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Lumbar Facet Joint Motion in Patients with Degenerative Disc Disease at Affected and Adjacent Levels:

An In Vivo Biomechanical Study

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Abstract

Study Design—Controlled laboratory study.

Objective—To evaluate the effect of lumbar degenerative disc diseases (DDD) on motion of the facet joints during functional weight-bearing activities.

Summary of Background Data—It has been suggested that DDD adversely affects the biomechanical behavior of the facet joints. Altered facet joint motion, in turn, has been thought to associate with various types of lumbar spine pathology including facet degeneration, neural impingement, and DDD progression. However, to date, no data have been reported on the motion patterns of the lumbar facet joint in DDD patients.

Methods—Ten symptomatic patients of DDD at L4–S1 were studied. Each participant underwent magnetic resonance images to obtain three-dimensional models of the lumbar vertebrae (L2–S1) and dual fluoroscopic imaging during three characteristic trunk motions: left-right torsion, left-right bending, and flexion-extension. *In vivo* positions of the vertebrae were reproduced by matching the three-dimensional models of the vertebrae to their outlines on the fluoroscopic images. The kinematics of the facet joints and the ranges of motion (ROMs) were compared with a group of healthy participants reported in a previous study.

Results—In facet joints of the DDD patients, there was no predominant axis of rotation and no difference in ROMs was found between the different levels. During left-right torsion, the ROMs were similar between the DDD patients and the healthy participants. During left-right bending, the rotation around mediolateral axis at L4–L5, in the DDD patients, was significantly larger than that of the healthy participants. During flexion-extension, the rotations around anteroposterior axis at L4–L5 and around craniocaudal axis at the adjacent level (L3–L4), in the DDD patients, were also significantly larger, whereas the rotation around mediolateral axis at both L2–L3 and L3–L4 levels in the DDD patients were significantly smaller than those of the healthy participants.

Conclusion—DDD alters the ROMs of the facet joints. The rotations can increase significantly not only at the DDD levels but also at their adjacent levels when compared to those of the healthy participants. The increase in rotations did not occur around the primary rotation axis of the torso motion but around the coupled axes. This hypermobility in coupled rotations might imply a biomechanical mechanism related to DDD.

Keywords

degenerative disc diseases; facet joint kinematics; *in vivo* spine biomechanics; lumbar spine; range of motion

The facet joint is one of the main structures that stabilize the lumbar spine. Facet joints are also believed to be the pain generators of approximately 15% to 37% of patients with low back pain (LBP).^{1,2} Previous studies showed that disc degeneration may precede facet joint osteoarthritis.^{3,4} Furthermore, with the onset of lumbar disc degeneration disease (DDD), it has been theorized that the increased loads on the facet joints because of decreasing disc height and altered mechanical properties in DDD affected levels result in alterations in facet degeneration and LBP.^{5,6} In addition, lumbar DDD has also been assumed to affect the biomechanical behavior of the facet joints of the adjacent segments.⁷

Numerous surgical techniques have been used to treat lumbar degenerative diseases with variable outcomes. These include fusion,⁸ disc arthroplasty,⁹ facet joints arthroplasty,¹⁰ and interspinous process devices.¹¹ An objective evaluation of the biomechanical functions of the facet joints of DDD patients is important for improving the surgical treatment efficiency. Therefore, it is necessary to determine the facet joints kinematics during functional activities. Few studies have used cadaveric specimens or animal models to examine the motion characteristics of the facet joints.^{12,13} Facet kinematics were also measured in living human participants using computed tomography¹⁴ and kinematic magnetic resonance imaging (MRI).^{15,16} However, a literature review reveals deficiency in the knowledge of lumbar facet joint motion in DDD patients. It is unclear how the lumbar DDD affects the mechanical properties of the facet joints in the diseased segments and in the segments adjacent to the degenerative levels.

Recently, we used a combined dual fluoroscopic imaging system and MRI technique to investigate the 6-degree-of-freedom (DOF) motion of the lumbar vertebrae and the facet joints of living asymptomatic human participants.^{17–19} These findings have provided baseline information for studying the kinematic changes that occur in pathologic lumbar spines such as with DDD. The purpose of this study was to evaluate the influences of DDD on the 6-DOF motions of the facet joints during functional weight-bearing activities. We studied a cohort of patients with clinically confirmed discogenic LBP at L4–L5 and L5–S1 and compared the results with those of an asymptomatic healthy group without degeneration at both the discs and facet joints.¹⁹ We hypothesized that the facet joints at the DDD levels and at the immediately adjacent levels would demonstrate distinct alterations in motion characteristics during active spinal motion *in vivo* when compared with those of the healthy participants.

MATERIALS AND METHODS

Patient Recruitment

Ten discogenic LBP patients with an age ranging from 40 to 60 years (7 men and 3 women; mean age = 51.8 ± 13.1 years; mean height = 169 ± 6.3 cm; mean weight = 65.7 ± 9.8 kg) were recruited in our study on DDD patient biomechanics. On the basis of clinical and radiographic assessments and further confirmation of discograms, all patients were

diagnosed with discogenic LBP originated from L4–S1. Degeneration of the discs was then graded using the Pfirrmann classification²⁰ (Table 1) and degeneration of the facet joints was graded using Weishaupt scales²¹ (Table 2). The participants were also evaluated for the absence of other spinal disorders and for operative history. Approval of the experimental design by the institutional review board and a written consent from each participant were obtained.

Three-Dimensional MRI-Based Model

MRI of the lumbar spine of each participant was obtained using a 3-T scanner (MAGNETOM Trio; Siemens, Erlangen, Germany) with a spine surface coil and a T2-weighted fat-suppressed three-dimensional spoiled gradient recall sequence.²² The parallel sagittal magnetic resonance images of the spinal segments were imported into a solid modeling software (Rhinoceros version 4.0; Robert McNeel & Associates, Seattle, WA) to construct three-dimensional anatomic vertebral models of L2, L3, L4, L5, and S1, using an established protocol¹⁷ (Figure 1A). Polygon mesh models of the vertebrae were created from the contour lines of the vertebrae (Figure 1B).

Dual Fluoroscopic Imaging

The lumbar spine was imaged using a dual fluoroscopic system^{17–19} (Figure 2). The participant was asked to stand and actively move the lumbar spine to different positions: standing position, maximum trunk flexion-extension, maximal left-right bending, and maximal left-right torsion. For each selected posture, the participant was asked to hold still for about 1 second while the two fluoroscopes took simultaneous images from two orthogonal directions. The postures were carefully monitored by an orthopedic surgeon to reduce variation. No constraint was applied to the hips of the participants while they performed active motions. However, the participants were asked to minimize their hip motions in order to maximize lumbar spine motion and to position the lumbar spine within the field of view of the two fluoroscopes.

Lumbar Facet Joint Motion

The *in vivo* positions of the vertebrae at various weight-bearing body positions were reproduced in the modeling software using the MRI-based three-dimensional models and the two orthogonal fluoroscopic images.¹⁷ The three-dimensional vertebral models were introduced into the virtual fluoroscopic system and viewed from the perspective views of the two virtual fluoroscopic cameras. The models of the vertebrae were then independently translated and rotated in 6 DOF until their outlines matched the osseous outlines captured on the two fluoroscopic images.¹⁷ Using this technique, the vertebral positions were reproduced at each studied posture. This system has been validated in its accuracy¹⁷ in determination of vertebral positions in space, where the accuracy was 0.3 mm in translation and 0.7° in orientation.

Right-hand cartesian coordinate systems were created to quantify the facet joint motions (Figure 3). The volumetric center of the facet capsule was selected as the origin of the coordinate systems at each vertebral level. The x-axis was perpendicular to the facet joint surface to represent the mediolateral direction. The z-axis was set in the plane parallel to the facet sliding surface and along the long axis of facet joint to represent craniocaudal direction of the facet joint motion and pointed in the cranial direction; and the y-axis was set in the sagittal plane perpendicular to the z–x plane to represent anteroposterior direction and pointed posteriorly. A set of two same coordinate systems were adopted for both the inferior facet of cranial vertebra and the superior facet of caudal vertebra at the standing position such that the standing position is used as a reference. After reproduction of the *in vivo* vertebral positions, the kinematics of the facet joints at different trunk positions was directly

measured from the coordinate system of the inferior facet joint with respect to that of the superior facet joint. Three translations were defined as the motions of the superior facet joint in the inferior facet joint coordinate system: mediolateral, anteroposterior, and craniocaudal translations. Three rotations were defined as the orientations of the superior facet joint around the origin of the inferior facet joint coordinate system using Euler angles in x–y–z sequence (in flexion, bending, and twisting sequence). The ranges of motion (ROMs) of the facet joints were then determined from the end ROMs of flexion-extension, left-right bending, and left-right torsion of the trunk.

Comparison with Healthy Participants

Eight asymptomatic participants with matched age, height, and weight (3 male and 5 female participants; mean age = 54.4 ± 3.5 years; mean height = 163.5 ± 5.8 cm; mean weight = 63.5 ± 11.1 kg) were recruited in a previous study.¹⁹ The participants were evaluated for the absence of LBP and other spinal disorders. The lumbar discs and the facet joints of the healthy participants were also graded with Pfirrmann classification²⁰ (Table 1) and Weishaupt scales²¹ (Table 2) for a quantitative comparison with those of the LBP patients.

Statistical Analysis

Within each group, a two-way repeated measures analysis of variance was used to compare the facet ROM at the L2–L3, L3–L4, L4–L5, and L5–S1 vertebral levels. The kinematics was the dependent variable and the vertebral level and activity were the independent variables. Level of statistical significance was set at $P < 0.05$. Another multiway analysis of variance was used to compare the kinematics between LBP patients and healthy participants. The participant group was the categorical factor and the level and the activity were the independent variables. When a statistically significant difference was detected, a *post hoc* Newman-Keuls test was performed and the level of significance was again chosen at $P < 0.05$. The statistical analysis was done using Statistica software (Statistica version 8.0; Statsoft, Tulsa, OK).

RESULTS

ROMs of Facet Joints in DDD Patients

Facet Motion During Left-Right Torsion of the Trunk—During left-right torsion of the trunk, the facet joint experienced coupled rotations and translations (Figures 4A and 5A). At the DDD levels (L4–L5 and L5–S1), the mean ranges of rotation around all three axes were from 2.6° to 3.6° . At the adjacent levels (L2–L3 and L3–L4), the mean ranges of rotation around all three axes were from 2.0° to 3.4° . There was no significant difference in the magnitude of rotations between different levels. The range of translations along anteroposterior (y-) axis was significantly greater in the caudal L5–S1 level than in the more cranial levels ($P = 0.036$). The mean ranges of translations along all three axes were from 1.5 to 2.7 mm at the DDD levels and 1.0 to 1.9 mm at the adjacent levels. Translations along craniocaudal (z-) axis were not significantly different between the studied levels.

Facet Motion During Left-Right Bending of the Trunk—During left-right bending of the trunk, there were also coupled rotations and translations found in all directions (Figures 4B and 5B). There was no predominant rotation and translation axis during this motion. At the DDD levels, the mean ranges of rotation around all three axes were from 2.6° to 3.6° , while they were between 2.3° and 3.3° at the adjacent levels L2–L3 and L3–L4. There was no significant difference in the magnitude of rotations between different levels. The mean translations along all three axes were between 1.4 and 2.0 mm at the DDD levels and between 1.0 and 2.0 mm at the adjacent levels. There was no significant difference between the studied levels in the ranges of translation.

Facet Motion During Flexion-Extension of the Trunk—During flexion-extension movements of the trunk, there was no predominant rotation and translation axis (Figures 4C and 5C). The mean ranges of rotation around all three axes were between 2.6° and 4.4° at the DDD levels and between 2.8° and 4.5° at the adjacent levels. There was no significant difference in the magnitude of rotations between different levels. The ranges of translation along all three axes were between 1.0 and 2.2 mm at the DDD levels and between 1.2 and 2.6 mm at the adjacent levels, which were not significantly different between the studied lumbar levels.

Comparison with Healthy Participants

Translations—The ranges of translation at L2–L3, L3–L4, and L4–L5 were compared between the DDD patients and the healthy participants. In the DDD patients, the ranges of translations were between 0.8 and 3.15 mm, while in the healthy participants, these were between 0.8 and 4.1 mm at all levels and in all activities. In general, there was no significant difference between the two participant groups.

Rotations During Left-Right Torsion of the Trunk—At the DDD level (L4–L5), the primary rotations around craniocaudal axis were not significantly different, although lower, than the healthy participants (Table 3). The coupled rotations of the DDD patients increased in general. Around the anteroposterior (y-) axis, the DDD patients had a range of rotation of $3.6^\circ \pm 2.5^\circ$ and the healthy participants had $1.7^\circ \pm 1.1^\circ$ ($P = 0.056$), whereas at the adjacent level L3–L4, no significant differences were observed between healthy participants and DDD patients. At the L2–L3 level, the rotation around mediolateral (x-) axis was significantly higher in the DDD patients (healthy = $0.6^\circ \pm 0.3^\circ$ vs. DDD = $2.0^\circ \pm 1.7^\circ$; $P < 0.05$).

Rotations During Left-Right Bending of the Trunk—At the DDD level (L4–L5), the primary rotations around anteroposterior axis were not significantly different, although lower, than the healthy participants (Table 3). The coupled rotations of the DDD patients increased in general. Around the mediolateral (x-) axis, the DDD patients had a range of rotation of $4.3^\circ \pm 2.8^\circ$ and the healthy participants had $1.6^\circ \pm 1.0^\circ$ ($P = 0.014$), whereas at the adjacent levels L3–L4 and L2–L3, the ranges of rotation during left-right bending activity were similar between the two groups.

Rotations During Flexion-Extension of the Trunk—At the DDD level (L4–L5), the primary rotations around mediolateral axis were not significantly different than those of the healthy participants (Table 3). The coupled rotations of the DDD patients increased in general. Around the anteroposterior (y-) axis, the DDD patients had a range of rotation of $4.4^\circ \pm 1.6^\circ$ and the healthy participants had $2.9^\circ \pm 1.2^\circ$ ($P = 0.037$), whereas at the adjacent level L3–L4, the DDD patients showed significantly lower rotation around the primary mediolateral (x-) axis (DDD = $2.9^\circ \pm 2.0^\circ$ vs. healthy = $5.7^\circ \pm 1.7^\circ$; $P = 0.009$) but had an increased coupled rotation around the craniocaudal (z-) axis (DDD = $4.5^\circ \pm 2.9^\circ$ vs. healthy = $2.0^\circ \pm 1.8^\circ$; $P = 0.042$). At the L2–L3 level, the rotation around primary mediolateral (x-) axis was significantly lower in the DDD patients (healthy = $6.5^\circ \pm 1.7^\circ$ vs. DDD = $3.8^\circ \pm 3.1^\circ$; $P = 0.028$), whereas at the coupled rotations, the average values increased in DDD patients, but not significantly.

DISCUSSION

This study reports on the motion characteristics of the lumbar facet joints in DDD patients. Patients had DDD at L4–L5 and L5–S1 levels and were studied in different weight-bearing positions of the trunk. The ROMs of the facet joints were compared with those of the

healthy control group,¹⁹ determined during the same trunk postures. Our data indicated that disc degeneration alters the ROM of the facet joints at the affected level. During the left-right bending and flexion-extension activities, the range of rotation of facet joints increased significantly compared with those of healthy controls. Interestingly, the increases in rotations did not occur around the primary trunk rotation axis but in the coupled rotations. For example, the primary axis of facet joint motion during trunk flexion-extension is the mediolateral (transverse) axis.¹⁹ However, there was no increase in rotation about this axis at the DDD levels. Instead, the rotation around the anteroposterior axis was significantly increased. During left-right bending, the increases occurred around the mediolateral axis instead of the primary rotation around the anteroposterior axis. We also found that disc degeneration can lead to changes in motion of the facet joints at the adjacent segments during flexion-extension of the trunk. Increased ROM was found in the coupled rotations (around the craniocaudal axis) and not in the primary rotation around the mediolateral axis. These findings demonstrated that the superior adjacent levels can also develop facet joint hypermobility in DDD patients.

In the literature, capsular strain measurement of the facet joints has been conducted using cadaveric specimens. Ianuzzi *et al*²³ performed a cadaveric experiment and found that the strain of the facet joints increased in magnitude with increasing displacements of vertebrae during lumbar motion. Little *et al*²⁴ found increased strain of facet joint capsule at the levels adjacent to the fixation level during lumbar motion. Few studies have reported on the facet joint kinematics *in vivo*. Wood *et al*¹³ measured the facet excursions at the L2–L3 motion segment during various functional activities using a dog model. They found that during walking the average excursions between opposing facets were 3.4 ± 1.3 mm as the facet surfaces glided on a ventral-dorsal slope. The similar magnitudes of excursion were reported by Schendel *et al*²⁵ using a similar dog model. Although there are studies investigating vertebral motions in healthy human participants and DDD patients,¹⁴ there is no study reported on the effect of disc degeneration on facet joint kinematics.

In this study, we found that the motion patterns of the facet joints in DDD patients were not the same as those observed in the healthy participants.¹⁹ There was no predominant direction of rotation and translation during each movement of the trunk. The DDD level had similar range of primary rotations as with the healthy participants but significantly greater coupled rotations during all activities. In the adjacent levels, the primary rotations decreased with DDD while the coupled rotations increased.

Because the role of the facet joints in pathogenesis of LBP remains unclear, these data may have valuable clinical and scientific implications. The hypermobility of the facet joints in coupled rotations of the DDD patients may cause increased compressive stresses between the articulating surfaces and facilitate cartilage degeneration.^{5,6} Furthermore, the lumbar facet joint capsule is innervated with nociceptors and mechanoreceptors. The strain of the facet joint capsule is thought to play an important role in LBP.^{26,27} The hypermobility of the facet joints in 6 DOF which can hardly be detected using dynamic radiographs or even dynamic MRI, might cause an increase in the strain of the facet joint capsule contributing to LBP in DDD patients.

There are many techniques used to treat lumbar degenerative disease.^{8–11} All these techniques and instruments might influence the facet joint biomechanics. For example, Rousseau *et al*²⁸ reported that disc arthroplasty may cause changes in the facet forces. However, few surgical techniques or implant designs have considered the biomechanics of the facet joints. The data of this study demonstrated that disc degeneration alters the kinematics and ROM of the facet joints in both DDD-affected and adjacent levels.

Therefore, more attention should be paid to the lumbar facet joints when treating DDD patients.

There are several limitations to the current study. It is not a generic comparison of DDD patients and asymptomatic participants. The patients involved in the study were specifically selected with DDD at L4–L5 and L5–S1 levels, which only represented a portion of all DDD patients. It is possible that in groups with different degenerative patterns (*e.g.*, DDD at different levels), the result can be different. Future studies should include patients with DDD at other segments such as single-level DDD at L4–L5 or at L5–S1. The sample sizes in the two groups were relatively small. Before the study, statistical power calculations showed that with 8 and 10 participants in the groups, 80% power can be achieved to detect a difference of $2.5^\circ \pm 2^\circ$ (mean $\pm$ SD). However, statistical power varies with different mean and SD in each studied position, which might limit our ability to detect differences. Another limitation is that the participants were within a narrow age range. However, the age range in this study closely reflects the demographics of the population that had the highest occurrence of LBP due to DDD. Although the two groups of participants were recruited at different times (the normal participants were recruited in a previous study¹⁹), the activities studied with dual fluoroscopic imaging system were closely monitored by the same spine surgeon and performed in identical manner for all patients in both groups. Even though we have tried to standardize the movement, DDD patients may move more or less differently. We did not artificially alter the motion in order to capture the true *in vivo* biomechanics. In addition, we investigated only the end-point positions of each trunk posture. Continuous and dynamic motions of the trunk should be investigated in future studies. Finally, this was a kinematics study and the forces imposed on the facets were not considered. We do not know whether the forces generated under the DDD conditions were sufficient to cause degeneration and pain in the facets, especially when the spine is under weight-bearing position. A technique using kinematics data to predict forces in finite element analysis should be developed in future investigations. Despite these limitations, this study presented new data on aberrant motion characteristics in this patient population and may contribute to better understanding of physiologic and pathologic motions of the human lumbar facet joints and inspire future research.

In summary, the current study used a validated imaging and modeling technique to quantify abnormal motion characteristics of lumbar facet joints in DDD patients. While DDD was shown to increase the coupled motion of the facet joints in DDD levels, it also reduced the primary rotations and increased the coupled rotations at the adjacent levels. The data can be used to evaluate the effects of surgical treatments of DDD on facet joint motion. Furthermore, knowledge of motion patterns of the lumbar facet joints is important for improving treatments of DDD and management of facet joint arthropathy, especially those aiming at restoration of normal motion, such as dynamic stabilization techniques and total disc arthroplasty.

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References

1. Dreyfuss P, Halbrook B, Pauza K, et al. Efficacy and validity of radiofrequency neurotomy for chronic lumbar zygapophysial joint pain. *Spine (Phila Pa 1976)*. 2000; 25:1270–7. [PubMed: 10806505]

2. Schwarzer AC, Aprill CN, Derby R, et al. The false-positive rate of uncontrolled diagnostic blocks of the lumbar zygapophysial joints. *Pain*. 1994; 58:195–200. [PubMed: 7816487]
3. Fujiwara A, Tamai K, Yamato M, et al. The relationship between facet joint osteoarthritis and disc degeneration of the lumbar spine: an MRI study. *Eur Spine J*. 1999; 8:396–401. [PubMed: 10552323]
4. Oegema TR Jr, Bradford DS. The inter-relationship of facet joint osteoarthritis and degenerative disc disease. *Br J Rheumatol*. 1991; 30(suppl 1):16–20. [PubMed: 1991235]
5. Panjabi MM, Krag MH, Chung TQ. Effects of disc injury on mechanical behavior of the human spine. *Spine (Phila Pa 1976)*. 1984; 9:707–13. [PubMed: 6505841]
6. Dunlop RB, Adams MA, Hutton WC. Disc space narrowing and the lumbar facet joints. *J Bone Joint Surg Br*. 1984; 66:706–10. [PubMed: 6501365]
7. Ruberte LM, Natarajan RN, Andersson GB. Influence of single-level lumbar degenerative disc disease on the behavior of the adjacent segments—a finite element model study. *J Biomech*. 2009; 42:341–8. [PubMed: 19136113]
8. Cheh G, Bridwell KH, Lenke LG, et al. Adjacent segment disease following lumbar/thoracolumbar fusion with pedicle screw instrumentation: a minimum 5-year follow-up. *Spine (Phila Pa 1976)*. 2007; 32:2253–7. [PubMed: 17873819]
9. Schmidt H, Midderhoff S, Adkins K, et al. The effect of different design concepts in lumbar total disc arthroplasty on the range of motion, facet joint forces, and instantaneous center of rotation of a L4–5 segment. *Eur Spine J*. 2009; 18:1695–705. [PubMed: 19763638]
10. Zhu Q, Larson CR, Sjøvold SG, et al. Biomechanical evaluation of the total facet arthroplasty system: 3-dimensional kinematics. *Spine (Phila Pa 1976)*. 2007; 32:55–62. [PubMed: 17202893]
11. Siddiqui M, Karadimas E, Nicol M, et al. Influence of X Stop on neural foramina and spinal canal area in spinal stenosis. *Spine (Phila Pa 1976)*. 2006; 31:2958–62. [PubMed: 17139227]
12. Adams MA, Hutton WC. The mechanical function of the lumbar apophyseal joints. *Spine (Phila Pa 1976)*. 1983; 8:327–30. [PubMed: 6623200]
13. Wood KB, Schendel MJ, Pashman RS, et al. *In vivo* analysis of canine intervertebral and facet motion. *Spine (Phila Pa 1976)*. 1992; 17:1180–6. [PubMed: 1440007]
14. Ochia RS, Inoue N, Takatori R, et al. *In vivo* measurements of lumbar segmental motion during axial rotation in asymptomatic and chronic low back pain male subjects. *Spine (Phila Pa 1976)*. 2007; 32:1394–9. [PubMed: 17545906]
15. Kong MH, Morishita Y, He W, et al. Lumbar segmental mobility according to the grade of the disc, the facet joint, the muscle, and the ligament pathology by using kinetic magnetic resonance imaging. *Spine (Phila Pa 1976)*. 2009; 34:2537–44. [PubMed: 19841613]
16. Kulig K, Powers CM, Landel RF, et al. Segmental lumbar mobility in individuals with low back pain: *in vivo* assessment during manual and self-imposed motion using dynamic MRI. *BMC Musculoskelet Disord*. 2007; 8:8. [PubMed: 17261197]
17. Wang S, Passias P, Li G, et al. Measurement of vertebral kinematics using noninvasive image matching method-validation and application. *Spine (Phila Pa 1976)*. 2008; 33:E355–61. [PubMed: 18469683]
18. Li G, Wang S, Passias P, et al. Segmental *in vivo* vertebral motion during functional human lumbar spine activities. *Eur Spine J*. 2009; 18:1013–21. [PubMed: 19301040]
19. Kozanek M, Wang S, Passias PG, et al. Range of motion and orientation of the lumbar facet joints *in vivo*. *Spine (Phila Pa 1976)*. 2009; 34:E689–96. [PubMed: 19730201]
20. Pfirrmann CW, Metzendorf A, Zanetti M, et al. Magnetic resonance classification of lumbar intervertebral disc degeneration. *Spine (Phila Pa 1976)*. 2001; 26:1873–8. [PubMed: 11568697]
21. Weishaupt D, Schweitzer ME, Alam F, et al. MR imaging of inflammatory joint diseases of the foot and ankle. *Skeletal Radiol*. 1999; 28:663–9. [PubMed: 10653360]
22. Disler DG, Peters TL, Muscoreil SJ, et al. Fat-suppressed spoiled GRASS imaging of knee hyaline cartilage: technique optimization and comparison with conventional MR imaging. *AJR Am J Roentgenol*. 1994; 163:887–92. [PubMed: 8092029]
23. Ianuzzi A, Little JS, Chiu JB, et al. Human lumbar facet joint capsule strains: I. During physiological motions. *Spine J*. 2004; 4:141–52. [PubMed: 15016391]

24. Little JS, Iannuzzi A, Chiu JB, et al. Human lumbar facet joint capsule strains: II. Alteration of strains subsequent to anterior inter-body fixation. *Spine J.* 2004; 4:153–62. [PubMed: 15016392]
25. Schendel MJ, Dekutoski MB, Ogilvie JW, et al. Kinematics of the canine lumbar intervertebral joint. An *in vivo* study before and after adjacent instrumentation. *Spine (Phila Pa 1976).* 1995; 20:2555–64. [PubMed: 8610250]
26. Cavanaugh JM, Ozaktay AC, Yamashita HT, et al. Lumbar facet pain: biomechanics, neuroanatomy, and neurophysiology. *J Biomech.* 1996; 29:1117–29. [PubMed: 8872268]
27. Cohen SP, Raja SN. Pathogenesis, diagnosis, and treatment of lumbar zygapophysial (facet) joint pain. *Anesthesiology.* 2007; 106:591–614. [PubMed: 17325518]
28. Rousseau MA, Bradford DS, Bertagnoli R, et al. Disc arthroplasty design influences intervertebral kinematics and facet forces. *Spine J.* 2006; 6:258–66. [PubMed: 16651219]

Key Points

- DDD alters the ROMs of the facet joints.
- The rotational motion changes significantly not only at the degenerated levels but also at their adjacent levels.
- At the degenerated levels, the increased rotations did not occur around the primary axis of rotation but around the axes of coupled rotation.

Figure 1.

A, Digitized contours of lumbar vertebrae in sagittal plane. **B,** Three-dimensional anatomic vertebral model constructed from the magnetic resonance images.

Figure 2.

A, The experimental setup of the dual fluoroscopic system for capturing lumbar spine positions *in vivo* in human participants. **B,** Virtual reproduction of the dual fluoroscopic system and the vertebral positions.

Figure 3.
Anatomic coordinate system to measure kinematics of the facet joints.

Figure 4.

Ranges of facet joint translations of patients with degenerative disc disease along three principal axes under (A) torsion, (B) bending, and (C) flexion of the torso. The symbols (*, +, x) represent statistical significance on between-level comparison ($P < 0.05$).

Figure 5. Ranges of facet joint rotations in patients with degenerative disc disease around three principal axes under (A) torsion, (B) bending, and (C) flexion of the torso. There was no statistical difference between levels.

TABLE 1

Pfrrmann Classification of Disc Degeneration in Normal Participants and in DDD Patients

	L2–L3	L3–L4	L4–L5	L5–S1
Normal (n = 8)	1.1 (0.4)	1.6 (0.5)	1.9 (0.6)	2.1 (0.4)
Range of grade	1–2	1–3	1–3	2–3
DDD (n = 10)	1.4 (0.5)	1.6 (0.8)	4.2 (0.8)	4.5 (0.5)
Range of grade	1–2	1–3	3–5	4–5

The values were presented as mean (SD).

DDD indicates degenerative disc disease.

Weishaupt Classification of Lumbar Facet Joint in Normal Participants and in DDD Patients

TABLE 2

	L2-L3		L3-L4		L4-L5		L5-S1	
	Left	Right	Left	Right	Left	Right	Left	Right
Normal (n = 8)	0	0	0.1 (0.4)	0	0.1 (0.4)	0.1 (0.4)	0.3 (0.5)	0.4 (0.5)
Range of grade	0	0	0-1	0	0-1	0-1	0-1	0-1
DDD (n = 10)	0.8 (0.5)	0.8 (0.5)	0.8 (0.5)	0.8 (0.5)	2.5 (0.8)	2.4 (0.7)	2.3 (0.9)	2.3 (0.9)
Range of grade	0-1	0-1	0-1	0-1	1-3	1-3	1-3	1-3

The values were presented as mean (SD).
DDD indicates degenerative disc disease.

TABLE 3

Comparison of Rotation Ranges Between Normal Participants and DDD Patients

	L2-L3			L3-L4			L4-L5		
	ML	AP	CC	ML	AP	CC	ML	AP	CC
Left-right torsion									
Normal	0.6 (0.3)	3.3 (1.4)	1.9 (1.4)	1.3 (0.8)	2.2 (1.3)	2.7 (1.4)	1.4 (1.1)	1.7 (1.1)	4.4 (1.5)
DDD	2.0 (1.7) [‡]	2.4 (1.5)	3.4 (2.1)	2.0 (1.8)	2.8 (1.5)	3.0 (2.2)	2.6 (1.8)	3.6 (2.5)	3.0 (2.3)
<i>P</i>	0.032	0.221	0.090	0.265	0.455	0.743	0.100	0.056	0.122
Left-right bend									
Normal	1.9 (1.3)	2.7 (1.0)	2.5 (1.0)	1.3 (1.1)	3.8 (1.7)	2.9 (1.2)	1.6 (1.0)	4.7 (1.1)	2.9 (1.6)
DDD	2.3 (1.9)	3.3 (1.4)	2.4 (1.8)	2.3 (1.6)	3.3 (2.7)	2.3 (2.5)	4.3 (2.8) [*]	3.2 (3.0)	3.0 (2.1)
<i>P</i>	0.668	0.322	0.828	0.128	0.657	0.516	0.014	0.173	0.898
Flexion-extension									
Normal	6.5 (1.7)	2.0 (1.7)	1.9 (1.0)	5.7 (1.7)	1.9 (1.4)	2.0 (1.8)	2.4 (1.7)	2.9 (1.2)	3.5 (1.2)
DDD	3.8 (3.1) [*]	3.1 (2.5)	2.8 (1.4)	2.9 (2.0) [‡]	3.3 (2.7)	4.5 (2.9) [*]	2.7 (2.3)	4.4 (1.6) [*]	3.6 (2.3)
<i>P</i>	0.028	0.303	0.105	0.009	0.171	0.042	0.764	0.037	0.921

For each activity, the primary axis of rotation was shaded.

Rotation around axis: ML, AP, and CC.

The values were presented as mean (SD) in degrees.

^{*} < 0.05[‡] < 0.01

AP, indicates anteroposterior; CC, craniocaudal; DDD, degenerative disc disease; ML, mediolateral.