More than 65 million Americans suffer from low-back pain annually. By the age of 50 years, 85% of the population will show evidence of disc degeneration. Lumbar DDD, the most common cause of low-back pain, is characterized by one or more of the following: lumbar instability, osteophyte formation, decreased disc height, thickening of ligamentous tissue, disc degeneration or herniation, and facet joint degeneration. Actually, DDD is not a disease but rather a degenerative condition that can be painful and can greatly affect one’s quality of life.

Several surgical techniques have been developed to treat lumbar DDD. As far as we know, the operative treatment has evolved along 2 pathways: fusion and arthroplasty. In the past few years, disabling discogenic back pain resulting from a discectomy that remains refractory to conservative management has been successfully treated with spinal fusion. Lumbar fusion has many disadvantages, such as the iatrogenic “collateral damage” of different approaches, high complication rates, adverse side effects, and variable ability of bone to fuse or “heal.” Nowadays, lumbar TDR seems to have become a potential alternative to lumbar fusion. Its primary purpose is to restore basic motion of the intervertebral segment and to protect adjacent levels against nonphysiological loading. Theoretically, the goal of lumbar TDR—one lacking significant evidence of success—is the reduction or elimination of adjacent-level disease requiring surgical intervention as compared with fusion or arthrodesis.

Authors of previous investigations have reported increases in adjacent-level IDPs, intersegmental motion, and facet joint stresses after interbody restructions.

Biomechanical comparison of lumbar total disc arthroplasty, discectomy, and fusion: effect on adjacent-level disc pressure and facet joint force

Laboratory investigation

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Object. With the increasing advocacy for total disc replacement (TDR) as a potential alternative to fusion in the management of lumbar degenerative disc disease, intradiscal pressures (IDPs) and facet joint stresses at the adjacent levels of spine have generated considerable interest. The purpose of this study was to compare adjacent-level IDPs and facet joint stresses among TDR, discectomy, and fusion.

Methods. Ten fresh human cadaveric lumbar specimens (L2–S1) were subjected to an unconstrained load in axial torsion, lateral bending, flexion, and extension by using multidirectional flexibility test. Four surgical treatment modes—control (disc intact), discectomy, TDR, and fusion—were tested in sequential order at L4–5. During testing, the IDPs and facet forces following each treatment were calculated at the adjacent vertebral levels (L3–4 and L5–S1).

Results. Intradiscal pressures and facet force pressures were similar between the intact condition and the TDR reconstruction at the L3–4 and L5–S1 levels under all loading conditions (p > 0.05). Compared with the intact and TDR groups, the discectomy and fusion groups had higher IDPs at the L3–4 and L5–S1 levels under all loading conditions (p < 0.05). No significant difference in the facet force pressure was noted among the intact, discectomy, and TDR groups at the L3–4 and L5–S1 levels under any loading conditions (p > 0.05). However, the facet force pressure produced for fusion was significantly higher than the mean values obtained for the intact, discectomy, and TDR groups at the L3–4 and L5–S1 levels under all loading conditions (p < 0.05).

Conclusions. Lumbar TDR maintained adjacent-level IDPs and facet force pressures near the values for intact spines, whereas adjacent-level IDPs tended to increase after discectomy or fusion and facet forces tended to increase after fusion. (DOI: 10.3171/2011.6.SPINE11250)

Key Words • arthroplasty • biomechanical test • lumbar spine • facet joint force • intradiscal pressure

Abbreviations used in this paper: DDD = degenerative disc disease; df = degrees of freedom; IDP = intradiscal pressure; PMMA = polymethylmethacrylate; ROM = range of motion; TDR = total disc replacement.

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with anterior or posterior fixation in the lumbar spine regions.\textsuperscript{13,16,28} Although lumbar arthroplasty is gaining in popularity, limited data highlighting changes in adjacent-level mechanics after surgery are available. Furthermore, reports on changes in IDPs and facet joint stresses after lumbar arthroplasty are scarce, as is any comparison of data between a discectomy and fusion model. The primary objective of the current study was to compare adjacent-level IDPs and facet joint stresses of the lumbar spine left intact or subject to discectomy, fusion, or implantation of a movable artificial disc under different loading conditions.

**Methods**

**Specimen Preparation**

Ten fresh-frozen human cadaveric lumbosacral spines—8 from males and 2 from females, with an average age ranging from 36 to 55 years at the time of death—were used in this study. Obtained from the Department of Anatomy at Central South University, the spine specimens were harvested and immediately packaged in double-thickness plastic bags and stored at $-20^\circ$C. Prior to potting, the thawed specimens were carefully denuded of paravertebral musculature, and the facet joint surfaces of the L-5 and S-1 vertebrae were exposed, avoiding disruption of the spinal ligaments, joints, and discs. All specimens were then sectioned, and the remaining lumbosacral segments (L2–S1) were thoroughly cleaned of all residual tissue. Ten hours before testing time, the spines were removed from the freezer and allowed to thaw to room temperature. Before biomechanical testing, all specimens were visualized on radiographs in the anteroposterior and lateral planes to ensure the absence of fractures, deformities, and any metastatic disease and to verify interssegmental motion. The specimens that were potted using polyurethane resin in a similar manner were discussed in further detail in previous studies.\textsuperscript{5}

Each lumbosacral L2–S1 specimen was fixed by drilling and inserting screws in the most superior and most inferior segments. The end segments and screws were capped with PMMA (COE tray plastic, GC America). The potting fixtures were used to attach the lumbosacral spines loaded onto a mechanical testing unit, and the cadavers were loaded in axial torsion, lateral bending, flexion, and extension planes. In the case of lateral bending, only right lateral bending was used for analysis, assuming similar behavior on the left due to spine symmetry with midline anterior and posterior implants.

Pressure transducers (Millar Instruments) configured with a measurements group signal conditioner (system 2100, Vishay Micro-Measurements) were used in this investigation. Pressure sensors were inserted and secured in the intervertebral disc spaces of L3–4 and L5–S1 to allow for IDP measurement at the distal adjacent levels. To protect the transducer from possible damage during testing, 4 transducers were used for 1 disc space (1 each for axial torsion, flexion, extension, and right lateral bending). Figure 1 shows the relative arrangement of the pressure transducers within the disc space. These positions were based on the approximate location of the instantaneous axis of rotation.\textsuperscript{29} Strain gauges (width 2.5 mm and height 0.3 mm) were also mounted on both left and right surfaces of the facet joints of L3–4 and L5–S1. As the force in the facet changes, the surface strain of the facet joint also changes, and thus, the force in the facet can be indirectly measured and compared with that in the intact spine. Pressure transducer signals and strain gauge signals were conditioned and amplified by a signal conditioner and recorded by the mechanical testing system.

**Biomechanical Testing**

Biomechanical analysis was performed using a WDW-1000 configured with a custom-built, 6-df spine simulator (Jinan Shijin Group Corp.) allowing unconstrained and nondestructive pure moments in axial torsion, lateral bending, flexion, and extension. Five load cycles were applied, and each loading condition was used for data analysis. In axial torsion, lateral bending, flexion, and extension, a torque of 2, 4, 6, 8, and 10 Nm was applied. To stabilize the viscoelastic effect, each mode of testing was performed 3 times, and only the results of the third test were used. All biomechanical tests were performed in the following sequence: intact condition, discectomy, TDR (Fig. 2), and fusion.

**Surgical Technique**

Discectomy, artificial disc replacement, and fusion procedures were performed by an orthopedist. After analysis of an intact specimen, a traditional discectomy (removing the nucleus pulposus) was performed at L4–5, and biomechanical testing was completed at L3–4 and L5–S1. The surgical procedure then performed was the same in all specimens using the Charité artificial disc prosthesis (DePuy Spine, Inc.), which at the time of implantation was known as the SB Charité III (Waldemar Link). The disc prosthesis was implanted according to the manufacturer’s specifications. Implant sizes and lordotic angles for the TDR prostheses were selected according to the preoperative radiographic evaluation of the respective disc spaces. Each step was performed according to the recommended surgical technique, and C-arm fluoroscopy was used throughout the procedure to verify the correct position of the artificial disc. After another round of biomechanical testing, artificial discs were carefully removed, 3 Steinmann pins were implanted in conjunction with PMMA-based bone cement (Palacos R, Heraeus Kulzer) to create the lumbar fusion mode at the surgically treated level (Fig. 3), and final biomechanical testing was completed.

**Statistical Analysis**

For data management and statistical analysis, we used SPSS for Windows (version 13.0). When the populations from which the samples were obtained were normally or approximately normally distributed and the variances of the populations were equal, the Student t-test was applied to compare the means of 2 independent groups, and a 1-way ANOVA was used to compare the means of more...
than 2 independent groups. Comparisons between groups were made using the Mann-Whitney U-test (2 groups) or Kruskal-Wallis test (> 2 groups) when the variances were not equal among the groups. Data were expressed as the means ± SDs. A p value < 0.05 was considered statistically significant.

**Results**

**Intradiscal Pressures**

The posterior, center, anterior, and lateral IDPs at the L3–4 and L5–S1 levels are shown in Fig. 4. Intradiscal pressure data obtained at the L3–4 and L5–S1 intervertebral levels during multidirectional flexibility testing revealed a stepwise IDP increase with the applied load. In axial torsion, with the artificial disc at L4–5, the center IDP of L3–4 and L5–S1 was unchanged compared with the intact state under 2, 4, 6, 8, or 10 Nm of torque (p > 0.05). In contrast, discectomy or fusion produced significantly greater IDP values at these vertebral levels under 2, 4, 6, 8, or 10 Nm of torque (p < 0.05). Similar findings persisted on flexion, extension, and right lateral bending under all 5 loading conditions.

**Facet Joint Force**

The facet forces at the L3–4 and L5–S1 levels are presented in Fig. 5. A gradual increase in facet joint force at these vertebral levels was observed with a stepwise-increasing load. On flexion, no significant difference in the facet force pressure at the L3–4 and L5–S1 levels was noted among the intact, discectomy, and TDR groups under 2, 4, 6, 8, or 10 Nm of torque (p > 0.05). Fusion showed a significant increase in facet force pressure at the L3–4 and L5–S1 levels under all 5 loading conditions compared with the intact, discectomy, or disc replacement groups (p < 0.05). Furthermore, the facet force in axial torsion, extension, and right lateral bending under all 5 loading conditions were in line with changes in flexion.

**Discussion**

The intervertebral disc is made up of the nucleus pulposus, anulus fibrosus, and vertebral endplates, with the nucleus serving to minimize vertebral endplate stress concentration and the anulus acting as a restraining liga-
ment. Magnetic resonance imaging studies show dehydration of the nucleus pulposus in the majority of people over the age of 40 years. Such a change affects the behavior of the intervertebral disc and its response to loading by altering the hydrophilic and viscoelastic properties. The hydrostatic properties in the nucleus pulposus and the integrity of the annulus fibrosis together are necessary for normal attenuation and transmission of spinal loads during activity. A microinstability environment can be created, promoting increased discal strain under loading even from normal activity. Disc degeneration is a continuum that begins with biochemical changes progressing to significant morphological changes and instability. A progressive loss of 1–3 mm of disc space can result in overloading of the facet joints and a decrease in the foraminal cross-sectional area that may compromise the neural elements. It is known that degenerative lumbar discs alter load transmission as well as the loading of both the annulus fibrosus and the subchondral bone of the vertebral endplates. Effects of excessive force transmission and microinstability acting on the annulus fibrosus may be transmitted through the sinuvertebral nerves and potentially cause pain. Intradiscal pressure is related to the biomechanical integrity of the disc. An unloaded healthy spine demonstrates a baseline pressure or prestress level arising from the disc hygroscopic properties, the elastic ligamentous and muscular tensions that provide a resting compression. Wilke et al. revealed that normal IDP will vary as much as 40% from changes in position and posture alone. An abnormally elevated IDP has been speculated to play a major role in the development of DDD by the disruption of metabolic nutrient exchange pathways within the nucleus pulposus.

The current study was undertaken to compare adjacent-level IDP and facet joint stress changes among the intact, discectomy, fusion, or movable artificial disc implantation states. Many authors have investigated adjacent-level IDP changes after lumbar fusion. Moreover, a positive correlation has been observed between the number of instrumented levels and adverse adjacent-segment biomechanical changes in the lumbar spine, stability of the posterior spinal instrumentation, and its effects on adjacent motion segments in the lumbosacral spine. Recent developments in the technology of artificial disc replacements and systems preserving physiological motion at the operative segment should, in theory, reduce adjacent-level biomechanical changes, as compared with fusion. Our data indicated no differences in the adjacent-level biomechanical parameters evaluated between intact controls and the 1-level lumbar TDRs. In contrast, consistent increases in adjacent-level IDPs and facet joint stresses were recorded after spine fusion, relative to intact controls. Furthermore, discectomy caused an increase in IDPs but did not increase facet joint stresses at the adjacent level relative to normal segments. Our results were similar to those previously reported in the literature. Ingalhalikar et al. showed that the artificial disc either maintains or reduces adjacent-level motion and pressure, as compared with the intact spine. The addition of pedicle screws to the artificial disc construct leads to significantly increased motion at adjacent levels on flexion and significantly increased IDP on lateral bending. Dmitriev et al. reported that no significant adjacent-level biomechanical changes were seen between 2-level arthroplasty and intact control groups. In contrast, significant alterations in ROM and IDP were recorded both proximally and distally after circumferential arthrodesis. Chen et al. explored biomechanical differences at the surgical level and both adjacent levels following artificial disc replacement and interbody fusion procedures using a 3D finite-element model. They revealed that adjacent levels, ROM, and annulus stress in the artificial disc replacement model were similar to those in the intact model. The adjacent levels had an obviously high ROM, annulus stress, and facet contact pressure in bilateral posterior lumbar interbody fusion. Rousseau et al. measured the facet forces and instant axes of rotation for different spinal positions under simulated weight-bearing conditions before and after TDR at L5–S1 using semiconstrained (3 df, Prodisc) and unconstrained (5 df, Charité) articulated implants. They

Fig. 3. Lateral radiograph showing 1-level lumbar fusion. Three Steinmann pins were used in conjunction with PMMA-based bone cement to create the fusion mode. White arrow indicates pin placements.
found that the degree of constraint affects postimplantation kinematics and load transfer. Their results highlight the important role facets play in guiding movement and show that implant constraint influences facet/implant synergy.

This study has several limitations. First, as a cadaver study simulating weight-bearing loads on the lumbar spine, the data are reported in IDPs and facet joint stresses from an upright posture of the torso without the head. The additional mass of the head or any other lifted

Fig. 4. Bar graphs showing adjacent-level IDP data obtained at the L3–4 (A) and L5–S1 (B) intervertebral levels during multidirectional flexibility testing, which revealed a stepwise IDP increase with the applied load. *p < 0.05, compared with the intact condition or TDR condition.
load could reduce the efficiency of the unloading effect proportionate to the additional load on the spine. Second, this study does not consider the effects of trunk muscle action and can only reflect changes in passive loads transmitted through the spine. We recognize the important role played by muscle forces in spinal motions. If muscle activity were to increase, then it would reduce the efficiency of unloading by competitive compression of the disc. If muscle action is reduced, then efficiency may not be significantly influenced. Additionally, looking at muscle behavior in clinical settings should be a part of future work. Third, 3 Steinmann pins were used in conjunction with the intact, discectomy, or TDR condition.
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with PMMA-based bone cement to create a lumbar fusion mode at the surgically treated level in this study. In fact, there are many surgical approaches and methods available to fuse the spine, and they all involve the placement of a bone graft between vertebrae. The spine can be approached and the graft placed from the back (posterior approach), from the front (anterior approach), or through a combination of both approaches. It is very rare in the clinical setting for a surgeon to put only an anterior intervertebral spacer or bone for fusion without any posterior stabilization. Because of their long lever arms, pedicle screws can control motion and unload the disc as well as the respective facets at the same level. Thus, there were also many differences between the fusion procedure in clinical practice and the fusion model in this study. Meanwhile, PMMA has a Young modulus greater than that of natural bone. Thus, there were actually some differences between bone fusion in clinical practice and PMMA-interbody fusion in this study. This is exactly what we are planning to improve in future research. Finally, note that the results in this study may not be generalizable to all TDR implants and other motion-preserving technologies. Our findings are based on the SB III Link Charité artificial disc implants; a comparison between SB III Link Charité artificial discs and other artificial discs is also necessary. Differences among TDR implants with regard to kinematics, constraint, location of instantaneous axis of rotation, and radius of curvature will likely affect their long-term performance.

Conclusions

In summary, in the current study we showed that lumbar TDRs can maintain adjacent-level IDPs and facet force pressures near the values in intact spines; however, adjacent-level IDPs tend to increase after discectomy or fusion and facet force pressure tends to increase after fusion. This information should prove useful in the biomechanical and clinical evaluation of lumbar TDR and other motion-preserving technologies. Furthermore, data in the present study, a biomechanical laboratory experiment, must be corroborated by long-term results of a randomized clinical trial to confirm the safety and efficacy of the SB III Link Charité artificial discs in the treatment of lumbar DDD.

Disclosure

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