Degenerative disc disease associated with disc degeneration, spinal instability, and pain often entails surgical management with or without arthrodesis. Total disc replacement arthroplasty serves as a novel alternative in the treatment of disc pathology. Implantation of an artificial disc in place of fusion aims to restore motion to the spine, reestablish stability, and protect the neural elements while avoiding the

**Key Words** • artificial disc • displacement control • biomechanical study • arthroplasty

Abbreviations used in this paper: BMD = bone mineral density; IDP = intradiscal pressure; PS = pedicle screw; ROM = range of motion.
possible development of adjacent-level degenerative changes. Clinical studies with total disc replacement, abroad and in the US, have been encouraging and have shown improvement in symptoms, with no worse complication rates than with anterior fusion techniques.29,30,31,32

Despite many clinical studies, fewer biomechanical studies have been carried out that have investigated the effect of the lumbar artificial disc on adjacent-level motion. The authors of one biomechanical cadaveric study used a load-controlled setup to compare total disc replacement arthroplasty using the SB Charité disc (DePuy Spine) with conventional stabilization techniques and the intact spine. The authors found that the artificial disc restored motion to the operative level (L4–5) in flexion/extension and lateral bending, and increased motion in axial rotation. At the adjacent levels (L3–4 and L5–S1), the authors reported that the artificial disc restored motion to that comparable to the intact state, as opposed to the significantly increased motion observed with fusion, in all 3 planes of motion.7

A second biomechanical cadaveric study compared the effect of complete anterior discectomy and subsequent replacement with a Maverick ball-and-socket arthroplasty on operative-level (L4–5) and adjacent-level (L3–4) motion by using a load-controlled setup. After complete anterior discectomy, the spine was found to have increased ROM at the operated level in all 6 degrees of freedom. After arthroplasty, however, motion at the operated level was found to be restored so that no significant difference was found with the intact condition. These authors concluded that the artificial disc was able to restore motion comparable to that of the intact state.26 In that model, however, the authors were unable to demonstrate appreciable differences in motion in either the discectomy or arthroplasty condition at the rostral adjacent level (L3–4). Hence, these and other authors have advocated the use of a displacement-controlled strategy, which has been reported to more closely resemble in vivo physiological conditions than load-controlled testing.5,12,21,27

The changes in adjacent-level intradiscal pressures after lumbar total disc arthroplasty have not been extensively investigated.4 Since increased motion and pressure at the adjacent segment after fusion are hypothesized as the reasons for adjacent disc degeneration, it is important to study the effect of arthroplasty on these 2 parameters. The objective of the present biomechanical study was to compare motion and IDP in a ball-and-socket artificial disc–implanted cadaveric lumbar spine with the intact spine, at the operative and adjacent levels, using a displacement-controlled setup.

In case of failure with lumbar arthroplasty, a number of revision strategies have been described, including posterior instrumentation or anterior explantation with revision or conversion to arthrodesis.1,32 The risk of injury to the great vessels and retroperitoneal structures is greater during anterior revision procedures. As such, for carefully selected patients, some authors have advocated the use of PS instrumentation as a supplement to the artificial disc, with the view that PSs may provide sufficient rigidity to counter persistent pain associated with hypermobility or facet arthropathy.1,32 As such, a secondary goal of the present study was to evaluate the biomechanics of a “salvage” PS construct, placed in the presence of the artificial disc, in comparison with the artificial disc and intact spine.

Methods

Specimen Preparation

Ten fresh frozen human cadaveric spine specimens were obtained from the deceased body program at the Department of Anatomy, University of Iowa. Spines were radiographed in the anteroposterior and lateral planes to ensure absence of fractures, deformities, and any metastatic disease. Age, sex, and BMD are shown in Table 1. The BMD was measured in the lateral plane using dual energy absorptiometry (DEXA) with a bone densitometer (QDR-2000, Hologic, Inc.). Specimens were then stored in double plastic bags at −20°C and allowed to thaw at room temperature prior to manipulation. Prior to potting, thawed specimens were carefully denuded of paravertebral musculature, avoiding disruption of spinal ligaments, joints, and discs. Each specimen was then potted at L-2 and at S-1 using a mixture of Bondo and resin (Bondo Corp.) in a ratio of 70:30. A setting time of 2 hours was allowed for each side of the potting. The spine was subsequently double bagged again and kept in the freezer. Ten hours prior to testing time, the spine was removed from the freezer and allowed to thaw to room temperature. Care was taken that the number of freeze–thaw cycles did not exceed 2.

Experimental Setup

A servohydraulic MTS Bionix 850 machine (MTS Systems) was used for the testing. A custom-designed loading fixture for the MTS actuator was used to apply

| TABLE 1: Summary of BMD, age, and sex for all spine specimens used in this study |
|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Characteristic and Experimental Spine No. | 23     | 101    | 105    | 152    | 301    | 373    | 406    | 415    | 464    | 494    |
| BMD (g/cm²)                  | 0.501  | 0.69   | 0.402  | 0.398  | 0.669  | 0.475  | 0.787  | 0.42   | 0.663  | 0.446  |
| age (yrs)                    | 60     | 70     | 83     | 83     | 59     | 74     | 79     | 77     | 58     | 50     |
| sex                          | F      | M      | F      | F      | F      | M      | F      | M      | F      |
| Mean ± SD                    | 0.545 ± 0.143 |

716
Lumbar arthroplasty and adjacent-level biomechanics

a predetermined unconstrained rotation to the potted spine in the sagittal and coronal planes. Displacement-controlled loading was applied in the following manner: 20° flexion, 15° extension, and 15° right lateral bending. These displacement values were finalized on the basis of previous studies quantifying the ROM of the ligamentous spine as well as trial tests, which confirmed that the intradiscal pressure did not reach the maximum calibration limit of the transducers. Three sequential trials were performed for each type of motion for each specimen to confirm repeatability, and the third trial was used for analysis. 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. A 6-axis force/torque sensor (MC3A, Advanced Mechanical Technology, Inc.) was mounted on the MTS platform to measure the forces and moments acting on the spine.

Displacement-Controlled Loading

A Vertical Biaxial Clinometer (Applied Geomechanics, Inc.) was fixed onto the L-2 potting surface to measure the rotation that was applied to the spine. The vertical displacement of the MTS actuator to achieve the set rotation of the spine was determined. The displacement rate of the actuator was calculated by dividing this displacement by the time duration for the loading cycle. The loading rate was 1°/second.

Motion Measurement

Motion of the spine was tracked using a real-time 3D Motion Analysis System (Motion Analysis Corp.), which uses 3 high-resolution digital video cameras to position a point in space to an accuracy of less than 0.1 mm. Three retroreflective markers were placed on the anterior surface of each of the L-3, L-4, and L-5 vertebral bodies. This yielded translations and rotations in the x, y, and z directions by representing each vertebra by a plane formed by the 3 reflective markers.

The specimens were tested for motion in the sagittal and coronal planes. Axial rotation was not considered, as the test fixture was not equipped to apply pure axial rotation. In the coronal plane, only right lateral bending was considered for analysis, assuming that the spine would show similar behavior for left lateral bending due to symmetry.

Pressure Measurement

Intradiscal pressure at the rostral adjacent motion segment (L3–4) was measured using SPR-24 pressure transducers (Millar Instruments). Three transducers were used (1 each for flexion, extension, and right lateral bending). Figure 1 shows the relative arrangement of the pressure transducers within the disc space. The flexion transducer was placed in the midline at the junction of the anterior and middle thirds of the disc space. The extension transducer was placed in the midline at the junction of the middle and posterior thirds of the disc space. The lateral transducer was placed in the middle of the right lateral half of the disc space. These positions were based on the approximate location of the instantaneous axis of rotation.

Data Acquisition

A KPCI–3101 DA board (Keithley Instruments, Inc.) was used to digitize the analog signals from the load cell, inclinometer, and pressure control units.

Spinal Instrumentation

The Maverick Total Disc Replacement (Medtronic Sofamor Danek), a ball-and-socket type of artificial disc, was used. The endplates of this disc are available in 3 sizes: small (25 × 32 mm), medium (27 × 35 mm), and large (30 × 39 mm). The available implant heights are 6, 9, and 12 mm. The available lordotic angulations are 6, 9, and 12°. Polyaxial CD-Horizon (Medtronic Sofamor Danek) PSs (6.5 × 45 mm) and rods (5.5 mm) were used for instrumentation at L4–5. The sizes of the discs used in each spine are tabulated in Table 2.

Data and Statistical Analyses

Repeatability of the data were established through the correlation coefficient R. Generalized linear model ANOVA (SAS version 9.2, SAS Institute) was used to adjust for the individual spines for the 3-group comparisons, with significance at p < 0.05. Subgroup pairwise analyses were done using the Tukey test for 95% significance at p < 0.05.

Results

Intraspecimen Repeatability

Intraspecimen repeatability was established by sequential loading of each specimen 3 times in all test constructs and loading directions. Figure 2 shows sample repeatability curves for intradiscal pressure for flexion. The average R values for intradiscal pressure and segmental motion were 0.99 and 0.98, respectively.

Kinematics in Flexion

At the implanted level (L4–5), the artificial disc
showed a nonsignificant decrease in flexion (22%) compared with the intact condition, whereas the PS construct decreased flexion significantly (61%) when compared with the intact spine (Table 3 and Fig. 3). Not only did the PS construct reduce flexion relative to the intact spine, the PS construct reduced flexion significantly (50%) relative to the artificial disc.

At the rostral level of L3–4, the artificial disc revealed a minor increase in flexion motion (20%) compared with the intact condition (p > 0.05), whereas the PS construct significantly increased flexion motion (42%) when compared with the intact spine (Table 3 and Fig. 3). Relative to the artificial disc, however, the increase in flexion due to the PS construct did not reach significance (18%).

At the caudal level (L5–S1), the artificial disc nonsignificantly increased the flexion motion at the caudal adjacent segment (L5–S1) by 13% compared with the intact spine, whereas PS fixation significantly increased flexion at L5–S1 by 33% compared with the intact), but increased extension by 27% compared with the artificial disc, neither of which reached significance.

In summary, there is no significant difference between the artificial disc and the intact state at either the operative or adjacent levels. The addition of PSs significantly reduces motion at the operative level with a compensatory increase in motion at both adjacent levels (p < 0.05).

Kinematics in Extension

At L4–5, the artificial disc demonstrated a significant increase in extension motion (84%) compared with the intact condition, whereas the PS construct showed an increase in extension by only 44% when compared with the intact spine (p > 0.05) (Table 3 and Fig. 4). When compared with the artificial disc, the PS construct reduced extension motion by 21%, but this reduction was not statistically significant.

At the rostral adjacent level (L3–4), the artificial disc revealed a significant decrease in extension motion (42%) when compared with the intact condition (Table 3 and Fig. 4). The PS construct decreased extension by 26% compared with the intact), but increased extension by 27% compared with the artificial disc, neither of which reached significance.

At the caudal adjacent level, L5–S1, compared with the intact condition, the artificial disc decreased extension by 33%, not meeting the criteria for statistical signifnicance, whereas the PS instrumentation significantly decreased extension motion by 45% when compared with the intact (Table 3 and Fig. 4). The PS fixation did not show any significant change from the artificial disc–implanted spine.

In summary, the artificial disc is associated with a significant increase in extension motion at the operative level and a compensatory decrease in motion at the rostral adjacent level, when compared with the intact spine. The decrease in motion at the caudal adjacent level did not reach statistical significance. Addition of PSs to the artificial disc limits the hypermobility in extension at the operative level and restores motion at the rostral level to baseline. The addition of PSs does restrict motion significantly at the caudal adjacent level, when compared with the intact state.

Kinematics in Lateral Bending

The artificial disc was associated with a significant decrease of 32% in right lateral bending at L4–5 compared with the intact condition. In addition, compared with the intact spine, PS instrumentation decreased right lateral bending by 61% (p < 0.05) (Table 3 and Fig. 5). Compared with the artificial disc–implanted state, the addition of PSs further significantly reduced right lateral bending by 44%.

At the rostral adjacent level, L3–4, changes in motion by the artificial disc and PS constructs were neither significantly different from the intact state nor from one another (Table 3 and Fig. 5).

Table 2: Dimensions of artificial discs placed at L4–5

<table>
<thead>
<tr>
<th>Experimental Spine No.</th>
<th>23</th>
<th>101</th>
<th>105</th>
<th>152</th>
<th>301</th>
<th>373</th>
<th>406</th>
<th>415</th>
<th>464</th>
<th>494</th>
</tr>
</thead>
<tbody>
<tr>
<td>size</td>
<td>M</td>
<td>S</td>
<td>M</td>
<td>S</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>lordosis (°)</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>height (mm)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

* L = large; M = medium; S = small.

![Fig. 2. Bar graph showing the repeatability of pressure data for sample specimen (R = 0.99).](image-url)
Lumbar arthroplasty and adjacent-level biomechanics

At the caudal adjacent level, L5–S1, the magnitude of lateral bending was very small in all 3 surgical constructs (Table 3). Compared with the intact state, artificial disc implantation increased lateral bending by 34%, and PS instrumentation increased lateral bending by 35%, but neither of these increases reached significance.

In summary, the artificial disc was associated with a significant decrease in right lateral bending motion at the operative level, but no significant difference at either of the adjacent levels. The addition of PSs further reduced motion at the operative level, but there was no significant change at either of the adjacent levels when compared with the artificial disc or the intact spine.

Intradiscal Pressure

In flexion, with the artificial disc at L4–5, the IDP of L3–4 was unchanged compared with the intact state (p > 0.05, Table 3 and Fig. 6). With the addition of PS instrumentation, there was no significant change in IDP, either when compared with the intact spine (6%) or the artificial disc–implanted state (8%).

In extension, the artificial disc showed a significant decrease in IDP at L3–4 (25%) compared with the intact condition. Similarly, the PS construct decreased the disc pressure significantly by 19% when compared with the intact state (Table 3 and Fig. 6). Although the PS fixation increased the disc pressure by 7% relative to the artificial disc implanted state, this increase was not significant.

In right lateral bending, the artificial disc showed a minor increase of 5% in intradiscal pressure when compared with the intact condition (p > 0.05, Table 3 and Fig. 6). Pedicle screw instrumentation increased IDP significantly by 17% compared with the intact state, but only by 11% when compared with the artificial disc (p > 0.05).

In summary, IDP was only measured at the rostral adjacent level. The IDP was not increased in any condition with the presence of the artificial disc, and was, in fact, significantly decreased in extension. This decrease of IDP in extension was not affected by the addition of PSs and remained significantly different from the intact spine. With the addition of PSs, the IDP was significantly increased only in right lateral bending, relative to the intact spine.

Brief Summary of Results

Artificial Disc. In flexion, no significant difference was noted between the artificial disc and the intact spine with regard to motion at the operative level, motion at adjacent levels, or IDP. In lateral bending, while the artificial disc significantly decreased operative level motion, no significant difference was noted in adjacent level mo-

### TABLE 3: Intersegmental flexibility at L3–4, L4–5, and L5–S1 and IDP at L3–4 for the 3 test constructs

<table>
<thead>
<tr>
<th>Motion Type</th>
<th>Intact Spine</th>
<th>AD-Implanted</th>
<th>PS-Instrumented</th>
<th>p Value†</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>flexion (°)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3–4</td>
<td>3.96 ± 1.71</td>
<td>4.75 ± 1.54</td>
<td>5.62 ± 1.11‡</td>
<td>0.0185</td>
</tr>
<tr>
<td>L4–5</td>
<td>6.27 ± 1.22</td>
<td>4.92 ± 2.24</td>
<td>2.45 ± 1.29§</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>L5–S1</td>
<td>4.74 ± 2.64</td>
<td>5.35 ± 2.66</td>
<td>6.32 ± 3.29§</td>
<td>0.0021</td>
</tr>
<tr>
<td>IDP at L3–4 (mm Hg)</td>
<td>1891 ± 980</td>
<td>1851 ± 949</td>
<td>2001 ± 968</td>
<td>0.6588</td>
</tr>
<tr>
<td><strong>extension (°)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3–4</td>
<td>3.20 ± 1.57</td>
<td>1.87 ± 1.01§</td>
<td>2.37 ± 1.20</td>
<td>0.0102</td>
</tr>
<tr>
<td>L4–5</td>
<td>3.40 ± 0.97</td>
<td>6.25 ± 2.70§</td>
<td>4.91 ± 1.97</td>
<td>0.0088</td>
</tr>
<tr>
<td>L5–S1</td>
<td>4.75 ± 2.32</td>
<td>3.16 ± 2.02</td>
<td>2.59 ± 1.39§</td>
<td>0.0253</td>
</tr>
<tr>
<td>IDP at L3–4 (mm Hg)</td>
<td>1722 ± 831</td>
<td>1292 ± 802§</td>
<td>1388 ± 774§</td>
<td>0.0001</td>
</tr>
<tr>
<td><strong>lat bending (°)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>4.87 ± 2.38</td>
<td>4.20 ± 1.85</td>
<td>4.98 ± 2.04</td>
<td>0.5114</td>
</tr>
<tr>
<td>L4–5</td>
<td>5.11 ± 1.54</td>
<td>3.49 ± 2.27‡</td>
<td>1.97 ± 0.83‡</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>L5–S1</td>
<td>0.89 ± 0.72</td>
<td>1.19 ± 1.34</td>
<td>1.20 ± 1.14</td>
<td>0.4588</td>
</tr>
<tr>
<td>IDP at L3–4 (mm Hg)</td>
<td>2542 ± 631</td>
<td>2681 ± 588</td>
<td>2985 ± 605§</td>
<td>0.0221</td>
</tr>
</tbody>
</table>

* Values are presented as means ± SDs. Abbreviation: AD = artificial disc.
† The p values were derived from the 3-way group comparison using generalized linear model ANOVA.
‡ Versus all groups.
§ Versus intact spine only.
tion or IDP. With regard to extension, the artificial disc significantly increased operative level motion, and simultaneously decreased the rostral adjacent level (L3–4) motion and IDP. Caudal adjacent level (L5–S1) motion was not significantly different.

In summary, the artificial disc either maintains or reduces adjacent-level motion and IDP, compared with the intact spine. At the operative level, the artificial disc is associated with hypermobility in extension (p < 0.05), decreased motion in lateral bending (p < 0.05), and no significant change in flexion (p > 0.05), compared with the intact spine.

**Pedicle Screw–Artificial Disc Construct.** With regard to flexion and lateral bending, the addition of PSs significantly decreased motion at the implanted level, when compared with both the intact spine and the artificial disc. This decrease in motion with the addition of PSs was associated with a compensatory increase in motion at both adjacent levels in flexion only (p < 0.05), but not in lateral bending (p > 0.05). The IDP was significantly increased in lateral bending, but not in flexion. With regard to extension, the significant decrease in IDP that was noted with the artificial disc persisted despite the addition of PSs (p < 0.05).

In summary, the addition of PSs to the artificial disc construct leads to significantly increased motion at adjacent levels in flexion, and significantly increased IDP in lateral bending, when compared with the intact spine. At the operative level, the hypermobility in extension that is associated with the artificial disc is reduced so that there is no significant difference between the intact state and the artificial disc after the addition of supplementary PSs. At the operative level, with regard to flexion and lateral bending, the loss of motion associated with the artificial disc is further reduced with the addition of PSs, now achieving statistical significance for flexion and lateral bending when compared with the intact spine.

**Discussion**

The artificial disc has been proposed as a potential alternate solution for the loss of motion and the development of adjacent-level degeneration that have been associated with spinal fusion. Currently, there are 2 main designs being proposed for lumbar intervertebral disc replacement: the fixed core ball-and-socket design, such as the Maverick (Medtronic Sofamor Danek) and Prodisc (Synthes Spine), and the slip-core design, such as the SB Charité (DePuy Spine) system. This biomechanical study intends to compare the pressure and motion characteristics in the following 3 states: intact; total disc arthroplasty with a fixed core ball-and-socket design; and a “salvage” construct consisting of the artificial disc with supplementary PS instrumentation, using a displacement-controlled setup.

The current work builds off prior in vitro biomechanical studies in which the artificial disc has been used. Two studies used load-controlled testing in human cadaveric spines with L4–5 instrumentation, and both studies concluded that the artificial disc maintains motion relative to the intact spine. Cunningham et al. went on to demonstrate that BAK cages and BAK cages plus ISOLA PS/rad fixation markedly reduced the flexion/extension ROM at the index level relative to the SB Charité prosthesis, with a compensatory increase in motion at the adjacent levels. While the SB Charité exhibited a minor increase in flexion/extension ROM versus the intact spine (3%), this was not significant in their study. We have previously demonstrated that, at loads of 3 Nm or greater, the loss of the tethering effect of the anterior longitudinal ligament after anterior discectomy without replacement instrumentation was associated with significant increases in flexion and extension motion, with greater movement allowed in extension. After placement of a Maverick artificial disc, the spine was restored to normal motion, with no significant difference noted between the intact and artificial disc–implanted spine. One key difference between these studies and the current study is the use of displacement-controlled testing versus load-controlled testing. Whereas the Cunningham study used a maximum load of 8 Nm and the prior study by our group used a maximum load of 6 Nm, the present study used sufficient force to achieve a target displacement.

**Advantages of the Displacement-Controlled Setup**

The displacement-controlled modality satisfies the laws of mechanics for studying adjacent-segment be-
Lumbar arthroplasty and adjacent-level biomechanics

**Interpretation of Results**

**Artificial Disc.** The results of the current study show that the artificial disc either maintains or reduces adjacent-level motion and pressure compared with the intact spine. At the operative level, the artificial disc is associated with hypermobility in extension (p < 0.05), decreased motion in lateral bending (p < 0.05), and no significant change in flexion (p > 0.05), compared with the intact spine.

While the 2 previously mentioned load-controlled cadaveric studies did not demonstrate significantly increased motion in the sagittal plane of the arthroplasty constructs relative to the intact spine, several other studies have shown an increase in sagittal plane motion associated with the artificial disc. Finite element models of lumbar arthroplasty, in conjunction with other biomechanical studies, and clinical radiographic follow-up have demonstrated significantly increased motion in the sagittal plane at the operative level in the presence of lumbar arthroplasty, with a concurrent decrease in adjacent-level motion, as seen in the present study.

In extension, the artificial disc increased motion at the operative level by 84% (Table 3 and Fig. 4). The excision of the anterior longitudinal ligament and anulus fibrosus necessary for device implantation would have accounted for this increase in extension, as mentioned above. In the current study, in conjunction with the increased extension motion seen at the implanted level, the amount of extension motion observed at the rostral adjacent level (L3–4) decreased significantly in comparison with the intact spine (Fig. 4). There was a similar sharp decrease in extension motion at the caudal adjacent motion level (L5–S1); however, this decrease did not reach significance. This reduced adjacent-level motion is attributed to the significant increase in operative-level motion, and it is unclear to what extent reduced motion is ameliorative or contributory to adjacent-level degenerative changes.

**Pedicle Screw–Artificial Disc Construct.** The results of the current study show that the addition of PSs to the artificial disc construct leads to significantly decreased motion in flexion and lateral bending at the operative level relative to the artificial disc construct and the intact spine. Simultaneously, there are statistically significant increases in flexion motion at the adjacent levels and significantly increased IDP in lateral bending at the rostral adjacent level, when compared with the intact spine. At the operative level, the hypermobility in extension that is associated with the artificial disc is reduced so that there is no significant difference between the intact state and the artificial disc plus PS construct. To our knowledge, this is the first biomechanical study attempting to evaluate the PS salvage construct with the artificial disc in place.

While the PS construct was able to return the hypermobility of the artificial disc construct in extension back to that of the intact state, the PS construct was not able to limit extension significantly more than the intact state, as seen in other studies in which BAK cages were used instead of artificial discs. The present study corroborates the strategy of using the PS salvage construct in selected patients in whom persistent pain after arthroplasty may be due to hypermobility and or persistent facet arthropathy. This construct, while significantly restricting flexion and lateral bending relative to the intact spine, is able to significantly reduce the hypermobility of extension assos-
associated with the artificial disc back to the intact state, but not further restrict extension motion, as seen in a fusion construct (Figs. 3 and 4). Should the patient proceed to have persistent pain due to hypermobility, riskier anterior revision strategies of replacement or arthrodesis could then be used.\textsuperscript{1,32}

**Lateral Bending.** In right lateral bending, the Maverick artificial disc reduced operative-level motion significantly by 32\% (Table 3 and Fig. 5). The implantation of the Maverick artificial disc involved the distraction of the endplates and consequently a preloading of the retained lateral anulus, secondarily increasing stiffness at the operated level. Hence, for the given total displacement of 15° in the coronal plane, we might expect a decrease in motion at the operated level, as seen here. The increased stiffness at the artificial disc–implanted segment is also evident from the increased axial force observed when compared with the intact spine (Fig. 7). Despite the significant decrease in motion at the operated level in right lateral bending, the artificial disc maintained near-normal motion at the rostral (L3–4) as well as caudal (L5–S1) adjacent levels. Similarly, the PS instrumentation decreased motion significantly at the operated level (L4–5) in right lateral bending, but there was no significant increase in motion at any of the adjacent levels. It is possible that the motion compensation may have taken place at the most rostral adjacent segment, L2–3, because of its nearly circular cross section compared with lower lumbar levels. Geometry of the motion segments plays an important role in determining the ROM.\textsuperscript{41}

**Intradiscal Pressure.** In the present study, pressure was measured at the rostral adjacent level, that is, L3–4 (Fig. 6). The artificial disc maintained similar pressure to the intact spine in flexion and lateral bending. In extension, the artificial disc registered a significantly lower pressure than the intact condition. This decrease in pressure was in conjunction with the increased motion at the implanted level (L4–5) and consequently decreased motion at L3–4.

Intradiscal pressure at L3–4 increased with PS instrumentation at L4–5 compared with the intact spine in flexion; however, this increase was not significant. With regard to PS instrumentation, in right lateral bending, the intradiscal pressure at L3–4 increased significantly compared with the intact spine (Fig. 6). In extension, the IDP decreased significantly compared with the intact spine. It is expected that had the fusion been simulated with an interbody cage and without the presence of the artificial disc, the change in IDP at L3–4 would have been significantly increased with fusion in all axes of motion, as shown in previous studies.\textsuperscript{8,40}

**Conclusions**

In flexion and lateral bending, the ball-and-socket design of the artificial disc maintained operative-level kinematics, as well as adjacent-level kinematics and IDP. In extension, the increase in operative-level motion is associated with a corresponding decrease in rostral adjacent-level motion and pressure. Thus, the artificial disc either maintains or reduces adjacent-level motion and pressure, compared with the intact spine.

When placed in the presence of the artificial disc, PSs provide significant rigidity to the spine in flexion and lateral bending, relative to the intact spine, and comparable rigidity to the spine in extension, relative to the intact state. The addition of PSs to the artificial disc construct leads to significantly increased motion at adjacent levels in flexion, and significantly increased rostral adjacent level IDP in lateral bending. Use of PS posterolateral instrumentation as a revision strategy to supplement a prior lumbar arthroplasty may be beneficial in select patients with persistent pain due to hypermobility prior to proceeding with an anterior revision.

**Disclosure**

The corresponding author (P.W.H.) acknowledges the financial support of Medtronic Sofamor Danek (Memphis, TN) in making this study possible.

**References**


A. V. Ingalhalikar et al.
Lumbar arthroplasty and adjacent-level biomechanics


Manuscript submitted January 12, 2009.
Accepted July 8, 2009.
Address correspondence to: Patrick W. Hitchon, M.D., University of Iowa Hospitals and Clinics, 200 Hawkins Drive/Rm 1847 JPP, Iowa City, Iowa 52242. email: patrick-hitchon@uiowa.edu.