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Changes in adjacent-level disc pressure and facet joint force after cervical arthroplasty compared with cervical discectomy and fusion

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Object. The authors of previous in vitro investigations have reported an increase in adjacent-level intradiscal pressures (IDPs) and facet joint stresses following cervical spine fusion. This study was performed to compare adjacent-level IDPs and facet force following arthroplasty with the fusion model.

Methods. Eighteen human cadaveric cervical spines were tested in the intact state for different modes of motion (extension, flexion, bending, and rotation) up to 2 Nm. The specimens were then divided into three groups: those involving the ProDisc-C cervical artificial disc, Prestige cervical artificial disc, and cervical fusion. They were load tested after application of instrumentation or surgery at the C6–7 level. During the test, IDPs and facet forces were measured at adjacent levels.

Results. In arthroplasty-treated specimens, the IDP showed little difference from that of the intact spine at both proximal and distal levels. In fusion-treated specimens, the IDP increased at the posterior anulus fibrosus on extension and at the anterior anulus fibrosus on flexion at the proximal level. At the distal level, the IDP change was not significant. The facet force changes were minimal in flexion, bending, and rotation modes in both arthroplasty- and fusion-treated spines. Significant changes were noted in the extension mode only. In extension, arthroplasty models exhibited significant increases of facet force at the treated level. In the fusion model the facet forces decreased at the treated segment and increased at the adjacent segment.

Conclusions. The two artificial discs of the semiconstrained systems maintain adjacent-level IDPs near the preoperative values in all modes of motion, but with respect to facet force pressure tended to increase after arthroplasty.
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Key Words • **arthroplasty** • **biomechanical test** • **cervical spine** • **facet joint force** • **intradiscal pressure**

The authors of previous clinical studies have reported an increased incidence of disc degeneration at levels adjacent to fusion sites in the cervical spine.[2,8,12] The cause of this subsequent disc degeneration, however, remains unknown. One of the suggested etiological factors is an increase in IDP. The IDP increase blocks the diffusion of nutrients from the endplate.[3,23] Impaired nutrition of the disc has been identified as the most significant cause of disc degeneration. The authors of several biomechanical reports have shown that the IDP increased at adjacent segments after ACDF.[7,9]

Although fusion techniques have led to adequate results, continuing advances in the field have led to the introduction of various arthroplasty techniques. Arthroplasty is performed to maintain ROM and decrease the rate of adjacent-segment disease. Many biomechanical tests have provided evidence that cervical artificial discs can preserve the motion comparable with the intact spine at the surgically treated segment.[7,9] For the artificial disc to prevent adjacent-segment degeneration, the IDP at the adjacent segment should not be increased after arthroplasty. Currently, reports on IDP changes after arthroplasty are scarce.

The facet joint can carry a significant amount of the total compressive load on the spine when the spine is hyperextended.[4] The authors of biomechanical reports of anterior L4–5 fusion found an increase in the plane strains in the L3–4 and L5–S1 facet joints.[14] They observed that the L4–5 facet capsules exhibited decreased strains. In the cervical spine, changes in facet force after arthroplasty have not

Abbreviations used in this paper: ACDF = anterior cervical discectomy and fusion; IDP = intradiscal pressure; PMMA = polymethylmethacrylate; ROM = range of motion.

been reported until now. Our goal was to investigate changes in IDP and facet force after cervical arthroplasty and to compare these data with those obtained in the fusion model.

Materials and Methods

Twenty-four human cadaveric cervical spines (C3–T2 specimens) were obtained from Science Care Anatomical and International Biological, Inc. After specimens containing bone abnormalities were excluded based on anteroposterior and lateral radiography findings, 18 cadaveric spines were used for the study. The specimens were thawed overnight at room temperature, and attached musculature was adequately removed to expose the facet joint surfaces of the C-5, C-6, and C-7 vertebrae. The cadaveric spines were divided into three groups, with six specimens in each group.

Each cervical C3–T2 specimen was fixed by drilling and inserting screws in the most superior and most inferior segments (extending into C3–4 and T1–2 segments). The end segments and screws were capped with PMMA (COE tray plastic, GC America), and the PMMA-covered ends were potted in polyester resin (Bondo). The potting fixtures were used to attach the cadaveric spines loaded onto a mechanical testing and simulation loading frame (MTS 858 MiniBionix), and the cadavers were loaded in flexion, extension, left and right lateral bending, and left and right rotation.

Pressure transducer needles (Model 6376, Robert A. Denton, Inc.) were inserted into the central anterior portion of the disc superior to C-6 and the disc inferior to C-7. Each needle had three pressure transducers spaced 5 mm apart. The needle tips were inserted approximately 2 cm into the disc so as to have pressure transducer No. 2 in the center of each disc, with No. 1 toward the posterior and No. 3 toward the anterior aspect (Fig. 1). Strain guages (model CEA-06-062UW-350, Vishay Micro-Measurements, Inc.) were also mounted on both left and right surfaces of the C5–7 facet joints as shown in Fig. 2. Pressure transducer signals and strain guage signals were conditioned and amplified by a signal conditioner (system 2100, Vishay Micro-Measurements) and recorded by the mechanical testing system.

The pressure in the posterior anulus fibrosus, center of the disc nucleus, and the anterior anulus fibrosus were measured using the No. 1, 2, and 3 pressure sensors of the pressure transducer needles. 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 of the intact spine. Artificial disc replacement, discectomy, and fusion procedures were performed by a neurosurgeon.

Discectomy and Artificial Disc Implantation

Anterior C6–7 discectomies were performed using the Smith–Robinson technique. The C6–7 disc space was chosen because the level exhibited the most adequate disc height. Most of the available human cadaveric spines had significant loss of disc height due to the degenerative process. When the middle segment of C5–6 and C6–7 processes in the final 18 selected specimens underwent radiography, the C6–7 level was shown to have better disc height preservation than C5–6.

The specimens were divided into three groups, with six specimens in each group and each group receiving an artificial disc implant (ProDisc-C [Synthes Spine] or Prestige [Medtronic Sofamor Danek]) or fusion in which a dense cancellous bone allograft (Osteotech) and anterior plate (SpineVision) were placed. The 7-mm-high ProDisc-C and 8-mm-high Prestige disc were adequate for the specimens. For specimens in the anterior cervical fusion group, a 7-mm, lordotic, tapered, dense cortical allograft was used in conjunction with rigid plate and screw fixation to maintain lordosis at the surgically treated level. Artificial discs were placed in a 36°C bath for 24 hours prior to implantation to allow the discs to be near a biophysiological condition. Each step was performed according to the recommended surgical technique, and the C-arm fluoroscopy was used throughout the procedure to verify the correct position of the artificial disc.

Biomechanical Testing

Biomechanical testing was performed in six modes of motion: flexion, extension, left and right lateral bending, and left and right axial rotation. In each loading mode, a maximum torque of 2 Nm was applied with a 100-N axial preload. Axial compression and axial rotation were determined by the upper spine fixator, whereas flexion, extension, and lateral bending were determined by the rotation of both spine fixators in the respective coronal and sagittal planes. To stabilize the viscoelastic effect, each mode of testing was performed three times, with only the result of the third test being used.

The outputs of the pressure transducers and strain guages were determined for each specimen in the following states: 1) intact condition, and 2) after artificial disc implantation or ACDF.

Statistical Analysis

Because the data could not be assumed to be normally distributed due to the sample size, nonparametric statistical methods were used to distinguish significant differences among groups and compare data with those acquired in the intact spines. Facet forces (output readings of the strain guages) and IDPs were normalized by dividing them by those of the intact spine. Paired comparisons between treatment groups were made using the Wilcoxon paired t-test, and statistical significance was assigned at a probability level of less than 0.05. Values are presented as the mean ± standard error of the mean.

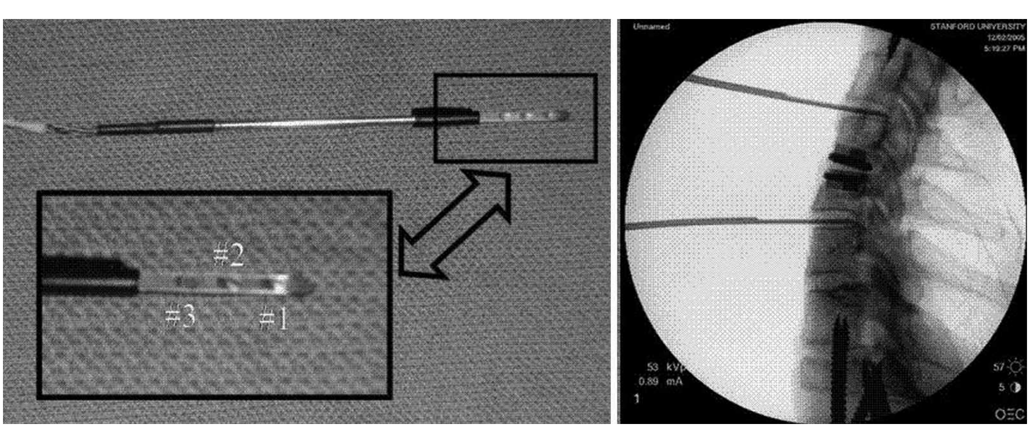

FIG. 1. *Left:* Photograph showing the needle pressure transducer. *Inset:* The position of individual pressure sensors (Nos. 1, 2, and 3: posterior anulus fibrosus, nucleus, and anterior anulus fibrosus, respectively). *Right:* Lateral radiograph demonstrating a specimen with the transducer in place.

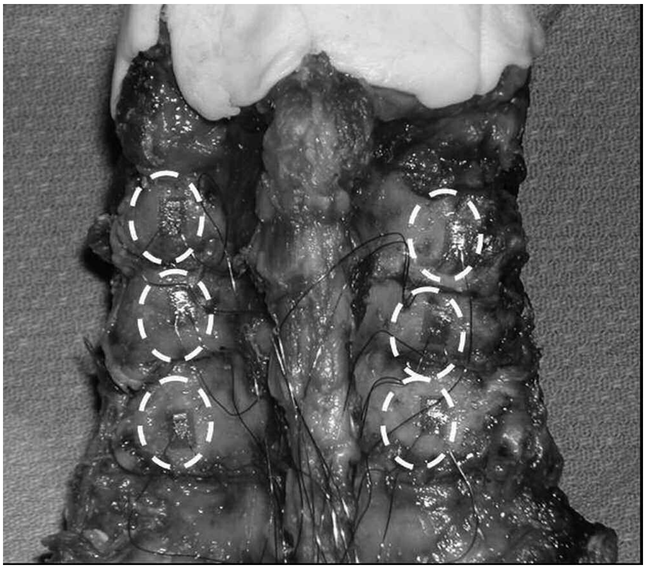

FIG. 2. Photograph showing the position of strain guages *(dashed circles)* on the C5–7 facet joint surfaces.

Results

The normalized posterior, center, and anterior IDPs at the level above (C5–6) and below (C7–T1) the treated level are shown in Figs. 3 and 4, respectively. The normalized facet forces at the level above (C-5), the same as (C-6), and below (C-7) the treated levels are shown in Fig. 5.

Intradiscal Pressure

In the arthroplasty groups at the disc above and below the target level, the IDP change typically did not differ much from that of the intact spine (< 10% difference) and all were without significance (Figs. 3 and 4). This finding was similar in both Prestige and ProDisc groups. The difference was not found among the three sites of IDP measurement.

In the ACDF group, however, at the superior level, the IDP was increased (46.5 ± 18.8%, p = 0.686) at the posterior anulus fibrosus during extension and was also increased (33.9 ± 8.9%, p = 0.686) at the anterior anulus fibrosus during flexion. In the center of the superior level, the IDP did not increase during any mode of motion (Fig. 3b). At the inferior level, the IDP change noted in the ACDF group was not significant compared with that of the intact spine in all modes of motion (Fig. 4).

Facet Joint Force

Extension. The facet forces documented in all artificial disc groups were increased except that at the superior level in the Prestige artificial disc (ProDisc-C artificial disc: 14.9 ± 11.9% at the superior level, 95.4 ± 13.9% at the same level, and 7.7 ± 7.7% at the inferior level; Prestige artificial disc: −4.0 ± 7.9% at the superior level, 25.1 ± 13.5% at the same level, and 2.5 ± 10.7% at the inferior level) compared with the intact spine. Although this group demonstrated a decrease in the facet force at the superior level in extension, this finding was not statistically significant. Similarly, the facet changes inferior to each artificial disc were not significant. At the same level, the facet force change in specimens fitted with the ProDisc-C artificial

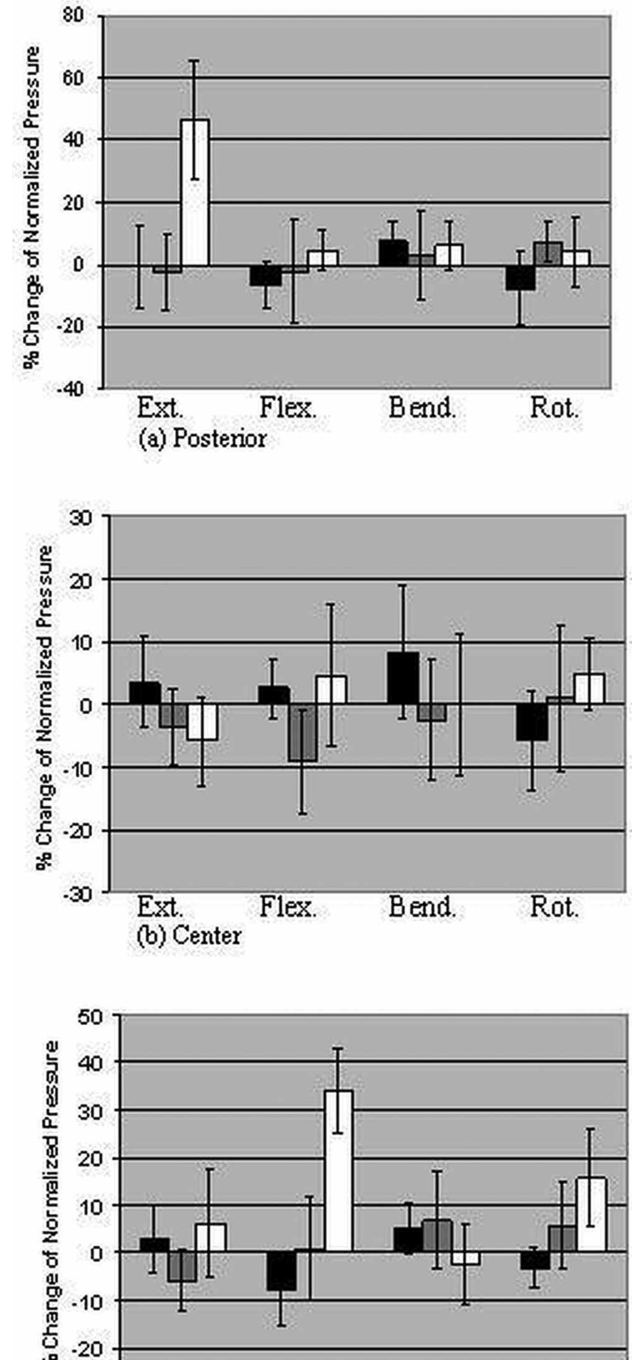

FIG. 3. Bar graphs demonstrating superior-level IDPs at the surgically treated (C5–6) segment in the posterior (a), central (b), and anterior (c) portions of the anulus fibrosus. *Black bars* represent the ProDisc-C group, *gray bars* represent the Prestige group, and *white bars* represent the ACDF group. Bend. = bending; Ext. = extension; Flex. = flexion; Rot. = rotation.

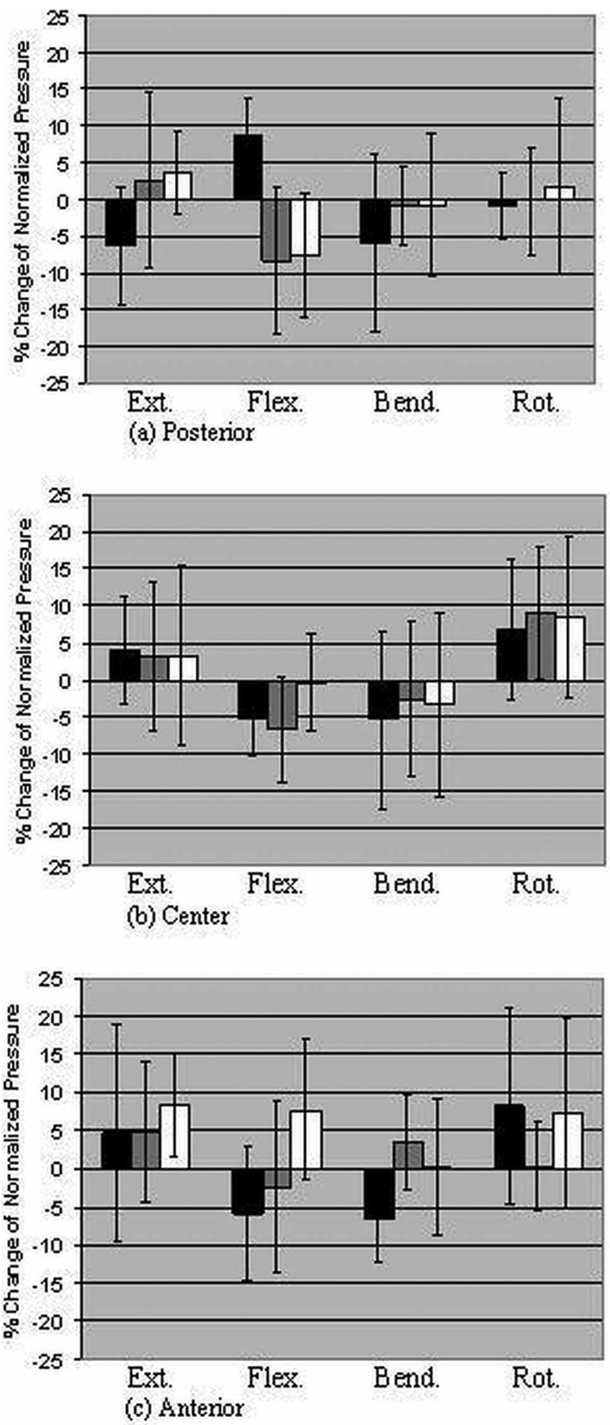

FIG. 4. Bar graphs revealing inferior-level IDPs at the surgically treated (C7–T1) segment in the posterior (a), central (b), and anterior (c) portions of the anulus fibrosus. *Black bars* represent the ProDisc-C group, *gray bars* represent the Prestige group, and *white bars* represent the ACDF group.

disc was significant (p = 0.043). The extent of the increase was more prominent at the same level than at the adjacent levels. In specimens treated with ACDF, the same-level facet force was reduced (18.3 ± 15.6%) whereas superior-level facet force was significantly increased (28.2 ± 10.7%, p = 0.043), and facet was also increased at the inferior level (24.0 ± 10.9%, p = 0.074). At the same level, the facet force in ACDF-treated specimens was significantly less than that in spines fitted with the ProDisc-C artificial disc (p = 0.018). At the superior level, the facet force was significantly higher than that of the Prestige artificial disc (p = 0.018).

Flexion. At the same level, the facet forces documented in ACDF-treated specimens (−19.5 ± 18.1%) were decreased whereas those in both ProDisc-C artificial disc–treated (19.7 ± 12.2%) and Prestige artificial disc–treated (22.4 ± 14.0%) specimens were both increased compared with forces in the intact spine, although significance was not achieved. At the superior level, the facet forces recorded in ProDisc-C artificial disc (11.8 ± 4.6%) and ACDF (13.3 ± 10.9%) groups were increased whereas those in the Prestige artificial disc group (−3.6 ± 8.8%) were decreased compared with forces in the intact spine. At the inferior level, the facet forces were decreased in spines fitted with the ProDisc-C artificial disc (−14.0 ± 12.8%), Prestige artificial disc (−4.7 ± 5.7%), and those that underwent ACDF (−1.5 ± 11.6%), but all the changes in superior and inferior facet force were of no significance.

Lateral Bending. At the same level, the facet force associated with the Prestige artificial disc (10.7 ± 13.9%) was increased whereas those associated with the ProDisc-C artificial disc (−6.4 ± 7.4%) and ACDF (−3.4 ± 4.9%) were decreased. The mean facet force changes for different treatments at the superior level were as follows: ProDisc-C artificial disc, −2.4 ± 8.6%; Prestige artificial disc, −7.9 ± 10.5%; and ACDF, 6.8 ± 6.8%. The mean facet force changes for different treatments at the inferior level were as follows: ProDisc-C artificial disc, −2.9 ± 10.1%; Prestige artificial disc, 11.5 ± 9.3%; and ACDF, −7.0 ± 9.0%. All the values were of no statistical significance.

Axial Rotation. At the same level, the facet forces in the ProDisc-C artificial disc (−0.3 ± 6.4%) and ACDF (−6.6 ± 8.2%) groups were decreased whereas that in the Prestige artificial disc group (5.9 ± 7.4%) was increased. The facet force changes associated with the different treatments at the superior level were as follows: ProDisc-C artificial disc, 5.3 ± 9.0%; Prestige artificial disc, 4.5 ± 10.3%; and ACDF, 11.8 ± 8.7%. The facet force changes for different treatments at the inferior level were as follows: ProDisc-C artificial disc, −7.8 ± 5.1%; Prestige artificial disc, −2.9 ± 9.8%; and ACDF, −2.2 ± 9.6%. The differences were not statistically significant.

Discussion

Facet Force Change

Facet forces vary according to the mode of motion. The facet joints were found to carry no load in flexion, large loads during extension (205 N at a 10-Nm moment and a 190-N axial load), rotation (65 N at a 10-Nm moment and a 150-N axial load), and lateral bending (78 N at a 3-Nm moment and a 160-N axial load) in physiological ROM.[21]

There are some published data on fact force change after lumbar fusion,[13,14] but few data are available on changes in the cervical spine.

In our experiment, the facet force changes were minimal

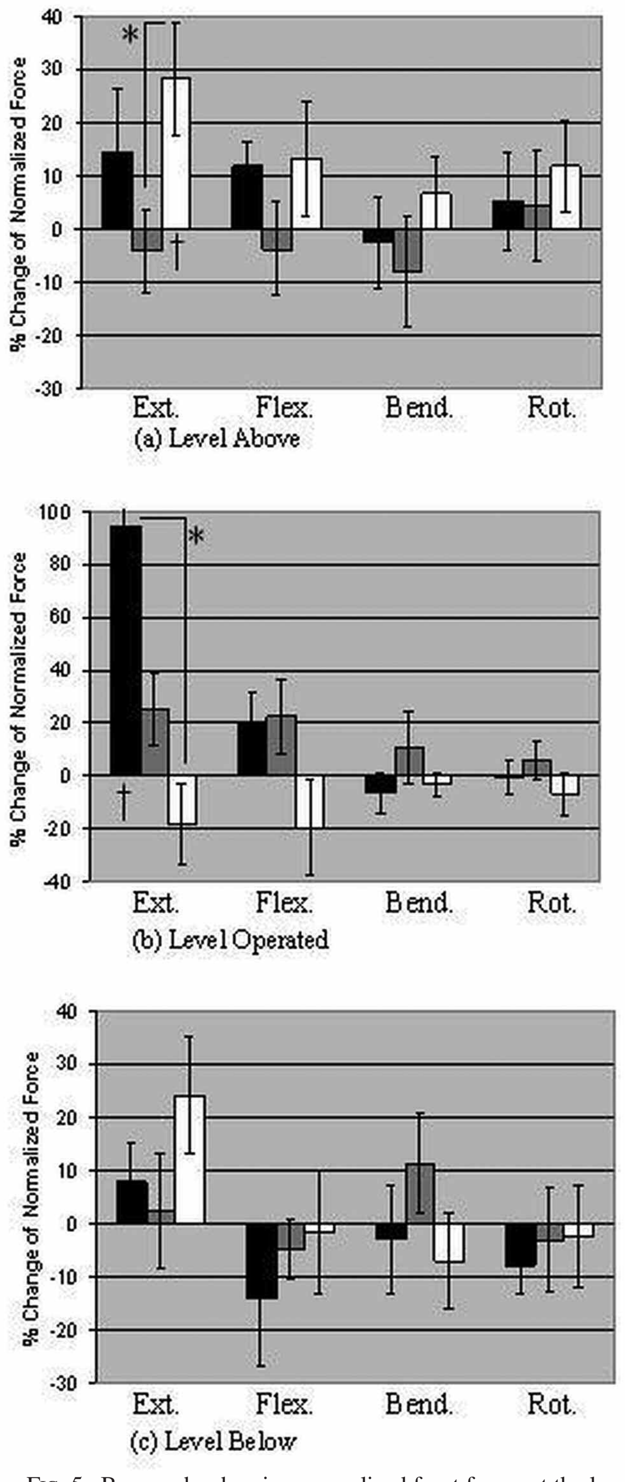

FIG. 5. Bar graphs showing normalized facet forces at the level (a) above (C-5), (b) same as (C-6), and (c) below (C-7) the surgically treated segment. An *asterisk* indicates a significant difference between groups; a *cross* represents a significant difference from intact spine.

in flexion, lateral bending, and rotation modes. This is common after both fusion and arthroplasty. Significant changes were noted in the extension mode only. In extension, arthroplasty models exhibited increased facet force, more at the surgically treated level and less at adjacent levels. In the fusion model, the facet forces showed a decrease at the treated segment and an increase at adjacent segments. The reason facet force increases at the treated segment after arthroplasty may be that, in most artificial discs, the instantaneous axis of rotation is located in the posterior portion of the designed implant.[19] As a result, the lordotic curve is restored and loading on the posterior element increases after arthroplasty.

When there is significant facet loading, the interior tips of the facets bottom out on the laminae below and act as pivots for the entire vertebra to rotate posteriorly, causing a visible stretch of the superior portion of the facet joint capsules.[26] It has also been noted that in extension there is contact between the tip of the facet joint and the lamina below and that a posterior rotation of the superior portion of the facet's inferior articular process occurs, causing the superior portion of the capsule to become extensively stretched.[4] The external geometry of the facet's superior portion is apparently a major factor in determining the magnitude of the stretch.

Change in IDP

Many authors have investigated adjacent-level IDP changes after lumbar fusion.[22,24] In these reports, the adjacent-level IDP increased as the length of fusion levels increased and as the range of flexion and extension motion increased.[24]

Also in the cervical spine, the authors of previous in vitro investigations have reported an increase in adjacent-level IDPs and facet joint stresses following anterior interbody fusion.[6,9,15,20,25] In the report by Dmitriev and colleagues[7] in which the C5–6 level was fused, the IDP change was more prominent at the distal than the proximal level. The IDP increased at the distal level in all modes of motion, but at the proximal level in bending and axial rotation. The great change noted at the distal segment on flexion/extension was consistent with findings reported by Pospiech et al.[20]

Eck and associates[9] reported that the IDP in the nucleus increased during flexion by 73.2% at the proximal level and by 45.3% at the distal level after C5–6 fusion. The pressure increase in extension was not significant. During extension, because a greater portion of the load is applied to the facet joints, the effect on the IDP is less than that found during flexion. In their experiment, the authors found that the increase of ROM accompanies the increase of the IDP.

Wigfield and colleagues[25] applied the techniques used by McNally and Adams[16] to the cervical spine and investigated the internal stress distributions in cadaveric cervical discs. In their report, the IDP was highest in the anterior anulus fibrosus when in the neutral position. A significant IDP increase after fusion was observed only in the anterior anulus fibrosus in flexion. After cervical arthroplasty, the anterior IDP increase disappeared and the IDP change was not noted in the region of nucleus.

Maiman and coworkers[15] analyzed adjacent-disc stress after cervical fusion by using an experimentally validated C4–6 finite element model. A C5–6 fusion resulted in a higher stress increase in the C4–5 disc space in compression than C4–5 fusion did in the C5–6 disc space. In flexion and extension modes, however, the stress change was not different at either proximal or distal levels.

In arthroplasty models, analysis of the data showed that IDP changes were associated with little difference in the intact spine at both proximal and distal levels. In the fusion model, the IDP increased at the posterior aspect of the anulus fibrosus on extension and at the anterior aspect of the anulus fibrosus on flexion at the proximal level. At the distal level, the IDP change was not significant in any mode. These findings show that the artificial disc model resulted in reduced stresses in the anulus fibrosus compared with the fusion model. Measurement of IDP is an appropriate method for characterizing spinal loading condition. Therefore, the little change in IDP after cervical arthroplasty indicates that spinal loading does not increase at the adjacent segments.

As for the fusion model, evaluation of our data demonstrated some differences compared with findings reported by others. In two studies, the IDP increased at both proximal and distal segments after fusion,[7] or greater change was seen at the distal level in rotation mode.[20] The data in the aforementioned studies were measured in the nucleus at each level. We found, however, a significant IDP increase at the proximal level only in flexion/extension mode. Additionally, significant IDP changes were noted at the anulus fibrosus region only. In the nucleus region, the IDP change was minimal. These differences may be due to the different surgically treated level and the use of an axial preload. A constant background load of 200 N during static loading may mask any smaller changes that occur as a result of instrumentation.

Measurement of Cervical IDP

McNally and Adams[16] measured stress profilometry in lumbar disc pressure with a technique that involved a fine-needle pressure transducer. They confirmed that vertical stress was more or less uniformly distributed across the nucleus and inner anulus fibrosus in the nondegenerated disc. Flexion and extension affected the shape of the stress profiles and the overall magnitude of stress.

Hattori and colleagues[11] measured the cervical IDP in patients with a change of posture and degeneration. They obtained pressure measurements in 80 cervical discs in 48 patients who were treated for cervical disc disease. They found a direct correlation between IDP and the extent of disc degeneration.

Pospiech and associates,[20] using small amounts of applied moments, evaluated the effect of anterior fusion on the change in cervical IDP under in vitro condition. When they compared their in vitro data with in vivo data reported by Hattori et al.,[11] they found the IDP changes were in a similar range.

The reason for the paucity of cervical IDP data is the technical challenge associated with placing a pressure sensor in the disc space. When the transducer is inserted into the disc space, the surgeon needs to ensure that the needle-mounted pressure sensor does not touch the endplate. If the sensor makes contact with the osseous structures, it may produce an artifact in the pressure signal. For safe placement, the guide tube may be used when the needle is inserted.[5] The height of the disc in a young individual is 3.8 mm.[10] Pospiech and coworkers[20] used a 1.3-mm-diameter needle. A 1.0-mm-diameter pressure needle would represent 26% of this cervical disc height. The measured values in the cervical disc are considerably higher than those in the lumbar disc at comparable load levels.[5] McNally and Adams[16] reported a pressure of 0.5 MPa for an L2–3 disc under 500 N of compression. Under the same amount of compression, however, the pressure was measured at 1.4 MPa for the C4–5 disc space.[5] This phenomenon can be inferred because the IDP for a given force is known to be inversely proportional to the disc's cross-sectional area.[17] As in the lumbar disc, the IDP varied linearly with the axial compression applied in the cervical disc.[5]

Relation Between IDP and Disc Degeneration

The intervertebral disc lacks a true blood supply. Instead, it depends on nutrients diffusing through the extracellular matrix from peripheral blood vessels and vertebral endplates. Small solutes, such as O_2, glucose, and sulphate, are transported into the disc chiefly by diffusion.[23] Increased pressure in the disc acts to alter the diffusion characteristics of nutrients delivered from the periphery blood supply and leads to an accumulation of waste products in the disc. Failure to remove waste products adequately from the disc can lead to increased lactate levels and decreased pH, which can impair metabolism and lead to cell death.[3]

Adams and colleagues[1] investigated the IDP in degenerated lumbar spine with a 1.3-mm transducer. The degenerative changes reduced the diameter of the central hydrostatic region of each disc (functional nucleus) and pressure within the nucleus. The width of the functional anulus fibrosus increased, and the height of the pressure peak within the anulus fibrosus also increased. This phenomenon was more prominent in the posterior anulus fibrosus than in the anterior anulus. In the healthy disc, the IDP is slightly higher in the posterior anulus than in the anterior anulus fibrosus. The nucleus is lowest. It has been predicted that degeneration will result in a transfer of compressive stress from the nucleus to the anulus fibrosus.[18]

Conclusions

Cervical arthroplasty maintained the adjacent-level IDPs near the values of the intact spines. In a fusion model, adjacent-level IDPs showed the increasing tendency in flexion/extension mode at the superior level. At the inferior level, significant IDPs changes were not noted. With regard to facet force, an increasing tendency was observed in extension at the treated segment. Although cervical arthroplasty can prevent adjacent-level IDP change, it may cause an increase of loading in posterior elements.

Disclaimer

The authors have no financial interest in, and will not benefit from a relationship with, the manufacturing of the devices named in this study.

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