into upper (T1-T4), middle (T4-T8), and lower (T8-L1) regions. The ribs attach to the thoracic vertebrae. A natural, slight kyphotic curve exists in the T-spine, meaning that the middle lies farther posterior than the ends. The lumbar spine (L-spine) consists of 5 vertebrae (L1-L5) in humans (some mammals, e.g., goats have 6 lumbar vertebrae). A natural, slight lordotic curve exists in the L-spine. The sacrum and coccyx consists of 5 fused vertebrae each (for the coccyx, 4 or 5).
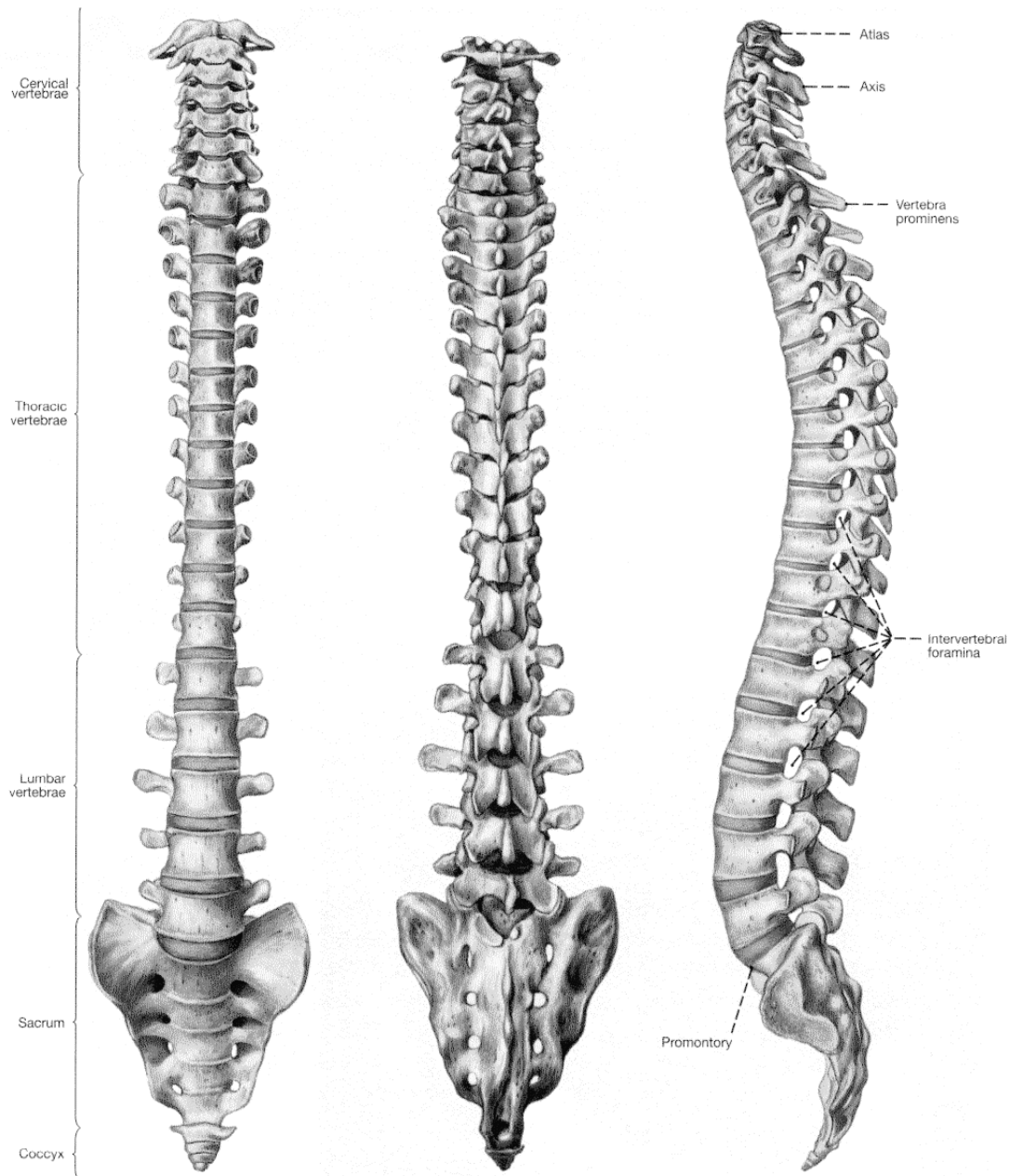
Figure 2. Macroscopic bony anatomy of the spine. From Clemente *Anatomy*.

The junctions between the broad regions, *i.e.*, the cervicothoracic, thoracolumbar, and lumbosacral junctions, frequently are sites for degenerative changes over the long term, most likely due to the abrupt change in "stiffness" that occurs at these junctions. Consider the cervicothoracic (C-T) junction. The C-spine essentially is free to rotate about the C-T junction due to the relative immobility of the trunk during head movement. The C-spine thus acts as a cantilever beam with the "fixed end" at the C-T junction, the location of the highest stresses.

The spine as a complete structure can undergo axial, lateral, and sagittal rotations and axial, lateral, and anteroposterior translations. Thus, the spine is said to posses 6 degrees of freedom (DOF). A functional spinal unit (FSU) is comprised of a superior vertebra-intervertebral disc-inferior vertebra osteoligamentous

unit. A FSU, therefore, possesses 6 DOF as well and is the basic unit of study of the spine. Motions are reported as one vertebra relative to another, hence the motion is that of a FSU. Surgical instrumentation frequently spans at least one FSU.

VERTEBRAL BONY ANATOMY

The upper two vertebrae are the atlas (C1) and axis (C2). The atlas, as in holding up the world, is a ring with no vertebral body whose bilateral superior facets articulate with the occipital condyles and whose inferior facets articulate with the axis, as in rotational axis for the head. The axis looks more like the other cervical vertebrae but has a prominent spire of bone thrusting cranially from its vertebral body called the odontoid process. This process serves to keep the head attached to the rest of the body. Except for the atlas and axis, each vertebra shares common morphologic characteristics (Figure 3). An anterior vertebral body (or centrum) and the posterior neural arch. Each vertebra consists of an outer shell, the end plate, of compacted cancellous (or trabecular) bone surrounding cancellous bone of varying porosity. The superior and inferior (or cranial and caudal, especially in quadrupeds) surfaces of the vertebral bodies transition to cartilaginous endplates to which the intervertebral discs are affixed. The neural arch begins bilaterally with the pedicles, bony beams whose axes are oriented anteroposteriorly and mediolaterally. The pedicles form a junction with the laminae, which extend around the spinal canal, the superior and inferior facets, and the transverse processes. The articulating facets serve to limit motion and transmit direct compressive forces and bearing compressive forces from bending and rotation. The laminae join at the most posterior aspect, from which the spinous process extends. In the T-spine, costovertebral (rib-vertebra) facets exist anterior to the transverse processes. the isthmus of bone between each pair of superior and inferior facets is the pars interarticularis, a site of fracture and bony nonunion for those with a condition known as spondylolysis.

SPINAL LIGAMENTS

Excluding the upper cervical spine, a FSU is connected by 10 ligaments, which serve to protect neural structures by restricting the motion of each FSU (Figure 4). The ligaments also absorb energy during high speed and potentially injurious motions. The spinal ligaments are primarily collagenous except for the ligamentum flavum, which is primarily comprised of elastin. The anterior longitudinal ligament (ALL) originates at the base of the occiput and extends the entire length of the spine into the sacral region along the anterior aspect of the spine. Fibers of the ALL firmly attach to each vertebra, as well as to the intervertebral disc. The posterior longitudinal ligament (PLL) also extends the length of the spine along the posterior aspect of each vertebral body and anterior to the spinal cord. The ligamentum flavum (LF) originates bilaterally on the anteroinferior aspect of the lamina of the superior vertebral body and inserts on the posterosuperior aspect of the lamina of the inferior vertebra. The intertransverse ligaments (ITL) and interspinous ligaments (ISL) join transverse and spinous processes, respectfully, of adjacent vertebrae. The supraspinous ligament (SSL) originates as the ligamentum nuchae (LN) of the neck and extends the length of the spine posterior to the ISL, while attaching firmly to the tip of each spinous process. The capsular ligaments (CL) surround each facet joint.

Mechanically, spinal ligaments behave as other soft tissues of the body: they are viscoelastic with nonlinear elastic responses. Their mechanical response has been characterized predominantly *ex vivo* (cadaveric tissue outside the living body) and little is known about their *in vivo* (within the living body) mechanical environment. In general, it is believed that spinal ligaments do not enjoy the same margin of safety as bones do, as they can operate under conditions relatively close to their failure strengths. This belief is based on combining the *ex vivo* mechanical behaviors of individual ligaments and FSU with motion radiographs and

mathematical models of the spine. Some failure properties of lumbar ligaments and estimated *in vivo* strains are provided in Table 1.
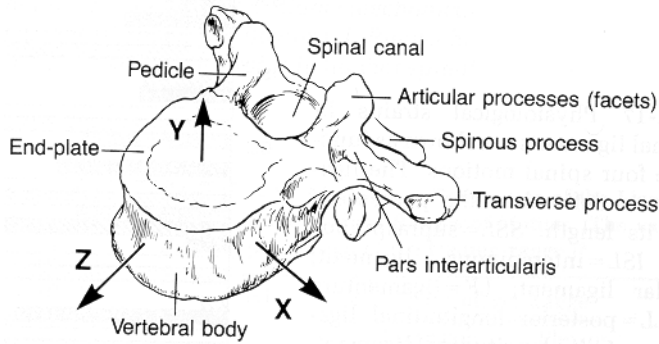

Figure 3. Bony anatomy of a lumbar vertebra. From White & Panjabi *Clinical Biomechanics of the Spine*.
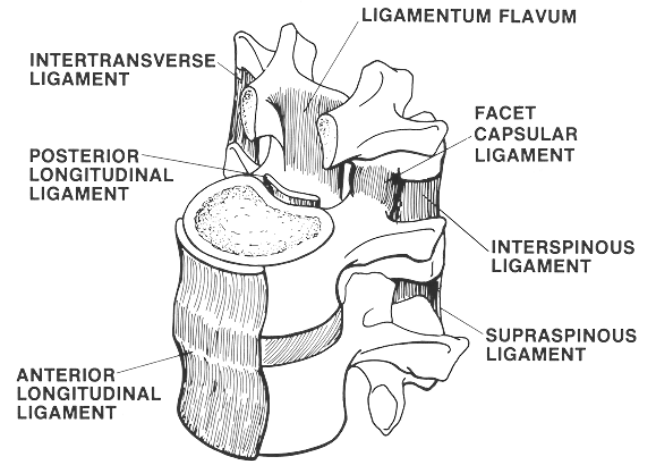

Figure 4. Ligaments of the spine excluding the upper cervical region. From White & Panjabi *Clinical Biomechanics of the Spine*.

Ligament	Failure Load (N)	Failure Strength (MPa)	Failure Strain (%)	Maximum *In Vivo* Strain (%)
ALL	450	11.6	37	13 (flexion)
PLL	324	11.5	26	13 (extension)
LF	285	8.7	26	15 (flexion)
CL	222	7.6	12	17 (torsion)
ISL	125	3.2	13	28 (flexion)
SSL	150	5.4	33	31 (flexion)

Table 1. Typical failure properties of the lumbar spinal ligaments and estimated maximum strains. Motion causing maximum strains *in vivo* given alongside value. From White & Panjabi *Clinical Biomechanics of the Spine*.

KINEMATICS

Kinematics is the study of the motion of bodies, and the motion patterns of the spine are complex. Normal patterns are characterized by parameters common across regions of the spine. If a load (moment or force) is applied to a FSU or a multilevel spinal unit (MSU), the unit first displaces from a neutral position to a position where an appreciable resistance is first encountered (Figure 5). The initial lax region of the motion is termed the neutral zone (NZ), analogous to the toe in region present in soft tissue elastic responses. The presence of a NZ allows the spine to undergo relatively large motions with very little muscular effort; enlargement of a NZ can indicate an abnormal structural change and be a cause for concern. Average values for the NZ in various regions of the spine are provided in Table 2. A region of stiffening next is encountered, termed the elastic zone (EZ). The displacement at the largest applied load or at the limit of motion for an activity is termed the range of motion (ROM). A compilation of ROM delineated by spinal level is provided (Figure 6). These 3 parameters have been effective in characterizing the complex nonlinear load-displacement relation of spinal units. Note that this nonlinear relation is similar to practically

every biologic tissue. Note also that the spine as a structure displays viscoelastic characteristics due to the viscoelastic nature of its constituents.

Other kinematic terms relevant to the study of spinal kinematics are flexion, extension, lateral bending, and axial rotation. Flexion refers to bending forward about an axis perpendicular to the sagittal plane; extension refers to bending backward about that axis. Together, flexion-extension is referred to as sagittal bending. Lateral bending refers to bending to either side and can be either left or right lateral bending. Axial torsion refers to turning the head, for example, and also can be either left or right.
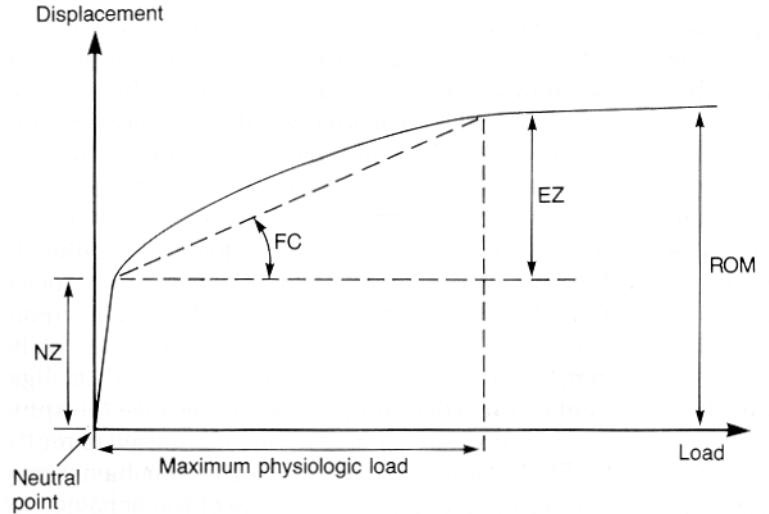

Figure 5. Typical load-displacement response for a spinal unit. From White & Panjabi *Clinical Biomechanics of the Spine*.
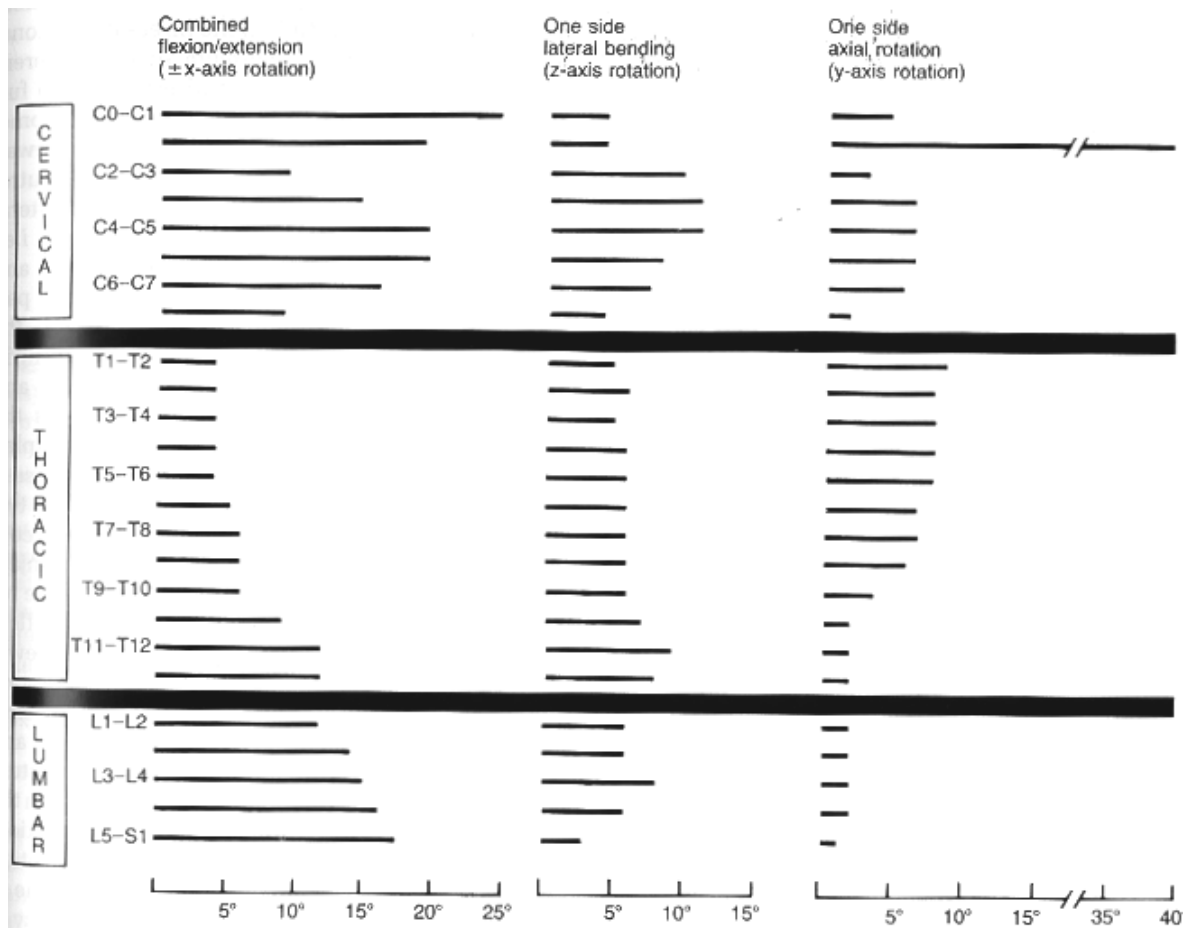

Figure 6. Ranges of motion throughout the normal spine. From White & Panjabi *Clinical Biomechanics of the Spine*.

Still more kinematic terms relevant to the study of spinal kinematics are motion pattern, coupling, instantaneous axis of rotation, and instability. Motion pattern refers to the displacement path a vertebral body follows under load. Consider a bead on a straight rod. Push the bead, and it moves down the rod along a straight path. Bend the rod, push the bead, and it moves along the now curved rod: the motion pattern of the bead has changed. For the spine, when motion patterns deviate from "normal," this can be an indication of an abnormality. Coupling refers to motion about or along axes secondary to those of the axis of applied load. For example, in the middle and lower cervical spine, left lateral bending produces a concomitant left axial torsion due to the orientation of the articulating surfaces of the facets. Coupling motions can change with abnormalities also. Taken together, abnormal motion patterns and coupling can be an indication for clinical instability, which ultimately must be treated in some manner. The instantaneous axis of rotation (IAR) is an axis about which a vertebral rotates at some instant of time. For normal spinal units, the IAR for each of the rotary modes (flexion, extension, lateral bending, and axial torsion) is confined to a relatively small area somewhere within the spinal unit (Figures 7-10). In the abnormal spinal unit, such as a unit with disc degeneration, the locations of the IAR can shift outside of the physical space of the unit and enlarge dramatically (Figure 11).
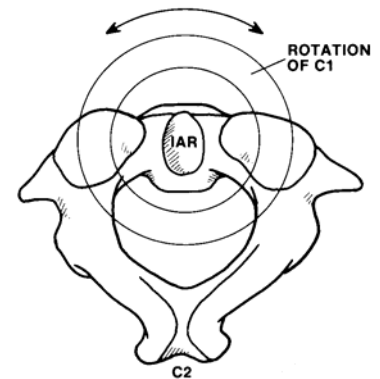

Figure 7. Instantaneous axis of rotation of C1 under axial torsion. From White & Panjabi *Clinical Biomechanics of the Spine*.
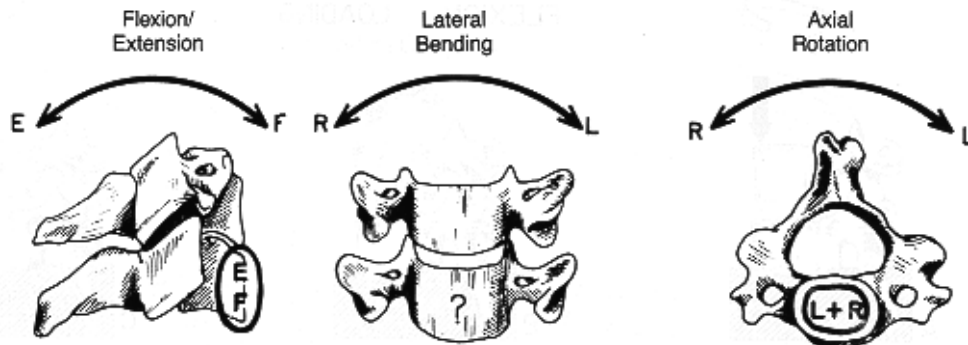

Figure 8. Instantaneous axes of rotation for the middle and lower cervical vertebrae. From White & Panjabi *Clinical Biomechanics of the Spine*.
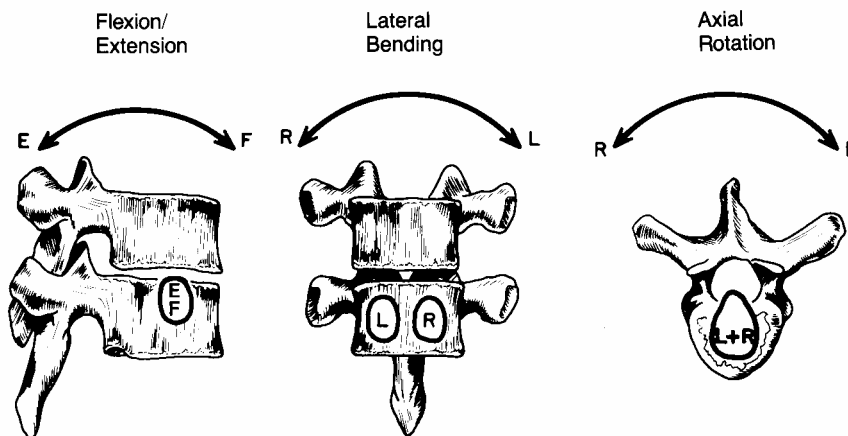

Figure 9. Instantaneous axes of rotation for the thoracic vertebrae. From White & Panjabi *Clinical Biomechanics of the Spine*.
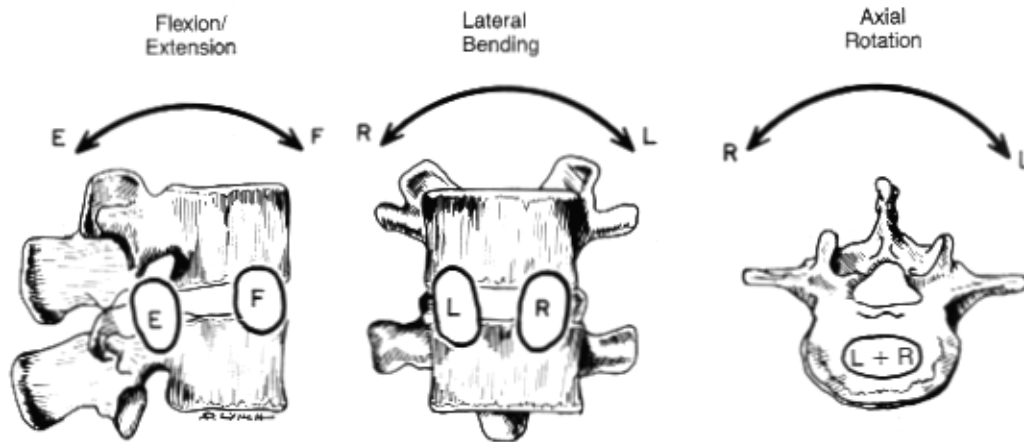
Figure 10. Instantaneous axes of rotation for the lumbar vertebrae. From White & Panjabi *Clinical Biomechanics of the Spine.*

IN VIVO LOADS ON THE SPINE

The determination of *in vivo* mechanical loading and motion is perhaps the most challenging aspect of biomechanics, especially for the spine, a structure with complex motion patterns. What little is known has been determined with a variety of methods. An analysis of a free body diagram can provide quasistatic forces acting on intervertebral joints. These kinds of analyses indicate compressive forces approaching 10 times the weight of the body above the joint of interest, for everyday activities such as bending over to pick up something off the floor. Another method is to combine measures of muscular activity (skin surface electrodes) with mathematical optimization schemes to determine the contribution of spinal muscles to spinal forces. These methods indicate that body part weights can be negligible compared to forces produced by muscles, especially while a person is performing at maximum effort, where compressive forces can exceed 50 times the body part weight above the joint of interest. Still another method has been the invasive measurement of pressures within the intervertebral disc *via* a microneedle pressure transducer. When combined

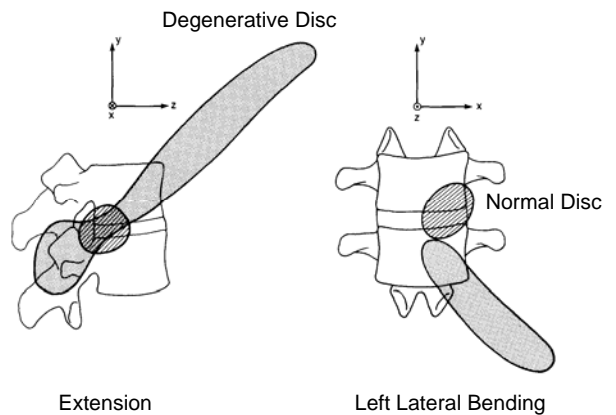**Figure 11.** A spinal pathology can shift and enlarge the region in which the instantaneous axes of rotation are located. From White & Panjabi *Clinical Biomechanics of the Spine.*

with a pressure-compressive force "calibration curve," determined from *ex vivo* experiments on MSU, these measurements can be used to estimate compressive forces on the spine while the subject undergoes various activities of daily living (Table 3).

Activity	Intradiscal Pressure (kPa)	Compressive Force (N)	% Weight Above L3-L4
Standing	270	380	100%+
Twisting	480	670	180%
Lateral Bending	620	870	230%
Flexion	710	990	260%
Extension	720	1,010	270%
Flexion + 40 N in Each Hand	1,620	2,270	600%

Table 3. Intradiscal pressure measurements and computed spinal compressive forces on the L3-L4 disc for various activities of daily living. A typical body weight of 380 N is used, 53% of which is above L3-L4.

VERTEBRAL BONE MECHANICAL PROPERTIES

Vertebrae are primarily composed of cancellous bone, an anisotropic viscoelastic material. Fortunately, for noninjurious values of strain and over a wide range of strain rates, cancellous bone behaves elastically. In general, the elastic moduli and strength of cancellous bone is dependent on its density to the second power. For normal adults, the absolute failure load increases from the cervical down to the lumbar spine, mostly due to the increasing sizes of the vertebrae (Table 4).

Spinal Region	C3-C7	T1-T6	T7-T8	T9-T12	L1-L5
Compressive Strength (N)	1,600	2,000	2,300	3,600	5,600

Table 4. Compression strength of vertebral bodies increases down the spine.

When normalized by the size of the vertebrae, however, a fairly consistent axial compressive failure strength of approximately 8 MPa results for the normal adult. Other axial compressive properties for the vertebral bodies are a yield stress of 2.5 MPa and an elastic modulus of 40 MPa. In general, a vertebral body is strongest in the center and weakest in the posterolateral regions. With age or pathology, porosity can increase dramatically, thus making a vertebral body compliant and weak: a 25% increase in porosity can result in a 50% decrease in strength.

INTERVERTEBRAL DISC ANATOMY

The vertebral bodies are connected and kept separated by the intervertebral discs. The disc is comprised of the annulus fibrosus and the nucleus pulposus (Figure 12) and is firmly joined with the endplates of the vertebral bodies around the outer periphery of the annulus. The endplates are composed of hyaline cartilage. Vascular channels within the vertebral bodies have been observed to run directly at the endplates, representing the predominant nutrient source for the adult disc cells. Some blood vessels approach the annulus at the periphery but do not penetrate. The endplates undergo progressive calcification with age which impedes the nutrient source and contributes to the progressive degeneration of the disc throughout adulthood.
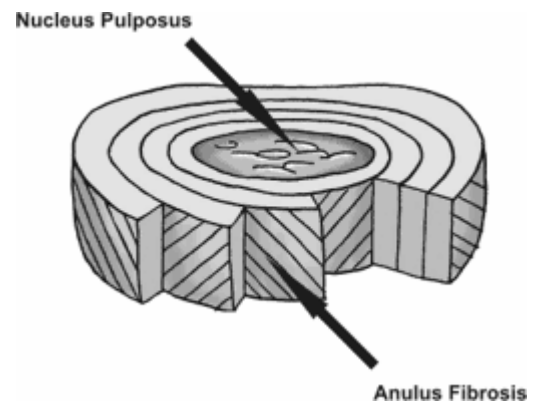

Figure 12. Schematic of intervertebral disc anatomy. From tamars.co.uk.

The nucleus pulposus is located posterocentral in the disc where, in the lumbar region, it fills 30% to 50% of the cross sectional area of the disc. The normal nucleus contains almost exclusively type II collagen fibers in an aqueous gel rich with proteoglycans. The collagen molecules in the nucleus also have been found to have proteoglycan molecules bound to their ends. The water content in the normal nucleus of human lumbar discs decreases from about 90% of its total volume during the first year of life to 74% in the eightieth year and beyond.

The annulus fibrosus is composed of concentric layers of collagen fiber bundles wound in a helicoid manner. Observations using scanning electron microscopy have shown the fibers in the inner third of the annulus to interconnect with the cartilaginous end plate; the fibers in the outer portion are firmly bonded to the epiphyseal ring of the vertebral body. The fibers in human and bovine and porcine discs have been found to be almost exclusively of type I collagen in the outer portion of the annulus and to gradually change to a 40% type I and 60% type II mixture in the inner portion. With degeneration, type I begins to replace type II collagen, and type III collagen begins to appear in the human disc.

The annulus has a laminate structure, with layers built up like older bias ply automobile tires. The fiber orientations alternate from layer to layer, with the fibers generally oriented at an angle of approximately ± 30° with respect to the horizontal plane and in any 2 adjacent layers at 120° with respect to each other. Specifically the fiber orientations change from about ± 31° in the outer annulus to ± 22° in the inner annulus. The number of distinct layers in lumbar discs has been found to vary circumferentially from 25 to 30 in the anterior annulus to 20 in the posterolateral annulus to less than 20 in the posterior annulus. However, at any given location, roughly 40% to 50% of these layers do not remain intact ± 10° circumferentially to either side of the location. In composite laminate terminology, the laminae (distinct layers) are "dropping off" within the laminate (annulus), creating a source of high interlaminar stresses that could predispose certain areas of the annulus prone to failure. In fact, the site of the maximum number of incomplete layers was found to be posterolateral. Although the layer thickness' remain approximately constant in the posterior (50 to 200 μm) and lateral (100 to 300 μm) portions of the annulus, the inner portions (200 to 300 μm) of the anterior annulus are thicker than the outer portions (50 to 100 μm).

The fact that soft tissues structures of the spine, including the intervertebral disc, are innervated has been known for some time. Only fairly recently has the extent and nature of the innervation of the disc been discovered, and then only for symptomatic disc material removed at time of surgery. In one study of such tissue, neuropeptides were immunochemically isolated at depths up to 3 mm into the anterior and anterolateral annulus. These neuropeptides were identified in the form of immunoreactive fibers associated with areas of degenerative changes including microvascularization and chondrocyte proliferation. Unfortunately, the neuropeptides identified are associated with pain reception (nociception) and transmission, neurogenic inflammation, and skeletal metabolism.

With regards to the anatomy of the intervertebral disc, the summary of what is known seemingly does not bode well for most of us. The disc is morphologically structured so as to be predisposed to injury at the site of high stress. Disc cells are poorly serviced with nutrients, a service which only gets worse with age. Injury or degeneration decreases the functional ability of the disc to transmit body forces through hydrostatic pressure, which in turn decreases the ability of the disc cells to maintain the extracellular matrix. Finally, injurious or degenerative changes are accompanied by an enhanced ability to sense and transmit pain.

DISC MECHANICAL PROPERTIES

The intervertebral disc is an inhomogeneous, anisotropic, porous, nonlinearly viscoelastic, damaging structure. Mechanical testing performed on discs generally can be divided into tests on annulus material and on intact whole discs. Tests on annular material predominantly have been tensile in nature, because the annulus is a tensile structure, at least in the nondegenerate disc. Tests on whole discs reflect the predominant compression loading to which it is subjected *in vivo* and its exhibited viscoelastic behavior.

Static tensile moduli and elongations have been determined for small rectangular annulus laminate specimens taken at different orientations with respect to the plane of the disc, at different depths (outer to inner), from donors of different ages and degrees of degeneration, and under 2 rates of deformation. The modulus of the outer annulus is greater in the horizontal direction (3.61 MPa) compared to both the outer fiber direction (2.64 MPa) and the vertical direction (0.49 MPa). The anterior annulus modulus is uniformly greater than the posterior annulus regardless of depth. The modulus is found to increase with age until approximately 26 years when it levels off. Specimens from degenerated discs have lower moduli compared to nondegenerated specimens. Loading rates of 0.08 and 0.8 mm/s have no effect on the modulus. The ultimate strength of a 1 mm thick outer annulus specimen in the fiber direction is 8.8 MPa (17.6 N) compared to 3.4 MPa (6.8 N) for a horizontally oriented specimen. In comparison, ultimate strengths of vertically oriented outer annulus specimens are 3.4 to 4.8 MPa for the anterolateral location and 0.7 to 2.1 MPa for the posterolateral location.

Other studies have focused on single lamina or used a novel loading direction. Specimens excised from a single lamina and failed in tension in the fiber direction exhibit ultimate strengths that vary anteriorly from 10.3 MPa for outer laminae to 3.6 MPa for inner laminae. Posteriorly, little difference is found between outer and inner laminae (5.6 and 5.8 MPa, respectively). Little difference has been found in the radial tension (load direction inner to outer) modulus or ultimate strength with respect to anterior-posterior direction (0.47 MPa modulus and 0.33 MPa strength). Differences have been found, however, with respect to the radial locations with both modulus and strength increasing from outer to inner. Tensile fatigue data from macroscopically normal excised disc specimens indicate an endurance limit type for hoop stresses below about 1.4 MPa, which drops over 25% for discs in early stages of degeneration.

Whole disc properties generally are reflected in the behavior of FSU subjected to various loading conditions. These properties are affected by contributions from other structures which cross the intervertebral space (*e.g.*, ligaments and facet joints). The effect of an annulus injury and simulated surgical discectomy on FSU properties is pronounced in axial torsion (Figure 12). Isolating the disc by removing these other structures also removes their confounding effects. Loading these isolated vertebral body-disc-body units in axial compression seems logical, as was done to determine these creep data (Figure 13). Disc bulge seems to be a maximum of 2 mm for normal discs and to increase for degenerated discs, under a variety of loading conditions.
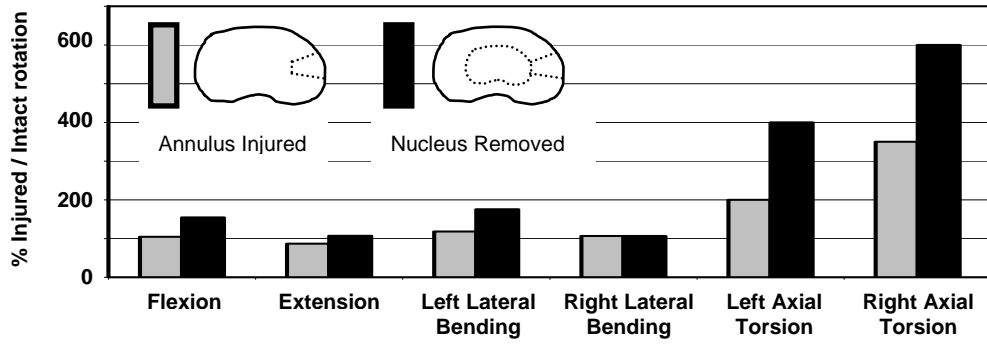
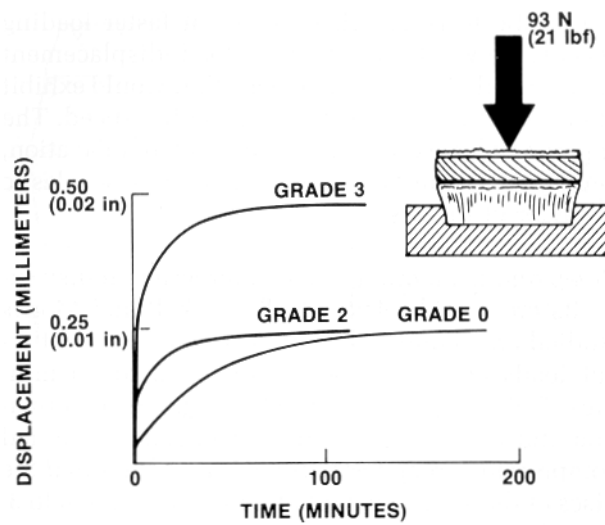**Figure 13.** Effect of annulus injury and simulated surgical discectomy on lumbar FSU rotations.

Figure 14. Creep behavior of normal (Grade 0) and severely degenerated (Grade 3) isolated body-disc-body units. From White & Panjabi *Clinical Biomechanics of the Spine.*