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The Kinematics and Spondylosis of the Lumbar Spine Vary Depending on the Levels of Motion Segments in Individuals with Low Back Pain

Bryce A. Basques, M.D.¹, Alejandro A. Espinoza Orías, Ph.D.¹, Grant D. Shifflett, M.D.¹, Michael P. Fice, B.S.¹, Gunnar B. Andersson, M.D., Ph.D.¹, Howard S. An, M.D.¹, and Nozomu Inoue, M.D., Ph.D.¹

¹Department of Orthopedic Surgery, Rush University Medical Center, 1611 W. Harrison St., Suite 201, Chicago, IL 60612

Abstract

Study Design—Prospective cohort study.

Objective—To identify associations of spondylotic and kinematic changes with low back pain (LBP).

Summary of Background Data—The ability to characterize and differentiate the biomechanics of both the symptomatic and asymptomatic lumbar spine is crucial to alleviate the sparse literature on the association of lumbar spine biomechanics and LBP.

Methods—Lumbar dynamic plain radiographs (flexion-extension), dynamic CT scanning (axial rotation, disc height) and MRI (disc and facet degeneration grades) were obtained for each subject. These parameters were compared between symptomatic and control groups using Student's *t*-test and multivariate logistic regression, which controlled for patient age and sex and identified spinal parameters that were independently associated with symptomatic LBP. Disc grade and mean segmental motion by level were tested by one-way ANOVA.

Results—Ninety-nine volunteers (64 asymptomatic/35 LBP) were prospectively recruited. Mean age was 37.3±10.1 y.o. and 55% were male. LBP showed association with increased L5/S1 translation (odds ratio [OR] 1.63 per mm, *p*=0.005), decreased flexion-extension motion at L1/L2 (OR 0.87 per degree, *p*=0.036), L2/L3 (OR 0.88 per degree, *p*=0.036), and L4/L5 (OR 0.87 per degree, *p*=0.020), increased axial rotation at L4/L5 (OR 2.11 per degree, *p*=0.032), decreased disc height at L3/L4 (OR 0.52 per mm, *p*=0.008) and L4/L5 (OR 0.37 per mm, *p*<0.001), increased disc grade at all levels (ORs 2.01–12.33 per grade, *p*=0.001–0.026), and increased facet grade at L4/L5 (OR 4.99 per grade, *p*=0.001) and L5/S1 (OR 3.52 per grade, *p*=0.004). Significant associations were found between disc grade and kinematic parameters (flexion-extension motion, axial rotation, and translation) at L4/L5 (*p*=0.001) and L5/S1 (*p*<0.001), but not at other levels (*p*>0.05).

Corresponding author: Nozomu Inoue, MD, PhD, Department of Orthopedic Surgery, Rush University Medical Center, 1611 W. Harrison St, Suite 201, Chicago, IL 60612, Tel: (312)-942-8151, Fax: (312) 942-2040, Nozomu_Inoue@rush.edu.

Level of Evidence: N/A

Conclusions—In symptomatic individuals, L4/L5 and L5/S1 levels were affected by spondylosis and kinematic changes. This study clarifies the relationships between kinematic alterations and LBP, mostly observed at the above-mentioned segments.

Keywords

Low Back Pain; Spinal Instability; Flexion-extension; Axial Rotation; Disc Degeneration; Spine Degeneration; Aging; Spondylosis; Spine Kinematics; CT 3D-Models

INTRODUCTION

Low back pain (LBP) is one of the major reasons for seeking medical care^{1–6} and it is estimated that over 80% of the population will experience LBP within their lifetime.⁷ Due to its prevalence, treatment and care for LBP is estimated to cost around \$50 billion dollars per year in the United States alone.^{8,9} Non-radicular back pain (LBP) is more common and less well understood than radicular pain, i.e., sciatica.¹⁰ Lumbar disc disease is cited as the most common etiology of persistent back pain and sciatica; however, many individuals with apparent disc disease on magnetic resonance (MR) images are asymptomatic. Segmental instability of the lumbar spine is another common cause of LBP but the anatomic changes in the intervertebral disc, vertebral body, and facet joints associated with instability are not clearly known. Because of these unknown variables, results of treatment are often unpredictable and the efficacy of different treatment modalities is difficult to assess. Exploring biomechanical characteristics of the symptomatic lumbar spine is necessary in order to better target and evaluate treatments for LBP.

While previous studies have found associations between LBP and biomechanical properties of the lumbar spine, including facet angle, intervertebral disc degeneration and axial rotation, the available literature is generally limited by inaccurate measurement of segmental motion *in vivo*, small sample sizes, and lack of appropriate control subjects matched by age and gender.^{11–16} Further, there are conflicting reports regarding certain spinal characteristics, such as facet angle,^{13,17,18} facet joint space area,^{12,19,20} and axial rotational movement.^{21–23}

In order to address the current limitations in the literature, the present study aims to use a large, prospective cohort of asymptomatic controls and patients with LBP to identify biomechanical characteristics associated with the development of LBP. This information will be useful in the diagnosis and treatment of lumbar spine pathology.

MATERIALS AND METHODS

Patient Selection

The local Institutional Review Board approved this study and all enrolled subjects provided informed consent. Both asymptomatic individuals and patients with LBP were recruited, aged 20 to 60 years. The inclusion criteria for patients with LBP includes recurrent pain in the low back with at least two episodes of at least 6 weeks brought on by modest physical exertion. Exclusions include prior surgery for back pain, contraindications to MR, severe osteoporosis, or severe disc collapse at multiple levels. Other exclusion criteria include

evidence of severe central or spinal stenosis, destructive process involving the spine, litigation or compensation proceedings, extreme obesity (body mass index greater than or equal to 40 kilograms per meter squared), congenital spine defect, previous spinal injury, or claustrophobia.

For asymptomatic individuals, exclusion criteria included current low back pain, previous spinal surgery, history of LBP, obesity, claustrophobia or other contraindications to MR and computed tomography (CT) imaging such as presence of a pacemaker, metallic implants, etc.

A power analysis was performed *a priori* and found that 64 subjects would be required to have 80% power to detect differences between means greater than 1.5 times the average of the standard deviations of the two populations.

qCT-based Bone Mineral Density Analysis

The CT data was employed determined a true volumetric measurement of the bone mineral density (BMD, g/cm³) at the L3 level^{24,25} using a quantitative-CT (qCT) routine implemented in the Mimics medical image post-processing environment (Mimics, Materialise Corp., Leuven, Belgium).

Imaging

For each subject, lumbar dynamic flexion/extension plain radiographs were obtained in the lateral decubitus position. Next, MR imaging was obtained for each subject. A 1.5-T MR unit (Signa, GE Medical Systems) was used to obtain 3.0 mm thick axial (proton density) and sagittal (T2-weighted) images. T2 weighted sagittal MR images were used to evaluate the disc degeneration in five grades (grade 1: normal – grade 5: advanced degeneration) using Pfirrmann's grading scheme.²⁶ Proton density axial images were used to assess the degenerative changes of the facet joints (facet grade) in terms of cartilage degeneration, subchondral sclerosis, and osteophyte formation according to the classification suggested by Fujiwara *et al.*²⁷

Intervertebral translation and flexion-extension angular range of motion were measured using the planar X-ray films. Each subject underwent dynamic flexion-extension radiographic examination. Flexion-extension radiographs were taken in the lateral decubitus position to eliminate the effect of gravity and elicit less pain during the examination. Each subject was instructed to make and maintain a full flexion (or extension) as much as the subject was able to while the radiographs were taken. The flexion-extension radiographs were scanned and stored in digitized form. Segmental rotatory and translational motions were measured using a custom software program.²⁸ In order to obtain precise and well-contrasted images, a Region of Interest (ROI) was set at each intervertebral level interactively on the computer screen and enlarged 400% using a bilinear-interpolation, size-conversion algorithm.²⁹ The most anterior and posterior margins of the vertebral endplates were digitized interactively on the computer screen to calculate flexion/extension motion and antero-posterior translation. The antero-posterior width of the L3 at the mid-vertebral body was also measured and calibrated by the width measured by the 3D CT model at the same location in order to calculate the absolute antero-posterior translation in millimeters.

Dynamic CT imaging was subsequently obtained for each subject (Volume Zoom, Siemens, Malvern, PA, tube voltage: 120 kV, tube current: 100 mAs, field of view: approximately 200 mm, image matrix: 512×512, slice increment: 1.0 mm, slice thickness: 1.0 mm). The subjects were placed in a body restraint and loading apparatus in the supine position in the gantry of the CT scanner. The subject's torso, pelvis, and thighs were held using custom made hip and chest restraints, allowing lumbar spine movements while preventing hip and sacroiliac joint rotation.³⁰ The lumbar spine was axially rotated externally and passively by spinning the chest using a specially designed apparatus. The subjects were told to limit voluntary muscle activity during testing. CT images of the twisted lumbar spine were obtained at a maximum rotation angle of 50° to the left and right.^{30,31} The CT data were post-processed (Mimics, Materialise Corp., Leuven, Belgium) to obtain point cloud 3D models of the lumbar spine (L1-S1) that were subsequently used to determine the axial rotation angular range of motion and the corresponding intervertebral disc height distribution.^{30,31}

The measurement method of the axial rotation was fully described previously elsewhere^{30,31} and will be described briefly here. The axial rotations were measured using the 3D CT models by a validated custom made 3D-3D registration algorithm (the volume merge method). In the volume merge method, a vertebral body in the neutral position (the moving vertebra) was virtually rotated and translated toward the same body in a rotated position (the stationary target). The rotations were performed in a sequence of axial rotation, lateral bending and flexion/extension about fixed axes determined by CT coordinates. These rotations and translations of the vertebral body were conducted in 0.1° and 0.1 mm increments, respectively, until the moving vertebra merged with the stationary target in the rotated position. An isotropic voxel with a dimension of 1.0 mm was created for each point of the stationary target. The number of these voxels with the points of the moving vertebra was normalized by the number of the entire voxels, and used as the degree of volume merging. The degree of volume merging was maximized in real-time through rotation or translation of the moving vertebra. The accuracy of the volume-merge method is reported 0.1 mm in translation and 0.2° in rotation.³⁰ Segmental rotations for each motion segment were calculated by Euler angles with a sequence of axial rotation, lateral bending and flexion/extension and the axial rotation angular range of motion was determined by the axial rotational angle.³²

Statistical Analysis

Statistical analyses were conducted using Stata® version 13.1 (StataCorp, LP, College Station, Texas, USA). All tests were two-tailed and statistical significance was established at a two-sided α level of 0.05 ($p < 0.05$).

Spinal parameters were compared between asymptomatic volunteers and patients with symptomatic LBP using Student's *t*-test and multivariate logistic regression. Multivariate regression controlled for patient age and sex and identified spinal parameters that were independently associated with symptomatic LBP. For parameters significant on multivariate analysis, the predicted probability of LBP was calculated and plotted for each unit increase in the corresponding variable. In addition, to explore associations between spondylotic

changes and kinematic changes, the association between disc grade and mean segmental motion by level were plotted and tested by analysis of variance (ANOVA). One-way ANOVA was used to perform comparisons of disc grade (independent variable) and individual kinematic parameters (dependent variables) at each motion segment level, while multivariate ANOVA was used to test the association of disc grade and all three kinematic parameters concurrently at each motion segment level. F tests were performed and p-values from these tests were reported. For analysis, age was binned into a categorical variable as is common when including age in a multivariate analysis.³³

RESULTS

A total of 99 volunteers (64 asymptomatic individuals and 35 patients with LBP patients) were recruited for this study. Mean age was 37.3 ± 10.1 years old and 55.6% were male. Differences between individuals with and without LBP are reported in Table 1. Patients with LBP were generally older ($p=0.036$), however groups did not differ by sex ($p=0.814$). As expected, a decrease in BMD was verified by age; however both asymptomatic/symptomatic and gender comparisons did not show significant differences (Table 1).

Symptomatic and asymptomatic patients were subsequently compared in terms of intervertebral translation, flexion-extension angular range of motion, axial range of motion, disc height, disc grade, and facet grade using Student's *t*-test. Multivariate logistic regression was next used to compare cohorts while controlling for patient age and sex. The results of these analyses are reported in Table 2. In this table, the odds ratios represent the odds of LBP given a one-unit increase in the specified measurement.

Low back pain was found to be associated with increased L5/S1 translation (odds ratio [OR] 1.63 per mm, $p=0.005$), decreased flexion/extension motion at L1/L2 (OR 0.87 per degree, $p=0.036$), L2/L3 (OR 0.88 per degree, $p=0.036$), and L4/L5 (OR 0.87 per degree, $p=0.020$), increased axial rotation at L4/L5 (OR 2.11 per degree, $p=0.032$), decreased disc height at L3/L4 (OR 0.52 per mm, $p=0.008$) and L4/L5 (OR 0.37 per mm, $p<0.001$), increased disc grade at all levels (ORs 2.01–12.33 per grade, $p=0.001$ – 0.026), and increased facet grade at L4/L5 (OR 4.99 per grade, $p=0.001$) and L5/S1 (OR 3.52 per grade, $p=0.004$). Figure 1 shows the average segmental motion at each disc grade for all levels (A), and for each level individually (B-F). ANOVA found significant association between disc grade and kinematic parameters (flexion/extension motion, axial rotation, and translation) at L4/L5 ($p=0.001$) and L5/S1 ($p<0.001$), but not at other levels ($p>0.05$).

Using one-way ANOVA to perform comparisons of disc grade and individual kinematic parameters at each motion segment level, several additional associations were found (Table 3). At L2/L3, disc grade was associated with flexion-extension motion ($p=0.019$). At L3/L4, disc grade was associated with axial rotation ($p=0.040$). At L4/L5, disc grade was associated with flexion-extension motion ($p=0.003$) and axial rotation ($p=0.002$). Similarly, at L5/S1, disc grade was also associated with flexion-extension motion ($p=0.019$) and axial rotation ($p=0.003$).

DISCUSSION

Low back pain is a challenging condition which incurs large costs on the healthcare system, yet the specific pathomechanics associated with LBP remains poorly understood.^{1–4,7–9,34} In order to inform the treatment and prevention of LBP, the present study aimed to identify biomechanical characteristics associated with LBP in a large, prospective cohort of asymptomatic controls and patients with LBP. This study found that low back pain was associated with increased L5/S1 translation, decreased flexion/extension angle at L1/L2, L2/L3, and L4/L5, increased axial rotation at L4/L5, decreased disc height at L3/L4 and L4/L5, increased disc grade at all levels, and increased facet grade at L4/L5 and L5/S1.

In terms of kinematics, it is notable that symptomatic patients demonstrated increased axial rotation at L4/L5 ($p=0.036$), decreased flexion-extension angular motion at L1/L2 ($p=0.004$), L2/L3 ($p=0.003$), and L4/L5 ($p<0.001$); as well as a trend in increased translational motion at L5/S1 ($p=0.057$) in our testing (Table 2). Distinct spinal motion abnormalities have been correlated with LBP,^{23,35–44} but the precise kinematics have not been fully elucidated. The finding of increased axial rotation and increased translation in the symptomatic patients corroborates prior investigators who correlated excessive lumbar motion with LBP.⁴⁰ However, other investigators have demonstrated decreased motion in patients with LBP which supports our finding of decreased angular motion in the symptomatic cohort.^{35,39}

Patients with LBP also had significantly different markers of spondylosis when compared to asymptomatic controls. The L4/5 motion segment had decreased disc height, increased disc grade, and increased facet grade. The L5/S1 segment had increased disc grade and increased facet grades. These results support the available literature which consistently links degenerative disc disease and disc height loss with LBP.^{45–47} Considerable debate, however, surrounds the association of facet joint degeneration and back pain.^{48–50} There are very few high quality studies investigating this link and many do not take advantage of advanced imaging modalities such as CT in their assessment of facet joint arthrosis which limits the assessment. In our investigation, we used CT, MRI and subject-specific 3D models to assess the facet joints between patients with and without back pain and noted a significant correlation between facet grade and back pain. Additionally, our findings showing that the lower lumbar segments are involved more commonly support the results from other reports in the literature about facet joints of the most caudal segments being the ones affected the most.^{27,49}

It is clear in the literature that degenerative changes in the lumbar spine are linked with abnormal kinematics, which echoes the findings of the current study. Kirkaldy-Willis proposed a theory of increasing instability with degenerative changes up to a point where advanced degenerative changes cause restabilization.⁵¹ More recently, Kong *et al.* performed a kinematic analysis and demonstrated increasing degrees of translational motion and decreasing angular motion with advancing degenerative changes in the lumbar spine.⁵² In our study, significant spondylotic changes at L4/L5 and L5/S1 were associated with differences in observed motion characteristics. Interestingly, Hayashi *et al.* have postulated that Modic changes^{53,54} may confer unique changes on the stability of the spine

independently of other degenerative changes.⁵⁵ We did not specifically evaluate Modic changes in our investigation but perhaps this too could explain the differences we observed. Finally, at L5/S1, there may have been greater translational motion observed in the symptomatic cohort because this tends to be a more inherently stable segment and so any instability likely represents pathology and manifests as pain. Instability is thus a very sensitive marker of pain in this setting. Additionally, this motion may reflect increased stresses experienced at this level as motion segments above go through the process of degeneration.

A unique finding of this investigation was indeed the preferential involvement of the lower lumbar segments in terms of both pathokinematic and spondylotic changes. This is commonly observed clinically and well-documented.²⁷ The pathomechanics of this process are poorly understood but are likely related to the rather distinct mechanical scenario encountered at the lower lumbar levels which involves shear loads and altered axial load transmission. Clinical biomechanical investigations have demonstrated kinematic differences in lumbar motion depending on the level examined with greater disturbances seen in the lower levels.^{56,57} As previously discussed, facet joint arthritis was seen more commonly at the caudal spinal segments.^{27,49} This stress likely concentrates to an even greater degree at the L4/L5 segment. As explained by Fujiwara *et al.*, the L4/L5 segment is more commonly involved because of the relative hypermobility of this segment adjacent to a relatively stiff L5/S1 segment.²⁷ This would explain the multiple kinematic and spondylotic changes seen at this level in the present study.

Investigations into adjacent segment disease and post-lumbar fusion motion characteristics support this stress related theory (L3, L4, and L5).⁵⁸ Lao *et al.* used kinetic MRI to evaluate lumbar kinematics associated with degenerative disc disease and they found that with advancing disc degeneration the lumbar segments L2/L3 and L3/L4 had significant decreases in angular motion while L4/L5 retained its degree of mobility.^{59,60} These findings support the regional differences which we observed in our LBP cohort. The evolution of these regional differences in the pathomechanics of the lumbar spine likely reaches a threshold where the degree of degeneration and motion at the lower levels becomes symptomatic. Developing a quantitative marker for when this balance is tipped was not evaluated in this study, but warrants clinical investigation.

This study is not without limitations. The first limitation is that long-term outcome data is not available for this cohort of patients. In addition, while the *a priori* power analysis indicated that the sample size for this study was appropriate, additional patients would allow for sub-group analyses that would better characterize the effects of specific biomechanical parameters on LBP. As seen in Figure 1, for certain grades of disc degeneration at each level, there were larger standard error values. This was determined to be due to lower numbers of patients at with these grades of degeneration at different levels, rather than the presence of outliers.

The lumbar segmental motions were measured in the supine position without axial loading in the present study. Previous studies using kinematic MR scanning demonstrated the validity of lumbar kinematics under weight-bearing.^{52,61} These measurements of spinal

instability under physiological loading conditions may provide clearer relationships between lumbar instability and LBP.

The results of this study have significant implications for clinical practice and future research into LBP. Unlike radicular pain, it is often difficult to clinically localize non-radicular LBP to a specific pathologic level, particularly in patients with changes at multiple levels. The strength of the present study was the ability to use multivariate analysis to identify spondylotic and kinematic changes, stratified by level, that were independently associated with non-radicular LBP compared to asymptomatic controls. These spondylotic and kinematic changes represent potential targets for future research and treatments.

Research into identifying precise markers of degeneration and instability that would result in LBP is warranted. Future investigations could also focus on correlating kinematic changes in the lumbar spine of symptomatic patients to better identify the pathologic level and allow for guided treatments. Moreover, research and development of motion preservation devices should look into the different kinematics at different levels.

This study is the first of its kind to prospectively investigate the kinematic and spondylotic differences between symptomatic LBP patients and asymptomatic controls. We demonstrated significant differences in both parameters between symptomatic and asymptomatic cohorts. This study provides important insight on the differences between patients with and without LBP. Further investigations into the clinical correlations of these findings will hopefully aid clinicians in their ability to diagnose and treat patients with LBP.

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Figure 1.
Association of disc grade with mean segmental motion, by motion segment level.

Table 1

Characteristics of the patient sample.

Demographics				
	All Patients	Asymptomatic	Symptomatic	<i>P</i>
Overall	99 (100%)	64 (64.6%)	35 (35.4%)	
Age group				0.036
20–29 years	25 (25.3%)	20 (31.3%)	5 (14.3%)	
30–39 years	35 (35.4%)	20 (31.3%)	15 (42.9%)	
40–49 years	24 (24.2%)	18 (28.1%)	6 (17.1%)	
50–59 years	15 (15.2%)	6 (9.4%)	9 (25.7%)	
Male sex	55 (55.6%)	35 (54.7%)	20 (57.1%)	0.814
Volumetric Bone Mineral Density (g/cm ³) – Mean (SD)				
	All Patients	Asymptomatic	Symptomatic	<i>P</i> (Symptomatic Vs. Control)
Age group				
20–29 years	315.3 (49.1) *, **, ***;	308.6 (54.8)	335.6 (18.0)	.3599
30–39 years	281.2 (44.0) †, ††	287.0 (29.0)	275.8 (55.1)	.5547
40–49 years	275.1 (46.0) §	282.9 (51.2)	259.5 (30.9)	.2837
50–59 years	234.6 (49.6)	240.5 (58.0)	231.4 (47.8)	.7558
Gender				
Male	275.5 (42.3)	280.7 (43.5)	268.6 (40.9)	.3945
Female	280.6 (61.8)	291.8 (57.7)	265.9 (65.7)	.2096

Notes For the BMD data: 1) Symbols denote significant differences ($p < 0.05$) between the following pairs:

- * 20s vs. 30s;
- ** 20s vs. 40s;
- *** 20 vs. 50s;
- † 30s vs. 40s;
- †† 30s vs. 50s;
- § 40s vs. 50s.

2) No differences by gender.

Table 2

Differences between asymptomatic and symptomatic patients, by spinal measurement and level.

Measurement	Asymptomatic (mean)	Symptomatic (mean)	T-test	Multivariate logistic regression		
			p	Odds Ratio	p	
Translation (mm)						
L1/L2	1.03	1.18	0.979	1.10	0.559	
L2/L3	1.55	1.02	0.061	0.83	0.194	
L3/L4	1.20	1.80	0.181	1.30	0.112	
L4/L5	1.86	1.35	0.081	0.79	0.163	
L5/S1	0.81	1.60	0.057	1.63	0.005	
Flexion/Extension Motion (degrees)						
L1/L2	6.30	4.48	0.004	0.87	0.036	
L2/L3	8.51	5.41	0.003	0.88	0.036	
L3/L4	10.67	7.60	0.424	0.99	0.550	
L4/L5	12.09	9.20	<0.001	0.87	0.020	
L5/S1	9.35	8.01	0.297	0.99	0.668	
Axial rotation (degrees)						
L1/L2	1.97	2.21	0.544	1.05	0.670	
L2/L3	2.32	2.13	0.237	0.59	0.120	
L3/L4	1.82	2.10	0.075	1.88	0.063	
L4/L5	1.55	1.86	0.036	2.11	0.032	
L5/S1	1.86	1.44	0.082	0.78	0.379	
Disc height (mm)						
L1/L2	6.34	5.97	0.119	0.66	0.092	
L2/L3	7.56	7.02	0.017	0.55	0.028	
L3/L4	8.30	7.56	0.004	0.52	0.008	
L4/L5	8.51	6.91	<0.001	0.37	<0.001	
L5/S1	6.56	5.78	0.041	0.77	0.104	
Disc grade						
L1/L2	2.44	3.00	0.002	2.01	0.026	

Measurement	Asymptomatic (mean)	Symptomatic (mean)	T-test		Multivariate logistic regression	
			p		Odds Ratio	p
L2/L3	2.61	3.22	<0.001		3.91	0.002
L3/L4	2.58	3.42	<0.001		12.33	<0.001
L4/L5	2.82	3.71	<0.001		8.48	<0.001
L5/S1	3.26	3.85	<0.001		3.81	0.001
Facet grade						
L1/L2	0.40	0.52	0.313		1.78	0.241
L2/L3	0.47	0.52	0.722		0.78	0.615
L3/L4	0.55	0.52	0.804		0.60	0.307
L4/L5	0.60	1.19	<0.001		4.99	0.001
L5/S1	0.73	1.29	<0.001		3.52	0.004

Bolding indicates statistical significance (p < 0.05). Odds ratios represent odds of symptomatic back pain for each one-unit increase in each parameter.

Table 3

Results of analysis of variance for association of disc grade with translation, flexion/extension motion, and axial rotation, by motion segment level.

Level	Overall	Translation	Flexion-extension motion	Axial rotation
	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
L1/L2	0.144	0.856	0.688	0.025
L2/L3	0.158	0.955	0.019	0.193
L3/L4	0.397	0.810	0.839	0.040
L4/L5	<0.001	0.120	0.003	0.002
L5/S1	<0.001	0.897	0.019	0.003