Update

Segmental Instability of the Lumbar Spine

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Basic Biomechanics of the Lumbar Spine

The lumbar spine, although often described as a single functional unit, is composed of 5 vertebrae forming what are called "motion segments" connected in series. Each motion segment consists of 2 adjacent vertebral bodies and the connecting ligaments. Spinal motion segments represent the smallest segments of the spine exhibiting biomechanical characteristics similar to those of the entire spine.

Translation and rotation can occur at each spinal motion segment. Translation occurs when a shear force causes one vertebra to move parallel to the adjacent vertebra. Rotation is the spinning of one
vertebra about a stationary axis relative to the adjacent vertebra caused by a torque. Translation and rotation occur at each motion segment during lumbar spine movements in any of the cardinal body planes. For example, lumbar flexion involves anterior translation and rotation, and lumbar extension involves posterior translation and rotation of each lumbar motion segment in the sagittal plane. The maintenance of stability of the lumbar spine during movements, therefore, requires the coordinated movements of multiple motion segments, and a lack of stability may potentially occur at any lumbar segment in either translational or rotational movements, or both.

**Definitions of Clinical Instability**

Segmental instability occurs when an applied force produces displacement of part of a motion segment exceeding that found in a normal spine. Several researchers have defined normal segmental motion in the lumbar spine. Most initial experiments were performed in vitro on cadaveric lumbar spines. Based on the results of these studies, the most commonly cited thresholds for segmental instability were (1) a sagittal-plane translation of at least 3 mm, or 9% of the vertebral body width, on either a flexion or extension radiograph, and (2) a sagittal-plane rotation of greater than 9 degrees for the lumbar motion segments between L1 and L5. More recently, researchers have studied the motion characteristics of the lumbar spinal segments in vivo by taking radiographs of subjects with the spine in neutral, flexed, and extended positions. These researchers found large variability in the segmental motions of individuals without LBP. Hayes et al found that 42% of subjects without LBP had at least one lumbar motion segment with at least 3 mm of sagittal-plane translation. Based on the results of in vivo studies, some authors have recommended that the criteria for diagnosing segmental instability be increased to 4 to 4.5 mm, or 10% to 15% of vertebral body width, of sagittal-plane translation. Thresholds for rotational instability, according to White and Panjabi, are greater than 15 degrees at L1 to L4, greater than 20 degrees at L4-5, and greater than 25 degrees at L5-S1.

The range of motions observed in motion segments of persons with LBP illustrates the difficulty in defining segmental instability strictly in terms of increased joint laxity. The frequent disparity between joint laxity and the development of symptoms has been described in other joints. Snyder-Mackler et al studied 20 patients with anterior cruciate ligament deficiencies and found no correlation between joint laxity and functional ability. They suggested that other factors, such as neuromuscular control, may influence the relationship between joint laxity and symptom development. A similar phenomenon may occur in the spine, with certain individuals unable to compensate for an excessive amount of joint laxity and with other individuals with equal amounts of laxity able to "cope" without substantial pain and disability. The rotational and translational movement criteria for diagnosing clinical instability have been established to identify patients requiring surgical fixation, but these criteria may not be adequate for detecting more subtle forms of segmental instability that can cause pain and disability.20

Definitions of segmental instability based solely on clinical findings have been proposed. Segmental instability has been defined as occurring in patients with low back problems whose clinical status is unstable, with symptoms fluctuating between mild and severe symptoms in response to even minor provocations. Paris defined instability as existing only when sudden aberrant motions such as a visible slip or catch are observed during active movements of the lumbar spine or when a change in the relative position of adjacent vertebrae is detected with palpation performed with the patient in a standing position versus palpation performed with the patient in a prone position. The validity of these clinical definitions has not been demonstrated. Frymoyer et al defined segmental instability as "a condition where there is loss of spinal stiffness, such that normally tolerated external loads will result in pain, deformity, or place neurological structures at risk."
A more recent theoretical premise of segmental instability using a "neutral zone" concept has been proposed by Panjabi. The neutral zone concept is based on the observation that the load-displacement curve of the typical spinal motion segment is highly nonlinear, with high flexibility for motion occurring around the neutral position of the spine and with increased passive resistance to motion nearer to the end-ranges of spinal motion. The total range of motion (ROM) of a spinal motion segment, therefore, may be divided into 2 zones: a neutral zone and an elastic zone. The neutral zone is the initial portion of the ROM during which spinal motion is produced against minimal internal resistance. The elastic portion of the ROM is the portion nearer to the end-range of movement that is produced against substantial internal resistance.

The neutral zone is the zone of high spinal flexibility, whereas movements occurring in the elastic zone encounter increased internal resistance to movement. An increase in the size of the neutral zone relative to the total ROM, therefore, increases the amount of laxity present and increases the demands on the stabilizing systems of the spine. In vitro studies suggest that an increase in the size of the neutral zone may be a better indicator of segmental instability than an increase in total ROM. Segmental instability, therefore, may be defined as a decrease in the capacity of the stabilizing system of the spine to maintain the spinal neutral zones within physiological limits so that there is no neurological deficit, no major deformity, and no incapacitating pain. Although further research is needed, this definition of segmental instability may prove to be useful because it describes the quality of motion throughout the ROM instead of relying solely on total ROM values for diagnosis. Clinical methods for quantitatively assessing the size of the neutral zone have not been developed, but this definition, emphasizing the quality as opposed to the quantity of motion, appears to fit the clinical observation that many patients with suspected segmental instability have greater difficulty moving in the mid-ranges of spinal motion than at the end-ranges. In addition, because muscle activity can affect the size of the neutral zone, the influence of factors such as muscle activity and neuromuscular control can be accounted for within this definition.

The Stabilizing System of the Spine

The stabilizing system of the spine must limit the excursion of spinal motion segments and maintain the proper ratio of neutral to elastic zone motion. Panjabi conceptualized the stabilizing system of the spine as consisting of 3 subsystems: (1) passive, (2) active, and (3) neural control. The functions of these 3 subsystems are interrelated, and reduced function of one subsystem may place increased demands on the other subsystems to maintain stability.

The Passive Subsystem

The passive subsystem consists primarily of the vertebral bodies, zygapophyseal joints and joint capsules, spinal ligaments, and passive tension from the musculotendinous units. The passive subsystem plays its most important stabilizing role in the elastic zone of spinal ROM (ie, near end-range). The relative contributions of structures to segmental stability have been investigated by serially cutting the structures and through mathematical modeling experiments. The posterior ligaments of the spine (interspinous and supraspinous ligaments) along with the zygapophyseal joints and joint capsules and the intervertebral disks are the most important stabilizing structures when the spine moves into flexion. End-range extension is stabilized primarily by the anterior longitudinal ligament, the anterior aspect of the annulus fibrosus, and the zygapophyseal joints. Rotational movements of the lumbar spine are stabilized mostly by the intervertebral disks and the zygapophyseal joints. Side-bending movements have not been studied extensively, but it appears that the
intertransverse ligaments may play an important role in segmental stability for movement occurring in the frontal plane.\textsuperscript{33}

In the neutral zone of ROM, the structures of the passive subsystem may function as force transducers, sensing changes in position and providing feedback to the neural control subsystem.\textsuperscript{30,33,38} Evidence for this role is provided by anatomical observations of afferent nerve fibers capable of conveying proprioceptive information in most of the structures of the passive subsystem, including the intervertebral disks, the zygapophyseal joint capsules, and the interspinous and supraspinous ligaments.\textsuperscript{31,38} Injury to the passive subsystem may have important implications for spinal stability. Intervertebral disk degeneration or disruption of the posterior ligaments of the spine may increase the size of the neutral zone, increasing the demands on the active and neural control subsystems to avoid the development of segmental instability.\textsuperscript{25,29}

The Active Subsystem

The active subsystem of the spinal stabilizing system consists of the spinal muscles and tendons. The active and neural control subsystems are primarily responsible for spinal stability in the neutral zone, where passive resistance to movement is minimal.\textsuperscript{30,34} In experiments performed with the musculature removed, the lumbar spine is known to be highly unstable at very low applied loads, attesting to the importance of muscle activity for spinal stability.\textsuperscript{39} The relative importance of different muscle groups in providing stability for the lumbar spine has been a topic of much debate and research.\textsuperscript{40–44}

Differing roles have been suggested for the deeper, unisegmental muscles and the more superficial multisegmental muscles such as the abdominal and erector spinae muscles.\textsuperscript{40} The unisegmental muscles of the lumbar spine, such as the intertransversarii and interspinalis muscles, are proposed to function primarily as force transducers, providing feedback on spinal position and movements to the neural control subsystem.\textsuperscript{30} Evidence for this role is provided by the small size of these muscles, their close proximity to the center of rotation for spinal movements, and the high concentration of muscle spindles located in the smaller, unisegmental muscles of the body.\textsuperscript{7,45}

The larger, multisegmental muscles are responsible for producing and controlling movements of the lumbar spine. Lifting and rotational movements have been studied most extensively because these are tasks frequently performed by the lumbar spine. The lumbar erector spinae muscle group provides most of the extensor force required for most lifting tasks.\textsuperscript{46} Rotation is produced primarily by the oblique abdominal muscles.\textsuperscript{41} The oblique abdominals and the majority of the lumbar erector spinae muscle fibers lack direct attachment to the lumbar spinal motion segments and, therefore, are unable to exert forces directly on individual motion segments. The multifidus muscle is better suited for the purpose of segmental control.\textsuperscript{47} This muscle originates from the spinous processes of the lumbar vertebrae and forms a series of repeating fascicles attaching to the inferior lumbar transverse processes, the ilium, and the sacrum. The multifidus muscle is proposed to function as a stabilizer during lifting and rotational movements of the lumbar spine.\textsuperscript{47} Stability of the lumbar spine during movements in the frontal plane has not been studied extensively, but the quadratus lumborum muscle has been proposed to be the primary active stabilizer for these movements.\textsuperscript{48}

The role of the abdominal muscles in spinal stability has been the topic of much debate. The abdominals have been proposed to play an important role in generating extensor force during lifting tasks, either by increasing intra-abdominal pressure or by creating tension in the lumbodorsal fascia.\textsuperscript{42,49} Research
indicates that the abdominal muscles are not capable of generating substantial extensor force through these mechanisms.\textsuperscript{43,50} The abdominal muscles are primarily flexors and rotators of the lumbar spine.\textsuperscript{41} The oblique abdominal and transversus abdominis muscles, with their more horizontal orientation, are thought to contribute to spinal stability by creating a rigid cylinder around the spine and by increasing the stiffness of the lumbar spine.\textsuperscript{44,51} This theory is supported by studies demonstrating continuous activity of the transversus abdominis muscle throughout flexion and extension movements of the lumbar spine.\textsuperscript{52}

**The Neural Control Subsystem**

The neural control subsystem is thought to receive input from structures in the passive and active subsystems in order to determine the specific requirements for maintaining spinal stability, then acting through the spinal musculature to stabilize the spine.\textsuperscript{30,44,53} Dysfunction in the neural control system may place other spinal structures at risk for injury.\textsuperscript{30} If proper functioning of the neural control system is not restored following an injury, the potential for reinjury may be heightened.\textsuperscript{53}

No evidence exists linking poor neuromuscular control with increased risk of an initial injury to the lumbar spine. Several studies\textsuperscript{44,54–57} have shown that patients with LBP often have persistent deficits in neuromuscular control, indicating that recovery of proper function of the neural control subsystem is not automatic following an initial injury. Studies\textsuperscript{54–56} have demonstrated increased postural sway and slower reaction times in patients with LBP when compared with subjects without LBP. Luoto et al\textsuperscript{54} found that improvements in reaction time correlated with reduced disability in patients undergoing rehabilitation. These results support the hypotheses that neuromuscular control deficits often exist following lumbar spine injury and that reduction in these deficits correlates with improvements in functional status.

The neural control system may play an important role in stabilizing the spine in anticipation of an applied load. Hodges and Richardson\textsuperscript{44,57} reported that the transversus abdominis and multifidus muscle activity consistently precedes active extremity movement in subjects without LBP. This finding suggests that the neural control system normally anticipates the need for stabilization against the reactive forces from limb movements. In a study of patients with LBP,\textsuperscript{44} the contraction of the transversus abdominis muscles was delayed, possibly indicating deficient neural control. Further research is needed to clarify the role of neural control in patients with LBP, but these preliminary findings indicate that enhancing neural control may be an important consideration in the prevention and rehabilitation of LBP.

**Diagnosing Spinal Instability**

In 1944, Knuttson\textsuperscript{58} described a method for diagnosing segmental instability by taking lateral radiographs of the lumbar spine with the patient performing a maximum active extension while standing and a maximum active flexion while sitting. The amount of sagittal-plane translation and rotation were then calculated from the 2 radiographs and compared with criteria defining segmental instability. Flexion-extension radiographs have now become the standard by which segmental instability is diagnosed.\textsuperscript{5,12,14} Variations in the exact technique used, large variability in the motion characteristics of individuals without LBP, and high false-positive rates using the established criteria, however, have caused many authors\textsuperscript{17,27} to question the usefulness of flexion-extension radiographs.

Friberg\textsuperscript{59} described an alternative diagnostic method in which radiographs are taken during axial
compression while the patient supports a weight on the shoulders and then during traction while the patient hangs from a bar. Anteroposterior translation occurring between the 2 positions was reported by Friberg to be more accurate in detecting abnormal movement in patients suspected of having segmental instability, but more recent work has questioned the accuracy of this technique.

Other authors contend that a decrease in symptoms with bracing provides evidence of segmental instability. This technique is limited by the inability of most braces to effectively immobilize the spine, and data have not been reported for a large group of patients. Olerud et al used an external fixation device to achieve immobilization and reported that patients experiencing relief with this technique were more likely to achieve favorable results with spinal fusion. The invasiveness of this technique, however, precludes its use with most patients.

Diagnosis of lumbar segmental instability may also be based on examination findings or the patient's history. Delitto et al believe that confirmatory data for segmental instability include frequent recurrences of LBP precipitated by minimal perturbations, deformity (eg, lateral shift) in prior episodes of LBP, short-term relief from manipulation, a history of trauma, use of oral contraceptives, or an improvement of symptoms with the use of a brace in previous episodes of LBP. Some authors contend that the presence of a "step-off" between the spinous processes of adjacent vertebrae felt with palpation or increased mobility with passive intervertebral motion testing are indicative of instability. The reliability of these techniques, however, has been questioned, and their validity has not been demonstrated. Other authors have emphasized that aberrant motions such as the "instability catch" occurring during active ROM testing of the motion indicate instability. The instability catch has been described by numerous authors as a sudden acceleration or deceleration of movement, or a movement occurring outside of the primary plane of motion (eg, side-bending or rotation occurring during flexion), and is proposed to indicate segmental instability. Its presence, however, has never been related to symptoms or abnormal movements in diagnostic imaging studies.

A diagnostic "gold standard" has not been identified for segmental instability. A criticism of current diagnostic imaging approaches is their inability to capture segmental spinal movements in the mid-ranges of spinal motion, where aberrant motions such as the instability catch are most likely to be observed. Flexion-extension radiographs taken at the end-range of movement will capture only the function of the passive stabilizing subsystem and fail to address the active and neural control subsystems. Because of the importance of motor control in spinal stability, some authors believe that electromyographic techniques may hold more promise in diagnosing segmental instability, but clinically useful techniques have yet to be described.

**Treatment of Segmental Instability**

Patients with segmental instability resulting in severe disability may be considered candidates for lumbar spinal fusion. The rate of lumbar spinal fusion is increasing rapidly in the United States, despite the fact that indications for the procedure are uncertain, costs and complication rates are higher than for other surgical procedures performed on the spine, and long-term outcomes are uncertain. Fusion for segmental instability is usually reserved for patients with severe symptoms and radiographic evidence of excessive motion (greater than 4 mm translation or 10° of rotation) who fail to respond to a trial of nonsurgical treatment.

The use of braces or corsets has been recommended in the treatment of persons with segmental instability.
instability. Spratt et al reported on a treatment program consisting of patient education, extension exercises, and bracing to prevent flexion in a group of patients with radiographic evidence of segmental instability. The treatment program was effective in reducing pain. The design of the study, however, did not allow for an evaluation of the efficacy of bracing alone.

Patient education may be an important component in the nonsurgical treatment of patients with segmental instability. Education should focus on avoiding end-range movements of the lumbar spine to avoid positions that may overload the passive stabilizing structures of the spine. Patients should be made aware that lifting even light loads from a position near the end-range spinal flexion can create potentially damaging forces in the passive stabilizing structures of the spine. Patients also should be made aware of the importance of maintaining muscle strength and endurance, particularly in the muscles of the lumbar spine. Fatigue can adversely affect the ability of the spinal muscles to respond to imposed loads and general strengthening programs have been shown to be effective in patients with chronic LBP.

The physical therapy treatment for segmental instability often focuses on exercises designed to improve stability of the spine. Several muscle groups have been identified in the literature as potentially playing an important role in stabilizing the spine. The lumbar erector spinae muscles are the primary source of extension torque for lifting tasks; therefore, strengthening this muscle group has been advocated. Callaghan et al studied erector spinae muscle activity and imposed loads on the lumbar spine during a variety of exercises thought to strengthen the back extensor muscles. Exercises performed with the patient in a quadruped position, including single-leg extension and contralateral arm and leg extension exercises, provided sufficient challenge to the erector spinae muscles without producing a high load on the lumbar spine. Active trunk extension exercises performed with the patient in a prone position produced high levels of activity in the erector spinae muscles, but also imposed a substantial load on the lumbar spine, which may make these exercises a contraindication in the rehabilitation process.

The abdominal muscles, particularly the transversus abdominis and oblique abdominals, and the multifidus muscle have been proposed to play an important role in stabilizing the spine by co-contracting in anticipation of an applied load. The multifidus muscle, because of its segmental attachments to the lumbar vertebrae, may be able to provide segmental control, particularly during lifting and rotational motions. Exercises targeting these muscle groups, therefore, may be desirable. Richardson and Jull described an exercise program that proposes to retrain the co-contraction pattern of the transversus abdominis and multifidus muscles. The exercise program is based on training the patient to draw in the abdominal wall while isometrically contracting the multifidus muscle. This co-contraction exercise is then performed in a variety of postures. O'Sullivan et al recently reported the results of a randomized trial comparing this exercise program with a program of general exercise (swimming, walking, gym exercises) in a group of patients with chronic LBP. The stabilization exercise group had less pain and functional disability following a 10-week treatment program than the general exercise group, a difference that was maintained at a 30-month follow-up.

Exercises proposed to address the abdominal muscles in an isolated manner usually involve some type of curl-up maneuver. McGill found that dangerously high compressive and shear forces are imposed on the lumbar spine during both straight and bent-knee curl-up exercises. A horizontal side-support exercise has been recommended as an alternative to curl-ups for strengthening the abdominal muscles. This exercise is performed with the patient side-lying and the upper body supported by the
elbow to create a side-bending of the spine. The patient then lifts the pelvis off the support surface to a position in line with the shoulders, eliminating the side-bending. This exercise provides a substantial challenge to the oblique abdominal muscles without imposing high compressive or shear loading forces on the lumbar spine.\textsuperscript{76} In addition, the horizontal side-support exercise challenges the quadratus lumborum muscle, which may be an important spinal stabilizer for movements occurring in the frontal plane.\textsuperscript{48}

Exercises designed to challenge the neural control subsystem also have been recommended in the treatment of persons with segmental instability.\textsuperscript{54} Effective exercises for achieving this outcome have not been identified. The use of unstable surfaces such as therapy balls have been recommended for this purpose. The efficacy of such an approach has not been investigated in the rehabilitation of patients with LBP, but similar approaches have been found to be effective in the treatment of patients with knee joint instability secondary to rupture of the anterior cruciate ligament.\textsuperscript{82}

**Conclusion**

The concept of lumbar segmental instability is receiving increased interest from researchers and clinicians alike as a potential pathomechanical mechanism in patients with LBP. At present, much controversy exists regarding the proper definition of the condition, the best diagnostic methods, and the most efficacious treatment approaches. Further research is needed to clarify these issues.

**References**


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