Three-dimensional motion analysis of the cervical spine for comparison of anterior cervical decompression and fusion versus artificial disc replacement in 17 patients

Clinical article

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Object. Cervical arthroplasty with an artificial disc (AD) has emerged as an alternative to anterior cervical discectomy and fusion (ACDF) for the management of cervical spondylosis. This study aims to provide 3D motion analysis data comparing patients after ACDF and AD replacement.

Methods. Ten patients who underwent C5–6 ACDF and 7 who underwent C5–6 AD replacement were enrolled. Using biplanar fluoroscopy and a model-based track technique (accurate up to 0.6 mm and 0.6°), motion analysis of axial rotation and flexion-extension of the neck was performed. Three nonoperative segments (C3–4, C4–5, and C6–7) were assessed for both intervertebral rotation (coronal, sagittal, and axial planes) and facet shear (anteroposterior and mediolateral).

Results. There was no difference in total neck motion comparing ACDF and AD replacement for neck extension ($43.3^\circ \pm 10.2^\circ$ vs $44.3^\circ \pm 12.6^\circ$, $p = 0.866$) and rotation ($36.0^\circ \pm 6.5^\circ$ vs $38.2^\circ \pm 9.3^\circ$, $p = 0.576$). For extension, when measured as a percentage of total neck motion, there was a greater amount of rotation at the nonoperated segments in the ACDF group than in the AD group ($p = 0.003$). When comparing specific motion segments, greater normalized rotation was seen in the ACDF group at C3–4 ($33.2\% \pm 4.9\%$ vs $26.8\% \pm 6.6\%$, $p = 0.036$) and C6–7 ($28.5\% \pm 6.7\%$ vs $20.5\% \pm 5.5\%$, $p = 0.009$) but not at C4–5 ($33.5\% \pm 6.4\%$ vs $31.8\% \pm 4.0\%$, $p = 0.562$). For neck rotation, greater rotation was observed at the nonoperative segments in the ACDF group than in the AD group ($p = 0.024$), but the differences between individual segments did not reach significance ($p \geq 0.146$). Increased mediolateral facet shear was seen on neck extension with ACDF versus AD replacement ($p = 0.008$). Comparing each segment, C3–4 (0.9 ± 0.5 mm vs 0.4 ± 0.1 mm, $p = 0.039$) and C4–5 (1.0 ± 0.4 mm vs 0.5 ± 0.2 mm, $p = 0.022$) showed increased shear while C6–7 (1.0 ± 0.4 mm vs 1.0 ± 0.5 mm, $p = 0.767$) did not.

Conclusions. This study illustrates increased motion at nonoperative segments in patients who have undergone ACDF compared with those who have undergone AD replacement. Further studies will be required to examine whether these changes contribute to adjacent-segment disease.
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KEY WORDS • artificial disc • cervical fusion • adjacent-segment disease

ANTERIOR cervical decompression and fusion (ACDF) is the most common treatment for patients with cervical spine disorders, with the number of procedures increasing by 114% from 1998 to 2008.⁶⁰ Numerous clinical studies have demonstrated the successful

long-term clinical outcome of anterior fusion.^{2,6,17,19,23,27,73} However, other studies have reported a high incidence of degeneration and subsequent symptoms at the adjacent vertebral segments following surgery, with degenerative changes seen in 25%–92% of patients and clinical symptoms presenting in 14%–26% of patients.^{15,22,28,37,41,62} Cervical fusion has been reported to alter adjacent-segment motion, load, and intradiscal pressures,^{3,14,36,46,59} and this

Abbreviations used in this paper: ACDF = anterior cervical decompression and fusion; AD = artificial disc; AP = anteroposterior; CASP = clinical adjacent-segment pathology; ML = mediolateral; RASP = radiographic adjacent-segment pathology; SI = superior/inferior.

This article contains some figures that are displayed in color online but in black-and-white in the print edition.

is believed to induce degenerative changes in the adjacent segments.²⁵ However, it remains unclear whether degenerative changes are the result of changes in the mechanical behavior of the cervical spine or simply a natural progression of the disease with aging.

Cervical arthroplasty with an artificial disc (AD) was designed as an alternative to cervical fusion, with the goal of preserving motion patterns at the implanted level and maintaining normal motion patterns in the adjacent segments. To date there have been several published reports of randomized controlled trials comparing ACDF with AD replacement with varying results.^{4,21,35,48,64,70,71} The results of these trials have shown that AD replacement has excellent outcomes and in some instances is superior to ACDF with lower reoperation rates as well as improved clinical outcomes. Biomechanical studies are important to better understand neck function postsurgery and may provide insight into the mechanical factors that contribute to a good or poor clinical outcome. Unfortunately, there are many gaps in our understanding of the biomechanics of the cervical spine in patients treated with cervical arthroplasty. Although it has been well documented that cervical arthroplasty results in greater motion at the surgical level than fusion,^{18,34,36,45,53,58,63} adjacent-segment biomechanics are less clear. Some studies have reported greater adjacent-segment motion in patients who have undergone fusion,^{18,45,72} while others have reported no difference between these treatment groups.^{34,36,58} One potential reason for the discrepancy in findings between previous studies may be due to the techniques used. Previous studies investigating cervical spine motion are often limited to a 2D analysis^{18,34,39,43,45,53} or cadaveric simulations.^{14,59} Although cadaveric simulations are ideal for measuring 3D motion patterns, they are not designed to reproduce the joint forces, muscle forces, and complex motion patterns associated with in vivo conditions. Two-dimensional analysis methods are well suited for measuring relatively planar movements, such as neck flexion and extension, but are highly susceptible to errors attributed to out-of-plane movement. This may also explain why in vivo studies comparing fusion and arthroplasty are typically isolated to neck flexion-extension motion activities, leaving a gap in our understanding of differences in biomechanics during axial neck rotation.

The mechanics of cervical arthroplasty in comparison with cervical fusion may be better understood using a validated 3D in vivo technique. The objective of this study was to compare in vivo, 3D, dynamic cervical spine kinematics between patients undergoing cervical arthroplasty and those undergoing cervical fusion. We hypothesized that adjacent-segment kinematics (in terms of vertebral rotation and articular facet translation) would be significantly greater in the patients who underwent surgical fusion.

Methods

Clinical Features

Following institutional review board approval and informed consent, 17 patients treated for cervical radicu-

lopathy at C5–6 were included. All patients who showed no complications or evidence of pseudarthrosis (ACDF group), device failure (AD group), or heterotopic ossification (AD group) and who had undergone their surgery at least 12 months earlier were eligible for inclusion. In addition, all patients included in the study had no evidence of ongoing radiculopathy at the index level. Ten subjects underwent single-level ACDF and 7 subjects underwent single-level cervical arthroplasty with an AD.

Motion Analysis

Subjects were seated with their neck centered in a biplane x-ray system (Fig. 1). Biplane radiographs were acquired during 2 motion activities: neck extension and axial neck rotation. Three motion trials were acquired for each motion task. The biplane radiographs had a 23-cm field of view and were acquired at 60 Hz for 2 seconds with the x-ray generators in pulsed mode (70 kV, 160 mA).

Following testing, CT images of each subject's cervical spine were acquired (LightSpeed VCT, GE Medical Systems). Imaging parameters included a field of view of 130 mm, a 512 × 512 acquisition matrix, and a voxel size of 0.25 × 0.25 × 0.625 mm. The CT images of C-3 through C-7 were then segmented from surrounding bones and soft tissues using commercial software (Mimics 12.0, Materialise) and reconstructed to generate 3D bone models of each vertebra.

The 3D position and orientation of each cervical vertebra was determined from the biplane radiographs using a model-based tracking technique.^{5,47} This technique allowed for the independent determination of the 3D position and orientation of 1 vertebra relative to an adjacent vertebra for all frames of each trial and is accurate to within 0.6 mm and 0.6°.⁴⁷

An anatomical coordinate system was created for each vertebra using custom software (Fig. 2 left).⁶⁶ The vertebral body coordinate system was defined by 3 orthogonal vectors oriented in the anteroposterior (AP) direction (AP axis), mediolateral (ML) direction (ML axis), and superoinferior (SI) direction (SI axis). Similarly, anatomical coordinate systems were created for each articular facet using anatomical landmarks and vector cross-products (Fig. 2 right).^{40,42,44} The x axis was oriented in the anterosuperior direction, the y axis was oriented in the lateral direction, and the z axis was oriented in the posterosuperior direction (Fig. 2 right). Outcome measures included vertebral rotation, facet translation, and estimated intervertebral disc height and were calculated based on the position and orientation data determined from biplane radiographs (Figs. 3 and 4). Vertebral rotations, facet translations, and estimated intervertebral disc height were calculated for the operative segment (C5–6), the adjacent segments (C4–5 and C6–7), and a remote segment (C3–4). Vertebral rotations were quantified using a technique described by Panjabi et al.⁵¹ As an additional outcome measure, vertebral rotation was also normalized as a percentage of the total subaxial neck rotation. Total subaxial neck rotation was defined as the full rotation of the C-3 vertebra with respect to the C-7 vertebra for each motion task. To describe facet translations, AP sliding was defined as translation of the inferior

3D motion analysis comparing ACDF with an artificial disc

Fig. 1. **Left:** Photograph of the biplane x-ray system used for this study. **Right:** Photograph of a subject sitting within the field of view of both x-ray cameras for testing.

articular facet along the x axis of the adjacent superior articular facet, and ML shear was defined as translation of the inferior articular facet along the y axis of the adjacent superior articular facet (Fig. 2 right). Facet translation was calculated as the average translation between the left and right facets for each motion segment. Estimated disc height was calculated as the average endplate-to-endplate distance between adjacent vertebrae.

Statistical Analysis

Differences in vertebral rotation, normalized vertebral rotation, facet translation, and estimated intervertebral disc height were compared between the fusion group and arthroplasty group. At the operative segment (C5–6), differences between groups were assessed using individual t-tests. At the nonoperative segments (C3–4, C4–5, and C6–7), differences between groups were assessed using 2-way ANOVA, with surgical treatment and vertebral level being the independent variables. Vertebral rotation, normalized vertebral rotation, facet translation, and es-

timated intervertebral disc height were also compared across all motion segments (both operative and nonoperative) using a 1-way analysis of variance for each group, with vertebral level being the independent variable. The translational components of facet translation were compared for each group using a paired t-test. Significance was set at $p < 0.05$.

Results

A total of 17 patients were included in the study. Ten patients underwent C5–6 ACDF, while 7 patients underwent C5–6 AD replacement. The mean age for the ACDF group was 48 ± 10.8 years, and the mean age of the AD group was 47 ± 7.0 years with no statistical difference between the groups ($p = 0.83$). The mean postoperative period at time of enrollment was 24.1 ± 7.4 months for the fusion group and 22.0 ± 3.3 months for the arthroplasty group with no statistical difference between the groups ($p = 0.50$).

Fig. 2. An anatomical coordinate system was defined for the vertebral body and each articular facet. **Left:** The vertebral body coordinate system was defined by 3 anatomical landmarks: the center of the vertebral body (1), and the centers of the left (2) and right (3) lateral masses. **Right:** Each articular facet coordinate system was defined by 4 anatomical landmarks: the anterosuperior (1), posteroinferior (2), medial (3), and lateral (4) aspects of each facet. X, Y, and Z denote the axes.

Vertebral Motion Between Groups in Neck Extension

During the neck extension motion task, total lower-neck rotation was $43.3^\circ \pm 10.2^\circ$ in the ACDF group and $44.3^\circ \pm 12.6^\circ$ in the AD group ($p = 0.866$). When comparing vertebral rotation between groups (Fig. 5), significant differences were found at the operative segment (C5–6), with vertebral rotation in the AD group ($8.8^\circ \pm 3.9^\circ$) being significantly greater than in the ACDF group ($2.8^\circ \pm 1.2^\circ$, $p = 0.002$). Although there was a trend for greater vertebral rotation in the ACDF group at the nonoperative segments (C3–4, C4–5, and C6–7), these differences were not statistically significant ($p = 0.093$, Fig. 5). Isolating differences in vertebral rotation by motion segment, differences between the ACDF group and AD group were most apparent at C6–7 ($12.4^\circ \pm 4.0^\circ$ vs $9.2^\circ \pm 4.2^\circ$, $p = 0.139$) and least apparent at C4–5 ($14.9^\circ \pm 5.9^\circ$ vs $13.9^\circ \pm 3.4^\circ$, $p = 0.711$). Differences in vertebral motion between

FIG. 3. Illustration of marker-less tracking and motion analysis. **A and B:** Oblique radiographs obtained in a patient at full flexion who underwent AD replacement. **C:** The 3D computer model generated after tracking, which is used for kinematic measurements. **D and E:** Oblique radiographs obtained in the same patient at full extension. **F:** The 3D computer model.

groups were more pronounced when evaluating vertebral rotations as a percentage of total lower-neck rotation (Fig. 6). Normalized vertebral rotation at C5–6 in the arthroplasty group ($19.7\% \pm 6.2\%$) was significantly greater than in the ACDF group ($6.8\% \pm 3.3\%$, $p < 0.001$). At the nonoperative segments, there was significantly greater motion in the ACDF group than in the AD group ($p = 0.003$). Isolating differences by motion segment, normalized vertebral rotation in the ACDF group was significantly greater than the AD group at C3–4 ($33.2\% \pm 4.9\%$ vs $26.8\% \pm 6.6\%$, $p = 0.036$) and C6–7 ($28.5\% \pm 6.7\%$ vs $20.5\% \pm 5.5\%$, $p = 0.009$), but not at C4–5 ($33.5\% \pm 6.4\%$ vs $31.8\% \pm 4.0\%$, $p = 0.562$).

Vertebral Motion Between Groups in Axial Neck Rotation

During the axial neck rotation motion task, total lower-neck rotation was $36.0^\circ \pm 6.5^\circ$ in the ACDF group and $38.2^\circ \pm 9.3^\circ$ in the AD group ($p = 0.576$). When com-

paring vertebral rotation between groups (Fig. 7), significant differences were found at C5–6, with vertebral rotation in the AD group ($7.2^\circ \pm 5.3^\circ$) being significantly greater than in the ACDF group ($2.4^\circ \pm 1.2^\circ$, $p = 0.035$). Vertebral rotation at the nonoperative segments (C3–4, C4–5, and C6–7) was greater in the ACDF group, but these differences were not significant ($p = 0.104$). Isolating differences in vertebral rotation by motion segment, differences between the ACDF group and AD group were most apparent at C3–4 ($12.5^\circ \pm 2.7^\circ$ vs $10.7^\circ \pm 1.6^\circ$, $p = 0.235$) and least apparent at C4–5 ($13.6^\circ \pm 3.4^\circ$ vs $12.6^\circ \pm 2.5^\circ$, $p = 0.511$). Differences in vertebral motion between groups were again more pronounced when evaluating normalized vertebral rotation (Fig. 8). Normalized vertebral rotation at C5–6 in the AD group ($17.2\% \pm 9.1\%$) was significantly greater than in the ACDF group ($6.7\% \pm 2.6\%$, $p = 0.004$). At the nonoperative segments, there was significantly greater motion in the ACDF group than

FIG. 4. An example of an ACDF patient's motion study at the fully extended position. **A and B:** Oblique radiographs obtained by the x-ray cameras. **C:** The 3D computer model generated after tracking, which is used for kinematic measurements.

3D motion analysis comparing ACDF with an artificial disc

Fig. 5. Vertebral rotation is shown for the neck extension motion task. Vertebral rotation was greater in the AD group at C5–6. There were differences in motion between groups at C3–4, C4–5, and C6–7, but these did not reach statistical significance.

in the AD group ($p = 0.024$). However, there were no significant differences at any nonoperative segment when differences between groups were isolated by motion segment ($p \geq 0.146$).

Vertebral Rotation Across Segments

Comparing vertebral motion across both operative and nonoperative segments, C5–6 rotation was significantly less in the fusion group than in any of the nonoperative segments for both motion tasks ($p < 0.001$). Rotation at C5–6 for the ACDF group ranged from 1.3° to 5.1° during neck extension and from 0.7° to 4.3° during axial neck rotation. For the AD group, there were no significant differences between C5–6 and either C3–4 or C6–7 ($p > 0.142$). However, C5–6 rotation was significantly less than C4–5 rotation for both neck extension ($8.8^\circ \pm 3.9^\circ$ vs $13.9^\circ \pm 3.4^\circ$, $p = 0.027$) and axial neck rotation ($7.2^\circ \pm 5.3^\circ$ vs $12.6^\circ \pm 2.5^\circ$, $p = 0.012$). Rotation at C5–6 for the AD group ranged from 4.5° to 14.0° during neck extension and from 2.3° to 14.2° during axial neck rotation.

Facet Translation Between Groups

For both motion tasks, facet translation in the AP slid-

Fig. 6. Normalized vertebral rotation is shown for the neck extension motion task. Normalized vertebral rotation was greater in the AD group at C5–6, and greater in the ACDF group at C3–4 and C6–7.

Fig. 7. Vertebral rotation is shown for the axial neck rotation motion task. Vertebral rotation was greater in the arthroplasty group at C5–6. There were no significant differences in motion between groups at C3–4, C4–5, and C6–7.

ing direction was greater than in the ML shear direction ($p < 0.001$, Figs. 9 and 10). Facet translation exhibited significantly greater ML shear during axial neck rotation than during neck extension ($p < 0.001$). Comparing differences between groups, facet translation at C5–6 was greater in the AD group than the ACDF group, although this difference was only significant in the AP sliding direction ($p < 0.001$ for neck extension, $p = 0.045$ for axial neck rotation). At the nonoperative segments, facet translation was greater in the ACDF group. However, these differences were only significant in the ML shear direction during neck extension ($p = 0.008$). Isolating differences by motion segment, ML shear in the ACDF group was significantly greater than the arthroplasty group at C3–4 (0.9 ± 0.5 mm vs 0.4 ± 0.1 mm, $p = 0.039$) and C4–5 (1.0 ± 0.4 mm vs 0.5 ± 0.2 mm, $p = 0.022$), but not at C6–7 (1.0 ± 0.4 mm vs 1.0 ± 0.5 mm, $p = 0.767$).

Intervertebral Disc Height Between Groups

Intervertebral disc height at C5–6 in the AD group

Fig. 8. Normalized vertebral rotation is shown for the axial neck rotation motion task. Normalized vertebral rotation was greater in the arthroplasty group at C5–6. Although differences in motion at the adjacent (C4–5 and C6–7) and remote (C3–4) segments were more pronounced compared with vertebral rotation, there were again no significant differences between groups.

FIG. 9. Facet translation in anterior sliding and lateral shear is shown for the axial neck rotation motion task. Facet translation was greater in the AD group at C5–6 for only anterior sliding. There were no significant differences in facet translation between groups at C3–4, C4–5, and C6–7.

(5.7 ± 0.7 mm) was significantly greater than in the ACDF group (1.9 ± 1.6 mm, $p < 0.001$, Fig. 11). In comparison, there was no significant difference in intervertebral disc height at the nonoperative segments ($p = 0.484$). Isolating by motion segment, differences in intervertebral disc height between the ACDF group and AD group were most apparent at C6–7 (3.2 ± 0.7 mm vs 3.8 ± 0.5 mm, $p = 0.107$) and least apparent at C4–5 (3.4 ± 0.8 mm vs 3.4 ± 0.3 mm, $p = 0.935$). In the AD group, C5–6 disc height was significantly greater than the nonoperative segments ($p < 0.01$). In the fusion group, C5–6 disc height was significantly less than the nonoperative segments ($p < 0.004$).

Discussion

Several studies have compared the biomechanical characteristics of the cervical spine following fusion and

arthroplasty. However, these studies are often limited to an assessment of vertebral body kinematics during only neck flexion or extension with lateral radiographs, and therefore can only assess motion in 2 dimensions. Sasso et al. published motion analysis results from their prospective, randomized multicenter trial with the Bryan Cervical Disc (Medtronic Sofamor Danek).⁶³ This study benefits from a large sample size with 221 ACDF patients and 242 AD patients. Flexion, extension, and neutral radiographs were used for motion analysis, using sagittal rotation in degrees as its primary end point. This study showed durability of device mobility after 2 years, with a loss of 0.87° from preoperative values in the AD group. Measurements of adjacent-segment rotation were also performed with no observed differences between caudal and cranial adjacent-segment motion between AD and ACDF cohorts.

Lazaro et al. published a study in which 60 patients

FIG. 10. Facet translation in anterior sliding and lateral shear is shown for the neck extension motion task. Facet translation was greater in the AD group at C5–6 for only anterior sliding, and statistically significantly greater in the ACDF group at C3–4 and C4–5 for only lateral shear.

3D motion analysis comparing ACDF with an artificial disc

Fig. 11. Intervertebral disc height is shown for each motion segment. The C5–6 disc height in the AD group was significantly greater than in the ACDF group.

were retrospectively analyzed using lateral flexion, extension, and neutral radiographs.⁴³ Three devices were included in that study: Bryan Cervical Disc, ProDisc-C (DePuy Synthes, Inc.), and Synergy Cervical Disc (Synergy Disc Replacement, Inc.). The study was concerned primarily with characteristics at the index level, analyzing postoperative range of motion, disc height, sagittal plane translation, angulation, and center of rotation. Of note, the Bryan disc group developed a significant shell kyphosis postoperatively. In addition, both the Bryan and Synergy discs maintained the natural center of rotation while there was a significant anterior shift with the ProDisc-C. This study did not analyze any adjacent-segment parameters.

Kowalczyk et al. published a follow-up study, this time comparing the Prestige LP disc (Medtronic Sofamor Danek) with the Bryan and ProDisc-C implants.³⁹ This study also used lateral radiographs and focused on various parameters at the index level including range of motion, disc angle, disc height and translation, and center of rotation. Again, the Bryan disc exhibited significant shell angle kyphosis postoperatively, while the ProDisc-C and Prestige LP discs retained lordosis. There was a loss of disc height following insertion of the Bryan disc. The importance of these findings relates to long-term outcome where kyphosis is associated with an increased incidence of adjacent-segment disease.²⁴ However, this study did not examine adjacent-segment parameters.

Anderson et al.¹ published a systematic review and meta-analysis of 12 studies, including 7 randomized control trials, 4 cohort studies, and 1 case-control study and examined kinematic measurements of adjacent segments after AD replacement and ACDF. End points of interest included adjacent-segment range of motion and centers of rotation after surgery. The authors found no statistical difference between the AD and ACDF cohorts. There was a difference in lordotic angulation of adjacent segments in patients who underwent AD replacement and those who underwent ACDF. However, there was no change in global sagittal alignment (C2–7) between the cohorts at the 2-year follow-up. Again, this study dealt exclusively with 2D parameters in the sagittal plane.

In this study, we conducted a thorough in vivo kine-

matic analysis of vertebral rotation and facet translation during both neck extension and axial neck rotation motion activities. To our knowledge, this is the first study that is able to assess vertebral motion in vivo and in 3 dimensions after ACDF or AD replacement. A further distinction of this study is that images were acquired in dynamic conditions during active motion, whereas traditional flexion-extension views are obtained at static positions, although the extent to which static testing is representative of dynamic conditions remains unknown. This research also includes analysis at a more remote motion segment, C3–4, in addition to the cranial and caudal segments adjacent to the index level. The findings from this study provide support for reduced vertebral motion across multiple nonoperative segments in arthroplasty patients when compared with fusion patients.

Although previous studies have shown a postsurgical increase in adjacent-segment motion during neck extension after cervical fusion,^{3,36} there is conflicting evidence when comparing adjacent-segment motion between fusion and arthroplasty subjects. Some studies have reported adjacent-segment motion to be greater in fusion subjects than in arthroplasty subjects,^{18,45} while others have reported no difference.^{34,36} Nonsignificant differences between groups in some instances may be explained by a distribution of motion across several motion segments. Although it has been reported previously that motion lost due to fusion is primarily transferred to the cranial adjacent segment,^{3,14,53,59} we found significant differences in motion at the caudal adjacent segment (C6–7) and a remote segment (C3–4), 2 levels cranial to the operative segment. This is similar to the results reported by Finn et al., where motion was simulated in 6 cadaveric specimens under intact, fusion, and arthroplasty conditions.¹⁸ The authors reported differences in motion between the fusion and arthroplasty conditions at all nonoperative segments (2 adjacent and 2 remote), where significance was seen in all but the caudal segment.

It has also been well documented that C5–6 is typically the most mobile segment of the lower cervical spine during neck flexion-extension, followed by C4–5.^{12,13,57} Vertebral motion at the implanted level of arthroplasty patients has been reported to be restored to preoperative levels.³⁶ However, it is unknown how preoperative motion at the implanted level may have been affected by cervical degenerative disc disease, making it challenging to determine the extent to which normal vertebral motion at the implanted level is restored postsurgery. A more appropriate approach may be to compare motion at the implanted level to the adjacent segments within the same subject. Kim et al. found no significant difference in motion between the implanted level and adjacent segments.³⁶ Similarly, Finn et al. measured cervical arthroplasty in cadaveric specimens and found no significant difference between vertebral levels in neck extension.¹⁸ In our investigation, we found C5–6 motion to vary widely among subjects, with C4–5 motion being greater than C5–6 motion in 6 of the 7 subjects, suggesting that cervical arthroplasty may not fully restore vertebral motion at the implanted level. However, our findings do illustrate durability of motion at the index level at a mean of 22 months postoperatively. In addition, this finding is also demon-

strated in 3 dimensions, with motion being preserved during axial neck rotation in addition to cervical extension.

In recent years, articular facet biomechanics has become a topic of interest,^{29–32,44,52} as significant changes in relative facet motion following trauma or surgery have been suggested to induce degenerative changes in the articular cartilage.^{55,65} Although studies have investigated in vivo facet kinematics at the lumbar spine,^{40,44} there are no known in vivo studies that have compared different surgical techniques on facet kinematics in the cervical spine. In our investigation, facet translations were described using local facet coordinate systems defined by facet-based landmarks.^{40,42,44} Facet translation during neck extension was primarily in the direction of AP sliding while a coupled translation of combined AP sliding and ML shear was more evident during axial neck rotation. Generally, there were greater translations at the nonoperative segments in the fusion group. The results of our investigation suggest that there may be some degree of hypermobility at nonoperative segments subsequent to cervical fusion, which has been suggested to result in increased compressive stresses between the articulating surfaces and facilitate cartilage degeneration.^{11,50} Although the inclusion of preoperative data are necessary to determine the extent to which facet joint kinematics are altered due to surgery, the differences between patients undergoing ACDF and AD replacement found in our study suggest that more attention should nonetheless be paid to the cervical facet joints when considering surgical treatment.

Despite the aforementioned differences in cervical kinematics observed between our ACDF and AD groups, the fact remains that recently published long-term studies of cervical AD results show fairly equivocal results in developing adjacent-segment pathology.^{7,8,16} This has led some authors to conclude that any degeneration at segments adjacent to a fusion is simply part of the natural history of spondylosis and, by extension, not necessarily an iatrogenic result from fusion.^{16,49} Some authors have advocated a shift in the semantics of adjacent-segment disease to adjacent-segment pathology, using descriptors of radiographic adjacent-segment pathology (RASP) and clinical adjacent-segment pathology (CASP) manifestations.⁶¹ A recent systematic review analyzed 6 randomized control trials, as well as 5 prospective cohort trials regarding the incidence of CASP and RASP.²⁶ The authors concluded that there is no significant difference in development of either CASP or RASP after AD replacement versus ACDF at short- to midterm follow-up. Therefore, if CASP has an equal incidence in both ACDF and AD populations despite observed differences in kinematics between the groups, the etiology of cervical spondylosis may not lie in motion characteristics but perhaps biological characteristics of the intervertebral disc and/or facet joints instead. Thus far, the causality between motion characteristics and a propensity for degeneration and pathogenesis of clinical symptoms by spondylotic pathology has not been clearly established. One possibility is that motion characteristics may be an observed consequence of degeneration as opposed to a cause and that the true underlying cause is an intrinsic biological defect within the joints of the spine. Regardless, additional lon-

gitudinal kinematic data in the same patient populations will prove useful in establishing what role motion plays in cervical degeneration.

There was no significant difference in intervertebral disc height between the ACDF and AD groups, except for at the operative level, where the AD group had significantly greater disc height than the fusion group. Changes in disc height resulting from cervical disc disease or surgical intervention have been suggested as a possible factor contributing to the progression of adjacent-segment degeneration, with a decrease in disc height resulting in increased intradiscal pressure and facet contact force.^{11,29,50,68} In our investigation, C5–6 disc height compared with the nonoperative segments was significantly greater in the AD group and significantly lower in the ACDF group. These findings are in agreement with previous studies.^{9,10,33,54,56,69} The evaluation of disc height as normal is typically based on comparing adjacent cranially or caudally located discs,³⁸ since the preoperative condition of the disc is often already affected by cervical disc disease. Intrasubject measurements of intervertebral disc height of the lower cervical spine have shown little variation across motion segments,²⁰ which suggests that adjacent disc height comparison is a suitable approach for the assessment of intervertebral disc height postsurgery.

Conclusions

We conducted an in vivo study that compared cervical spine kinematics during both neck extension and axial neck rotation between patients undergoing ACDF and AD replacement. Patients treated with cervical fusion of the C5–6 vertebrae had, generally, greater adjacent-segment vertebral rotation and facet translation than the arthroplasty patients. We also found differences in motion at a remote motion segment, suggesting that motion lost due to fusion may be transferred across more than just the adjacent segments. However, our results also suggest that, while arthroplasty results in decreased adjacent segment motion compared with fusion, arthroplasty may not restore motion at the operative segment, possibly due to changes in disc height or heterotopic ossification.⁶⁷ We recognize that this study has some weaknesses such as the relatively small sample size and a lack of preoperative data for comparison. Notwithstanding these limitations, the data reported here contribute to our understanding of cervical spine kinematics in patients treated with either ACDF or AD replacement, and provide support for reduced vertebral motion across multiple nonoperative motion segments in patients undergoing cervical arthroplasty when compared with those undergoing cervical fusion. An understanding of cervical spine kinematics following either fusion or arthroplasty is an important step toward understanding the relationship between motion and the progression of adjacent-segment degeneration postsurgery.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

3D motion analysis comparing ACDF with an artificial disc

Author contributions to the study and manuscript preparation include the following. Conception and design: Chang, Bartol. Acquisition of data: Chang, CP McDonald, M McDonald, Ramo, Bey. Analysis and interpretation of data: all authors. Drafting the article: Chang. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Chang. Study supervision: Bartol.

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