

Degenerative spondylolisthesis

Anatomy & Pathophysiology

OSSEOUS ANATOMY

- The bony anatomy of the spine consists of 7 cervical vertebrae, 12 thoracic vertebrae, 5 lumbar vertebrae, 5 fused sacral vertebrae, and 4 or 5 fused coccygeal vertebrae [3].
- The vertebral body consists of a fairly cylindrical mass of bone connected by pedicles to the posterior arch, which consists of the lamina and spinous process [3].
- The vertebral bodies function primarily to bear weight and transfer forces to the pelvis and hips, while the posterior elements provide protection to neural structures and function as a tension band [3].
- The thoracic spine represents two transitional zones: from the highly mobile cervical spine into the more rigid thoracic region, and then back to the more mobile lumbar spine [5].
- The thoracic spine forms a bony “cube” with the ribs and sternum, which is an inherently stable structure providing protection to the heart and lungs [5].
- The vertebral bodies of the thoracic spine are larger than those of the cervical spine but smaller than the lumbar vertebrae [5].
- The pedicles of the thoracic spine arise more superiorly from the posterior vertebral body than in the cervical or lumbar spine and project obliquely from superodorsal to inferoventral [5].
- The spinous processes of the midthoracic spine project sharply obliquely, overlapping the lamina and spinous processes inferiorly [5].
- The superior articular facets of the thoracic spine project cranially from the junction of the laminae and pedicles and are oriented coronally [5].
- The orientation of the thoracic articular facets permits only a small arc of motion [5].
- The rib heads articulate with the lateral aspect of the vertebral bodies, with a shared articulation at the level of the disk space referred to as a demifacet [5].
- The transverse processes of the thoracic spine project obliquely superolaterally, with the costotransverse joint located along their ventral aspect [5].
- There is no costotransverse articulation at T11 or T12, which represent a transitional zone to the lumbar spine with shorter transverse processes projecting more laterally [5].

- The vertebral column comprises 33 vertebrae divided into five sections: 7 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 4 coccygeal [11].
- The sacral and coccygeal vertebrae are fused, which typically allows for 24 mobile segments [11].
- A typical vertebra comprises an anterior body and a posterior arch that enclose the vertebral canal [11].
- The neural arch is composed of two pedicles laterally and two laminae posteriorly that are united to form the spinous process [11].
- The articular processes articulate with adjacent vertebrae to form synovial joints, and their relative orientation accounts for the degree of flexion, extension, or rotation possible in each segment [11].
- The spinous and transverse processes serve as levers for the numerous muscles attached to them [11].
- The length of the vertebral column averages 72 cm in men and 7 to 10 cm less in women [11].
- The vertebral canal extends throughout the length of the column and provides protection for the spinal cord, conus medullaris, and cauda equina [11].
- Each vertebra is composed of an anterior portion (vertebral body) and a posterior arch formed by the pedicle, facet, lamina, and spinous process [8].
- The vertebral body is composed of an inner region of cancellous bone surrounded by a thin shell of cortical bone [8].

INTERVERTEBRAL DISC ANATOMY

- The intervertebral disc (IVD) separates each successive vertebral body except between the atlas (C1) and the axis (C2) [8].
- The IVD provides a unique combination of compressive stiffness and flexibility to support normal spine biomechanics [8].
- The IVD is composed of an inner nucleus pulposus (NP) and an outer ring termed the annulus fibrosus (AF) [8].
- The nucleus pulposus serves as an osmotic pump to attract water and generate hydraulic pressure when subjected to significant loads during activities of daily living [8].
- The annulus fibrosus encapsulates the gelatinous nucleus pulposus and provides mechanical support to contain NP pressure and constrain intervertebral rotations [8].
- The outer annulus fibrosus is integrated with the vertebral rim via a fibrocartilage enthesis that consists of a thin layer of calcified cartilage, or “tidemark” [8].
- The end plate is a bilayer of cartilage and bone that separates the disk from adjacent vertebrae [8].
- The cartilage end plate integrates with the inner annulus fibrosus to fully encapsulate the nucleus pulposus [8].
- The end plate must be strong and thick to resist significant loads but also permeable to favor chemical transport and disk cellular vitality [8].

LIGAMENTS AND SOFT TISSUE

- Each successive vertebra is connected anteriorly via the IVD and posteriorly via the facet joints [8].
- Additional soft-tissue structures providing passive support include the anterior longitudinal ligament, posterior longitudinal ligament, ligamentum flavum, facet joint capsule, interspinous ligament, and supraspinous ligaments [8].
- The spinal column is stabilized by paraspinal muscles including the erector spinae, psoas, and multifidus [8].
- The erector spinae runs longitudinally on the dorsal surface of the spinal column and functions to extend the spine [8].
- The psoas runs longitudinally on the ventrolateral surface of the spinal column and serves to flex the hip or laterally bend the trunk [8].
- The multifidus connects intersegmentally to stabilize the spine by acting like a bowstring to maintain lordosis [8].

BIOMECHANICS AND ALIGNMENT

- Normal cervical alignment is approximately 15° of lordosis [7].
- The thoracic spine generally ranges from 20° to 40° of kyphosis [7].
- The lumbar spine has approximately 40° to 50° of lordosis [7].
- The sacrum is kyphotic [7].
- Kyphotic segments (thoracic, sacral) are considered “primary” curvatures present in utero and at birth, while lordotic curvatures of the cervical and lumbar spine develop secondarily later in life [7].
- The center of gravity of the spinal column runs from the odontoid process proximally through the sacral promontory caudally [7].
- Changes in sagittal balance that shift the center of gravity too far ventrally can result in significant pain and disability [7].
- The basic motion segment of the spine, or “functional spinal unit,” consists of two vertebrae, the disk between them, and the facet joints and their capsules [7].
- The functional spinal unit serves to limit motion of the spine within the confines of protecting the neural structures contained therein [7].
- Vertebral bodies are loaded in series, with more caudal levels supporting more weight than more cranial segments [7].
- The vertebral bodies bear 70% to 90% of the static axial load of the spine [7].
- The facet joints support 10% to 20% of axial load in a standing, neutral alignment [7].
- In extension, the facet joints may bear up to 30% of the axial load [7].
- In flexion, the facet joints may be burdened with up to 50% of the anterior shear load [7].
- The intervertebral disk helps absorb axial loads by deforming the nucleus pulposus, which redistributes axial forces radially [7].

- The radial pressure generated by the nucleus pulposus is resisted by the tensile properties of the alternating bands of fibers within the annulus fibrosus [7].
- The spinous processes and transverse processes act as lever arms, providing mechanical advantage for the muscles that insert along their surfaces [7].

VASCULAR ANATOMY

- The thoracic and lumbar levels are supplied by paired segmental arteries which originate directly from the aorta along its posterior surface [12].
- Branches of the segmental arteries supply the vertebral body, the paraspinal musculature, and the spinal cord [12].
- The cervical spine derives its circulation primarily from the vertebral arteries [12].
- The vertebral arteries arise from the subclavian arteries and typically enter the transverse foramen at the C6 level [12].
- The vertebral arteries run proximally through the transverse foramina to C1, course posteriorly over the superior aspect of the C1 ring, and enter the foramen magnum to form the basilar artery [12].
- There is a great deal of variability in the anatomy of the vertebral artery, including one side being more dominant and occasional entry through the transverse foramen of C7 rather than C6 [12].
- The vascular supply of the spinal cord is primarily from the medullary branches of the segmental spinal arteries [12].
- These branches merge to feed the anterior spinal artery, which is responsible for supplying approximately 80% of the vascular supply to the spinal cord [12].
- The arteria medullaris magna (AMM), also known as the arteria radicularis magna or artery of Adamkiewicz, is the largest anterior segmental artery [12].
- The AMM typically arises on the left side anywhere between the T8 and L1 level, although right-sided origins are not uncommon [12].

NEURAL ANATOMY

- A typical mixed spinal nerve has three distinct components: motor, sensory, and sympathetic [13].
- Motor rootlets leave the anterolateral sulcus of the spinal cord and unite to form each motor root, with fibers arising from anterior horn cells to innervate skeletal muscles [13].
- Sensory fibers arise from pain, thermal, tactile, and stretch receptors, with cell bodies located within the dorsal root ganglia [13].
- Fibers conveying joint or position sensibility and some tactile fibers turn cephalad in the dorsal columns and do not synapse before reaching the gracile and cuneate nuclei at the cervicomedullary junction [13].
- Pain and temperature fibers synapse in the substantia gelatinosa and cross to ascend in the dorsal spinothalamic tract [13].
- Tactile fibers enter, synapse, and cross to ascend in the ventral spinothalamic tract [13].

CQ HAND + UPPER LIMB

- The sympathetic component of all 31 mixed spinal nerves leaves the spinal cord along only 14 motor roots [13].
- The cells of origin for sympathetic fibers are in the intermediolateral cell column that extends throughout the thoracic and upper lumbar cord segments [13].
- Sympathetic fibers exit from the cord with the 12 thoracic and first two lumbar motor roots, enter the respective mixed spinal nerve, and emerge as white rami [13].
- White rami pass anteriorly to the corresponding sympathetic ganglion, where synapse may occur or fibers may pass for variable distances up or down the paravertebral chain [13].
- Postganglionic fibers pass along gray rami to cervical, lower lumbar, or sacrococcygeal mixed spinal nerves having no white rami [13].
- Mixed spinal nerves, having left the intervertebral foramina, receive their sympathetic component and branch into anterior and posterior primary rami [13].
- The posterior primary rami are directed posteriorly and supply the paraspinal musculature and the skin along the posterior aspect of the trunk, neck, and head [13].
- The upper three cervical posterior rami are larger than their corresponding anterior rami, supplying relatively large areas of the scalp posteriorly and the musculature around the craniocervical junction [13].
- With exceptions for the upper cervical levels, posterior primary rami are small, and the major part of each spinal nerve continues laterally in an anterior primary ramus to enter a plexus or become an intercostal nerve [13].
- Anterior primary rami of all cervical, the first thoracic, and all lumbosacral nerves join in the formation of plexuses [13].
- The upper four cervical anterior rami form the cervical plexus, and the lower four cervical and first thoracic anterior rami form the brachial plexus [13].
- The first three and a part of the fourth lumbar anterior rami form the lumbar plexus [13].
- The sacral anterior rami along with the fifth lumbar and a part of the fourth join to form the lumbosacral plexus [13].
- The area of skin supplied by the fibers of a single spinal root is called a dermatome [13].
- Segmental dermatomal patterns are well preserved in the thoracic region but not in the limbs [13].
- Migration of the limb buds accounts for the displacement of midcervical dermatomes along the lateral aspect of the arm and radial aspect of the forearm [13].
- Migration of the limb buds accounts for the displacement of lower cervical and upper thoracic dermatomes along the medial aspect of the arm and the ulnar aspect of the forearm [13].
- Lumbar and sacral dermatomal alignment along the various aspects of the lower extremity is explained by limb bud migration [13].
- The line separating the more rostral segmental dermatomes from the more caudal ones is called the axial line and may be followed into the spinal axis [13].

PATHOPHYSIOLOGY OF DEGENERATION AND STENOSIS

- Degeneration of the disc occurs with disc narrowing and subsequent ligamentous redundancy, which compromises the spinal canal area [17].
- Instability may ensue from disc degeneration, and this relative hypermobility precipitates the formation of facet overgrowth and ligamentous hypertrophy [17].
- The ligamentum flavum may be markedly thickened into the lateral recess where it attaches to the facet capsule, causing nerve root compression [17].
- Central spinal stenosis denotes involvement of the area between the facet joints, which is occupied by the dura and its contents [17].
- Stenosis in the central region is usually caused by protrusion of a disc, bulging anulus, osteophyte formation, or buckled or thickened ligamentum flavum [17].
- Symptomatic central spinal stenosis results in neurogenic claudication with generalized leg pain [17].
- The lateral canal contains the nerve roots, and compression in this region results in radiculopathy [17].
- The lateral recess, also known as “Lee’s entrance zone,” begins at the medial border of the superior articular process and extends to the medial border of the pedicle [17].
- The borders of the lateral recess are the pedicle laterally, the superior articular facet dorsally, the posterior ligamentous complex to disc and floor of the canal, and the central canal medially [17].
- Facet arthritis most frequently causes stenosis in the lateral recess zone, along with vertebral body spurring and disc or anulus pathology [17].
- “Lee’s midzone” describes the foraminal region, which lies ventral to the pars [17].
- The borders of the foraminal region are the lateral recess medially, the posterior vertebral body and disc ventrally, the pars and intertransverse ligament dorsally, and the lateral border of the pedicle laterally [17].
- The foramen is essentially the area between the cephalad and caudal pedicles [17].
- The dorsal root ganglion and ventral motor root occupy 30% of the foraminal space [17].
- The foramen is the point where the dura becomes confluent with the nerve root as epineurium [17].
- Causes of stenosis in the foraminal area are pars fracture with proliferative fibrocartilage or a lateral disc herniation [17].
- Thickening of the ligamentum flavum sometimes extends into the foramen and can be associated with a spur from the undersurface of the pars, especially if foraminal height is less than 15 mm and posterior intervertebral disc height is less than 4 mm [17].
- The exit zone is identified as the area lateral to the facet joint [17].
- The nerve root in the exit zone can be compressed by a “far lateral” disc, spondylolisthesis and associated subluxation, or facet arthritis [17].
- The most common type of spinal stenosis is caused by degenerative arthritis of the spine, including Forestier disease, characterized by hyperostosis and spinal rigidity in elderly patients [17].
- Acquired forms of spinal stenosis are usually degenerative and most commonly localized to the facet joints and ligamentum flavum [17].

- The L4-5 level is the most commonly involved in degenerative spinal stenosis, followed by L5-S1 and L3-4 [17].
- Disc herniation and spondylolisthesis may exacerbate the narrowing of the spinal canal further [17].
- Spondylolisthesis and spondylosis rarely cause spinal stenosis in young patients [17].
- Congenital spinal stenosis usually is central and is evident on imaging studies [17].
- Idiopathic congenital narrowing usually involves the anteroposterior dimension of the canal due to short pedicles, with the posterior otherwise normal [17].
- In achondroplasia, the canal is narrowed in the anteroposterior plane owing to shortened pedicles and in lateral diameter because of diminished interpedicular distance [17].

Investigations

MAGNETIC RESONANCE IMAGING (MRI)

- MRI is the standard for advanced imaging of the spine and is superior to CT in most circumstances, particularly for identifying infections, tumors, and degenerative changes within the discs [23].
- MRI is superior to CT for imaging the intervertebral disc and directly imaging neural structures [23].
- MRI typically shows the entire region of the spine (cervical, thoracic, or lumbar) [23].
- MRI allows for the imaging of the nerve root in the foramen, which is difficult even with postmyelography CT because the subarachnoid space and contrast agent do not extend fully through the foramen [23].
- MRI evidence of disc degeneration has been reported in the cervical spine in 25% of patients younger than 40 years and in 60% of patients 60 years and older [23].
- Lumbar disc degeneration was found in 35% of patients aged 20 to 39 years and in 100% of patients older than 50 years [23].
- The best way to obtain meaningful clinical information from MRI is to have a specific question derived from the patient's history and physical examination, posed using the parameters of neural compression, instability, and deformity [23].
- Only abnormalities in the categories of neural compression, instability, or deformity are important for operative treatment [23].
- Failure to interpret MRI in the context of specific clinical questions leads to poor clinical choices and outcomes due to the modality's sensitivity to anatomic abnormalities [23].
- A normal intervertebral disc exhibits signal hyperintensity on T2-weighted images due to its high water content [22].
- The aging process results in gradual desiccation of disc material and loss of T2-weighted signal hyperintensity [22].
- Disc herniations or extrusions appear as convex or polypoid masses extending posteriorly into the ventral epidural space, frequently maintaining a signal intensity similar to that of the disc of origin [22].

- Sagittal T2-weighted or gradient-echo images create a “myelographic” effect useful for evaluating compromise of the subarachnoid space [22].
- Sagittal T1-weighted images should be examined to identify narrowing of the neuroforamina, where normal hyperintense perineural fat provides contrast to darker displaced disc material [22].
- Far lateral disc herniations are best seen on selected axial images localized through disc levels [22].
- Free disc fragments appear discontinuous with the intervertebral disc and usually exhibit intermediate T1-weighted signal in contrast to hypointense cerebrospinal fluid [22].
- MRI can detect significant spinal cord compromise, with edema within the cord demonstrated as hyperintensity on T2-weighted images [22].
- Diffusion tensor imaging has been reported to demonstrate spinal cord impairment in patients with early stage cervical spondylosis before it is visible on plain MRI scans [26].
- Lumbar facet joint effusion on MRI is a sign of instability in degenerative spondylolisthesis [21].
- A practical MRI grading system exists for lumbar foraminal stenosis [21].

COMPUTED TOMOGRAPHY (CT)

- CT has largely supplanted plain radiographs as the initial screening study of choice for spine injuries due to its combination of high sensitivity and specificity [24].
- CT allows for the identification of subtler fractures that might remain undiagnosed on plain radiographs and provides additional three-dimensional detail [24].
- CT is particularly useful in differentiating compression fractures from burst fractures and in identifying features such as facet widening [24].
- CT evaluation is essential in determining the stability of thoracic and lumbar spine fractures [24].
- The primary disadvantage of CT imaging compared to MRI is that it does not provide as good a visualization of soft tissues [24].
- CT myelography is reserved for patients who have contraindications to MRI or who have equivocal MRI examinations [22].
- CT myelography is invasive and more costly than MRI [22].

DIAGNOSTIC TERMINOLOGY AND CORRELATION

- A disc bulge is defined as a circumferential, symmetric extension of the disc beyond the interspace around the endplates [22].
- A disc protrusion is defined as a focal or asymmetric extension of the disc beyond the interspace, with the base against the disc of origin broader than any other dimension of the protrusion [22].
- A disc extrusion is defined as a more extreme extension of the disc beyond the interspace, with the base against the disc of origin narrower than the diameter of the extruding material itself or with no connection between the material and the disc of origin [22].
- A disc sequestration specifically refers to a disc fragment that has completely separated from the disc of origin [22].

- MRI findings must be carefully correlated with the clinical impression because anatomy may be abnormal but asymptomatic [23].

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