A commentary by Ferhan A. Asghar, MD, is available at www.jbjs.org/commentary and is linked to the online version of this article.

Segmental Lumbar Rotation in Patients with Discogenic Low Back Pain During Functional Weight-Bearing Activities

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Background: Little information is available on vertebral motion in patients with discogenic low back pain under physiological conditions. We previously validated a combined dual fluoroscopic and magnetic resonance imaging system to investigate in vivo lumbar kinematics. The purpose of the present study was to characterize mechanical dysfunction among patients with confirmed discogenic low back pain, relative to asymptomatic controls without degenerative disc disease, by quantifying abnormal vertebral motion.

Methods: Ten subjects were recruited for the present study. All patients had discogenic low back pain confirmed clinically and radiographically at L4-L5 and L5-S1. Motions were reproduced with use of the combined imaging technique during flexion-extension, left-to-right bending, and left-to-right twisting movements. From local coordinate systems at the end plates, relative motions of the cephalad vertebrae with respect to caudad vertebrae were calculated at each of the segments from L2 to S1. Range of motion of the primary rotations and coupled translations and rotations were determined.

Results: During all three movements, the greatest range of motion was observed at L3-L4. L3-L4 had significantly greater motion than L2-L3 with left-right bending and left-right twisting movements ($p < 0.05$). The least motion occurred at L5-S1 for all movements; the motion at this level was significantly smaller than that at L3-L4 ($p < 0.05$). Range of motion during left-right bending and left-right twisting at L3-L4 was significantly larger in the degenerative disc disease group than in the normal group. The range of motion at L4-L5 was significantly larger in the degenerative group than in the normal group during flexion; however, the ranges of motion in both groups were similar during left-to-right bending and left-to-right twisting.

Conclusions: The greatest range of motion in patients with discogenic back pain was observed at L3-L4; this motion was greater than that in normal subjects, suggesting that superior adjacent levels developed segmental hypermobility prior to undergoing fusion. L5-S1 had the least motion, suggesting that segmental hypomobility ensues at this level in patients with discogenic low back pain.

Clinical Relevance: These data may be used to study the effects of spinal arthrodesis and to further define the mechanical component of adjacent-segment degeneration.

Intervertebral discs at a vertebral level adjacent to a degenerated disc have a high prevalence of degeneration^{1,2}, particularly following surgical arthrodesis for the treatment of the diseased level^{3,4}. While some have advocated that this degeneration might be due to the natural aging of the discs^{5,6},

many have assumed that altered mechanical loading and motion patterns are the causative factors of adjacent intervertebral disc degeneration^{7,8}. Few quantitative data have been reported on how the degenerated disc affects the biomechanical environment of the involved and adjacent intervertebral discs⁹.

Disclosure: In support of their research for or preparation of this work, one or more of the authors received, in any one year, outside funding or grants of less than \$10,000 from the National Institutes of Health (#1R21AR057989). Neither they nor a member of their immediate families received payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity.

The kinematics of the lumbar spine in individuals with low back pain have been studied with use of a variety of techniques. In vitro studies have involved the use of cadaveric lumbar specimens to determine the motion characteristics of lumbar segments with various degenerative grades¹⁰⁻¹². Dynamic sagittal plane radiographs have been used to detect the sagittal plane rotations in normal and symptomatic subjects¹³. Recently, advanced computed tomography (CT) and magnetic resonance imaging (MRI) techniques have also been used to measure axial rotation in normal and symptomatic subjects¹⁴⁻¹⁹. Many of those studies have focused on the study of motion in select planes, under nonphysiological loading conditions, and have focused on patients with nonspecific low back pain. The effect of degenerative diseases on rotations and translations of the vertebral segments in three-dimensional (3-D) space under weight-bearing physiological loading conditions has yet to be determined, to our knowledge.

Recently, we validated a combined dual fluoroscopic and MRI/CT imaging system (DFIS) to investigate in vivo lumbar spine kinematics in human subjects^{20,21}. We studied a cohort of patients with discogenic low back pain immediately prior to spinal arthrodesis and compared the results with our previously published results for an asymptomatic group without evidence of degenerative disc disease²². We hypothesized that the lumbar vertebrae at the levels immediately adjacent to those that were symptomatic would demonstrate distinct motion patterns during active in vivo spine motion prior to surgical arthrodesis.

Materials and Methods

Patient Recruitment

Approval of the study by our institutional review board was obtained prior to the initiation of this study. Informed consent was obtained from each patient before any testing was performed.

Ten symptomatic subjects with low back pain (seven men and three women) were recruited from the practices of two full-time fellowship-trained spine surgeons at a single academic center. The patients had a mean age of 51.8 years (range, fifty to sixty years), a mean height of 169.7 cm, and a mean weight of 65.7 kg. The patients were screened for exclusion on the basis of clinical history, physical examination, and radiographic findings. The exclusion criteria included previous spinal surgery, spinal abnormality at segments other than L4-S1, facet joint arthritis, ligamentum flavum hypertrophy, gross segmental instability, scoliosis, spondylolisthesis, central or foraminal spinal stenosis, paralysis, lower extremity weakness, myelopathy, radicular symptoms, history of mental illness, radiation treatment within the previous year, and pregnancy. All patients were diagnosed as having discogenic low back pain that originated from the L4-S1 segment. The presenting chief complaint for all patients was mechanical low back pain, which was defined as worsening symptoms with weight-bearing for prolonged periods of time, exacerbation of pain while sitting and bending forward, and absence of radicular symptoms. Radiographic confirmation of discogenic low back pain was determined by the treating surgeon and a neuroradiologist. The degree of

degeneration was graded with use of the scales described by Modic²³⁻²⁵ and Pfirrmann et al.²⁶. The Modic system classifies degenerative end-plate and vertebral body changes seen on MRI as Type I (acute inflammation), Type II (chronic changes, including end-plate disruption and fatty degeneration), or Type III (end-plate sclerosis and loss of vertebral cancellous bone). The Pfirrmann system classifies the morphology of the disc as seen on axial T2-weighted MRI as Grade I (a homogeneous bright white disc with clear distinction of the anulus fibrosus and the nucleus pulposus) to Grade V (an inhomogeneous black disc with lost distinction of the anulus and the nucleus). In order to be included in this study, all patients also had a discogram, performed by an interventional radiologist, demonstrating concordant symptoms at the involved levels with discordant findings at the adjacent levels. All patients had a minimum Pfirrmann grade of IV at the L4-L5 and L5-S1 discs. The mean Pfirrmann grade was 4.2 ± 0.6 at L4-L5 and 4.5 ± 0.5 at L5-S1. L3-L4 was the adjacent level, with a mean Pfirrmann grade of 1.6 ± 0.8 (Table I). All patients had non-operative management for a minimum of six months prior to arthrodesis. Following confirmation of the diagnosis, all patients consented and were scheduled to undergo surgical arthrodesis within two weeks in order to be considered for inclusion.

Eight asymptomatic subjects (five men and three women) ranging from fifty to sixty years of age were recruited as described in our previous study²² (mean age, 54.4 years; mean height, 164.7 cm; mean weight, 63.5 kg). The subjects were evaluated for the absence of low back pain (past or present) as well as the lack of evidence of degenerative disc disease and other spinal disorders. The data on this group of normal subjects served as a control. Pfirrmann scores were evaluated on the basis of MRI (Table I).

Combined Imaging Technique

Subjects underwent a lumbar MRI scan with use of a 3.0-T scanner (MAGNETOM Trio; Siemens Medical Solutions, Malvern, Pennsylvania) with a spine surface coil and a T2-weighted fat-suppressed 3-D spoiled gradient recalled sequence. The subject was then scanned in a supine, relaxed position. Parallel digital images with a thickness of 1.5 mm and with a resolution of 512×512 pixels were obtained (voxel size, $0.45 \times 0.45 \times$

TABLE I Disc Degeneration Graded with Pfirrmann System for Normal and Degenerative Disc Disease Groups

Level	Normal*	Degenerative Disc Disease*
L2-L3	1.1 ± 0.4	1.8 ± 0.5
L3-L4	1.6 ± 0.5	1.6 ± 0.8
L4-L5	1.9 ± 0.6	4.2 ± 0.6
L5-S1	2.1 ± 0.4	4.5 ± 0.5
*The values are given as the mean and the standard deviation.		

1.5 mm). The magnetic resonance images of the spinal segments were then imported into modeling software (Rhinoceros; Robert McNeel & Associates, Seattle, Washington) to construct 3-D anatomical vertebral models of the lumbar spine²¹. The contours of the vertebrae were digitized manually with use of B-spline curves. Mesh models of the vertebrae were then created from the contours (Fig. 1). The mean accuracy of our image-matching technique in determining translation has been

shown to be 0.40 mm. The repeatability of the method in reproducing in vivo human spine six-degrees-of-freedom kinematics was <0.3 mm in translation and $<0.7^\circ$ in orientation²⁰. Following MRI scanning, the lumbar spines of the subjects were imaged with use of a dual orthogonal fluoroscopic system. Two fluoroscopes (BV Pulsera; Philips, Bothell, Washington) were positioned with their intensifiers orthogonal to capture images of the segments at different postures simultaneously

Fig. 1

Creation of the three-dimensional model. *a*: Typical T2-weighted magnetic resonance image showing degenerative disc disease at L4-L5 and L5-S1 in a patient with low back pain. *b*: Digitized contours of the lumbar vertebrae in the sagittal plane. *c*: Three-dimensional anatomical vertebral model from L1 to S1, constructed from the magnetic resonance imaging.

Fig. 2

The experimental setup of the dual fluoroscopic imaging system (DFIS). *a*: The dual fluoroscopic system allows for capturing the lumbar spine positions of living subjects. *b*: The virtual dual fluoroscopic system mimics the actual fluoroscopic system and was used to reproduce the in vivo vertebral positions.

(Fig. 2, *a*). The kinematics of L2-S1 were captured during three physiological body motions in a predetermined sequence: 45° flexion of the trunk relative to vertical and maximum extension, maximum left-to-right bending, and maximum left-to-right twisting.

Reproduction of in Vivo Weight-Bearing Spine Kinematics

The pair of fluoroscopic images captured at a specific posture were imported into the modeling software and were placed in calibrated orthogonal planes, reproducing the positions of the intensifiers. Two virtual cameras were created inside the virtual space to reproduce the positions of the x-ray sources with respect to the image intensifiers. Therefore, the geometry of the dual-orthogonal fluoroscopic system was recreated. The vertebral models were introduced into the virtual system and were viewed from the perspective views of the two virtual

cameras (Fig. 2, *b*). The models were independently translated and rotated in six degrees of freedom (that is, the set of independent displacements and/or rotations that specify completely the displaced position and orientation of a rigid body) until their outlines matched those captured on the two orthogonal fluoroscopic images according to an existing protocol established in our laboratory^{20,21,27,28}. The software allowed the model to be manually translated and rotated in increments of 0.01 mm and 0.01°, respectively. The vertebral positions during in vivo weight-bearing activities were reproduced, representing the six-degrees-of-freedom kinematics of the vertebrae at each in vivo posture. Relative motions of the cephalad vertebrae with respect to the caudad vertebrae were analyzed with use of right-hand Cartesian coordinate systems constructed at the center of the end plate of each vertebra. Three rotations were defined as orientations of the cephalad vertebral coor-

Fig. 3

Local coordinate systems used to calculate the relative six-degrees-of-freedom kinematics of the cephalad vertebra with respect to the caudad vertebra. Three rotations were defined as the orientations of the cephalad vertebral coordinate system in the caudad vertebral coordinate system with use of Euler angles: a (flexion-extension rotation), b (left-right bending rotation), and γ (left-right twisting rotation).

dinate system in the caudad vertebral system with use of Euler angles: sagittal plane flexion-extension, coronal plane left-to-right bending, and transverse plane left-to-right twisting rotations (Fig. 3).

Data Analysis

After the determination of vertebral positions at each posture, we determined the range of motion of each vertebral level between flexion and extension, left and right bending, and left and right axial rotation. The range-of-motion data included both the primary rotations and coupled translations and rotations during each activity. A repeated-measures analysis of variance (ANOVA) was used to compare the range of motion at the L2-L3, L3-L4, L4-L5, and L5-S1 vertebral levels during each of the three functional activities. The level of significance was set at $p < 0.05$. When a significant difference was detected, a Newman-Keuls post hoc test was performed. The statistical analysis was performed with use of Statistica software (StatSoft, Tulsa, Oklahoma).

Source of Funding

Funding for the completion of this study was received from a grant from the NIH, which was used to partially cover the costs of imaging in this study.

Results

Primary Rotations in Patients with Degenerative Disc Disease

We observed the following primary ranges of motion during movement activities. The mean flexion and extension

ranges during the flexion and extension movements were $3.7^\circ \pm 3.7^\circ$, $5.6^\circ \pm 2.7^\circ$, $4.4^\circ \pm 2.8^\circ$, and $2.5^\circ \pm 2.6^\circ$ for the L2-L3, L3-L4, L4-L5, and L5-S1 levels, respectively. The mean left-to-right bending ranges during lateral bending movements were $3.3^\circ \pm 2.4^\circ$, $5.1^\circ \pm 2.8^\circ$, $3.2^\circ \pm 2.6^\circ$, and $2.1^\circ \pm 1.7^\circ$ and the mean left-to-right twisting ranges during twisting movements were $3.0^\circ \pm 1.5^\circ$, $4.2^\circ \pm 2.5^\circ$, $2.8^\circ \pm 2.1^\circ$, and $2.4^\circ \pm 1.5^\circ$ for the L2-L3, L3-L4, L4-L5, and L5-S1 levels, respectively (Table II).

During flexion-extension, the greatest range of motion was observed at the L3-L4 level, which was the superior adjacent level with respect to the degenerative disc disease levels. The lowest range of motion was observed at L5-S1; this range was significantly less than the range at L3-L4 ($p = 0.021$). During left-to-right bending, the greatest range of motion was observed at the L3-L4 level and the lowest range of motion was observed at the L5-S1 level. The range of motion at L5-S1 was significantly less than that at L3-L4 ($p = 0.008$). The range of motion at L3-L4 was significantly larger than that at L2-L3 ($p = 0.035$). During left-to-right twisting, the greatest range of motion was observed at the L3-L4 level and the lowest range of motion was observed at L5-S1. The range of motion at L5-S1 was significantly less than that at L3-L4 ($p = 0.017$). The range of motion at L3-L4 was significantly larger than that at L2-L3 ($p = 0.041$).

Overall, the greatest ranges were observed at the L3-L4 level during all three movements, which was the superior adjacent disc level in all patients. The lowest range of flexion occurred at the L5-S1 level for all three movements. During all three movements, L5-S1 demonstrated significantly less motion than L3-L4 ($p = 0.021$, 0.008 , and 0.017 for flexion-extension, left-to-right bending, and left-to-right twisting, respectively). Thus, the pattern of peak motion at L3-L4 and most diminished motion at L5-S1 was observed during all three activities. We did not detect any trends in movement patterns on the basis of the available anthropometry or age of the subjects.

Coupled Translations and Rotations

During the flexion-extension motion, there were coupled translations in all three directions (Table II). The coupled motions in the anterior-posterior and cephalad-caudad directions were similar. On the average, the translation range was 1.1 to 3.1 mm. The coupled translation in the left-to-right direction was significantly lower at L4-L5 (1.1 ± 0.5 mm) than at other levels. The coupled flexion rotation ranged from 2.3° to 3.1° , and the coupled twisting rotation ranged from 2.5° to 4.3° .

During the left-to-right bending motion, the coupled translations at all of the vertebral levels were not significantly different in the three directions and, on the average, ranged from 0.9 to 2.1 mm (Table II). The coupled flexion rotation ranged from 2.4° to 4.1° . The coupled twisting rotation ranged from 3.2° to 4.6° . No significant difference was noticed either between the levels or between the flexion and twisting rotations.

During the left-to-right twisting motion, the translations were, in general, significantly smaller at L3-L4 in the anterior-to-posterior direction (1.0 compared with 2.1 to 2.6 mm) and

the left-to-right direction (1.1 compared with 1.5 to 2.7 mm). The translation in the cephalad-to-caudad direction was between 0.7 and 1.1 mm, which in general was lower than the coupled motion in the other two directions. The coupled flexion range was smaller at L3-L4 (1.8° compared with 3.0° to 3.3°). The coupled bending rotation was also smaller at L3-L4 (1.2° compared with 2.9° to 3.4°).

Comparison with Normal Subjects

We compared the motion in patients who had degenerative disc disease with that in normal subjects and noted several significant differences in primary motions. Details on the normal motion kinematics with use of our technique have been reported previously²². The range of motion at L3-L4 during left-to-right bending was significantly larger in the

degenerative disc disease group than in the normal group ($5.1^\circ \pm 2.8^\circ$ compared with $3.4^\circ \pm 2.1^\circ$; $p = 0.038$), as was the range of motion at L3-L4 during left-to-right twisting ($4.2^\circ \pm 2.5^\circ$ compared with $2.4^\circ \pm 2.6^\circ$; $p = 0.043$). However, there was no significance during flexion ($p = 0.29$), although the mean flexion-extension range of motion was still higher in the patients with degenerative disc disease ($5.6^\circ \pm 2.7^\circ$ compared with $4.3^\circ \pm 3.4^\circ$). The range of motion at L4-L5 was significantly larger in the degenerative disc disease group than in the normal group during flexion ($4.4^\circ \pm 2.8^\circ$ compared with $1.9^\circ \pm 1.1^\circ$; $p = 0.005$) and was similar during left-to-right bending ($3.2^\circ \pm 2.6^\circ$ compared with $4.7^\circ \pm 2.4^\circ$; $p = 0.32$) and left-to-right twisting ($2.8^\circ \pm 2.1^\circ$ compared with $2.9^\circ \pm 2.1^\circ$; $p = 0.93$) (Fig. 4). In our previously published data on normal subjects, we observed an increasing range of motion pattern

Fig. 4

Bar graphs showing primary rotation range of motion (ROM) (and standard deviation) of patients with degenerative disc disease (DDD) and normal subjects at different levels during physiological activities. The numbers on the x axis indicate the vertebral level; for example, "23" indicates L2-L3, "34" indicates L3-L4, and so on. *Significantly different within degenerative disc disease group ($p < 0.05$). #Significantly different between degenerative disc disease group and normal group ($p < 0.05$).

TABLE II Six-Degrees-of-Freedom Translational and Rotational Range of Motion in Degenerative Disc Disease Group*

	Translation (mm)			Rotation (deg)		
	Anterior-Posterior	Left-Right	Cephalad-Caudad	Flexion	Bending	Twisting
Flexion-extension						
L2-L3	1.1 ± 1.3	2.6 ± 1.8	1.3 ± 1.0	3.7 ± 3.7	3.1 ± 2.5	3.0 ± 1.4
L3-L4	1.4 ± 1.0	2.4 ± 1.5	1.8 ± 1.9	5.6 ± 2.7	2.3 ± 2.5	4.3 ± 3.0
L4-L5	1.8 ± 1.8	1.1 ± 0.5	1.7 ± 1.3	4.4 ± 2.8	3.0 ± 2.0	3.6 ± 2.4
L5-S1	1.1 ± 0.8	3.1 ± 1.6	1.0 ± 1.3	2.5 ± 2.6	2.9 ± 1.9	2.5 ± 2.1
Left-right bending						
L2-L3	0.9 ± 1.0	1.0 ± 0.6	0.9 ± 0.6	2.8 ± 1.9	3.3 ± 2.4	4.3 ± 1.8
L3-L4	1.8 ± 1.4	2.1 ± 1.3	0.9 ± 0.8	2.4 ± 1.5	5.1 ± 2.8	3.2 ± 3.0
L4-L5	1.5 ± 1.1	1.7 ± 1.2	1.1 ± 0.9	4.1 ± 2.1	3.2 ± 2.6	3.4 ± 2.5
L5-S1	1.9 ± 1.4	2.1 ± 1.2	1.0 ± 1.8	3.1 ± 2.7	2.1 ± 1.7	4.6 ± 3.9
Left-right twisting						
L2-L3	2.1 ± 1.4	1.5 ± 1.2	1.1 ± 0.9	3.1 ± 2.5	3.4 ± 1.6	3.0 ± 1.5
L3-L4	1.0 ± 0.9	1.1 ± 0.9	0.9 ± 0.7	1.8 ± 1.2	1.2 ± 1.1	4.2 ± 2.5
L4-L5	2.6 ± 1.7	2.2 ± 2.2	0.7 ± 0.4	3.0 ± 4.5	3.2 ± 2.2	2.8 ± 2.1
L5-S1	2.1 ± 2.2	2.7 ± 0.9	1.1 ± 0.8	3.3 ± 2.9	2.9 ± 1.3	2.4 ± 1.5

* The values are given as the mean and the standard deviation. Shaded cells represent the primary rotations.

with ascending vertebral level in flexion, a decreasing range of motion pattern in left-to-right bending, and a flat pattern in left-to-right bending. However, the degenerative disc disease group in the present study had a pattern of peak motion at L3-L4 and diminished motion at L5-S1 independent of the activity.

Discussion

Although there are many contributions to low back pain related to degenerative disc disease, mechanical dysfunction is integral to its occurrence⁷. Bakker et al.²⁹ found that certain work-related tasks, including repetitive bending and twisting, were associated with low back pain. Stokes and Iatridis⁸ concluded that abnormal loading can produce adaptations resulting in symptomatic degenerative disc disease. In the present study, we characterized mechanical dysfunction among patients with confirmed discogenic low back pain, relative to asymptomatic controls without degenerative disc disease, by quantifying abnormal motion. The data revealed interesting findings at levels that were responsible for low back pain. During all movements, L5-S1 had the least flexion and had significantly less motion than L3-L4. Given that L5-S1 was the level at which all patients had degenerative disc disease, this finding suggests that, with severe degenerative disc disease requiring surgery, segmental hypomobility ensues. Degenerative disc disease at L4-L5 resulted in a relatively increased range of motion in flexion-extension, demonstrating that hypermobility in the sagittal plane develops at this level when it is adjacent to an affected L5-S1 level, despite similar degenerative disc disease grades. It should be noted that there is considerable intersubject variance in terms of range of motion, despite consistent trends across lumbar levels; i.e.,

cephalad levels have greater range of motion in the sagittal plane with respect to caudad levels, whereas caudad levels are more mobile in the axial and coronal planes²² because of facet orientation³⁰⁻³².

There have been several in vitro attempts to quantify mechanical dysfunction in patients with low back pain^{18,33-35}. In a cadaveric study, Fujiwara et al.¹⁰ noted that segmental motion initially increased with degeneration but then decreased in extreme degeneration. Wilke et al.¹² found that segmental stability increased in flexion-extension and lateral bending but decreased in axial rotation with increasing degenerative disc disease grades. In the present study, degenerative disc disease increased the range of motion in flexion-extension, with similar rotations in left-to-right bending and twisting. Comparison between studies is difficult given differences in testing conditions. In vivo attempts to study degenerative disc disease kinematics are scarce, with most having been performed in patients with nonspecific low back pain^{13,14,36-38}. Studies correlating degenerative disc disease with abnormal movement have focused on motion in limited planes and under nonphysiological conditions and have included patients solely on the basis of radiographic findings. Digital fluoroscopic video has been commonly used because it captures dynamic motion, despite low resolution, slow frame rates, and inaccuracy^{16,39-45}. Teyhen et al.¹³ validated a technique with higher resolution and distortion-compensated analysis to study segmental angular and linear displacement in patients with low back pain and in healthy individuals during flexion-extension. Although linear hypomobility was seen, it is difficult to compare these findings with ours given the different subject populations. The study by Teyhen et al.¹³ included patients with a history of low back pain,

representing a diverse population. Our findings are specific to patients with discogenic low back pain who were awaiting arthrodesis. Karadimas et al.³⁶ used positional magnetic resonance imaging to study segmental changes in patients with low back pain while the patients moved from supine to standing positions. The authors documented that, in patients with degenerative disc disease, anterior and middle disc heights changed significantly between positions, similar to our observation of increased flexion-extension in segments with degenerative disc disease³⁶. The major limitation of that study was the inclusion of patients on the basis of low back pain and the retrospective analysis of normal versus abnormal-appearing discs without correlating symptoms. Data were determined in several degrees of freedom but with the exclusion of complex movements such as bending, and actual movements were not quantified. Furthermore, the majority of healthy discs that were studied were located at cephalad lumbar levels, in contrast to degenerative levels, which were caudad.

Degenerative changes in the lumbar spine have been related to future changes at adjacent levels¹. Waris et al.² demonstrated that early degenerative disc disease predicted further development of symptomatic degenerative disc disease. Biomechanical changes have also been noted at adjacent levels. Ruberté et al.⁹ modified a finite element model to simulate L4-L5 degeneration and found that the superior adjacent level had increased rotation in lateral bending, axial rotation, and flexion-extension⁹. We also observed that the greatest ranges were at the superior adjacent level (L3-L4) during all movements. In addition, range of motion during left-to-right bending at L3-L4 was smaller among controls, and degenerative disc disease significantly increased motion at L3-L4 in axial rotation. We included patients with minimal degenerative disc disease at L3-L4. This is important because mild degenerative disc disease has been associated with increased segmental motion^{10,11}. These findings suggest that degenerative disc disease itself causes the superior adjacent level to develop segmental hypermobility. Adjacent-segment degeneration also has been reported following arthrodesis^{3,4}. While changes in mechanical loading have been assumed in the progression of adjacent-level degenerative disc disease, our study indicates that the adjacent L3-L4 level had increased range of motion and that kinematic changes occurred at the adjacent L3-L4 level prior to arthrodesis. It is unclear how this hypermobility is

related to long-term degeneration. Increased range of motion theoretically can lead to intervertebral disc deformation and overloading. Future studies can use finite element models to calculate stress distributions in adjacent discs and compare them with asymptomatic spines to evaluate the effect of degenerative disc disease on the adjacent-disc loading environment. This information will be instrumental for understanding the mechanisms of adjacent-segment degeneration and its prevention.

The present study used an in vivo technique to quantify abnormal motion in patients with confirmed discogenic low back pain prior to arthrodesis. A limitation of the present study was that the images were obtained at the end points of motion, which did not allow us to characterize midrange abnormalities^{46,47}. We did not examine instantaneous positions dynamically. Although no restriction was applied to subjects, they were instructed to limit flexion in order to keep the spine within view of the fluoroscopes. Comparative control data were not available at L5-S1. Because of the sample size, we were unable to investigate the effects of different degenerative disc disease grades. Despite these limitations, the present study represents the best information to date on aberrant vertebral motion in this population. Although degenerative disc disease affects segments in a complicated way, range of motion in the cephalad adjacent level was increased. Our findings represent the first reported data specific to this population that can be used to study the effects of arthrodesis and to further define the mechanical component of adjacent intervertebral disc degeneration. ■

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