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Kinematic Analysis of the Cervical Spine Following Implantation of an Artificial Cervical Disc

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Study Design. Prospective cohort study.

Objective. To assess the biomechanical profile of the cervical spine following cervical arthroplasty.

Summary of Background Data. Spinal arthroplasty offers the promise of maintaining functional spinal motion, thereby potentially avoiding adjacent segment disease. Disc replacement may become the next gold standard for the treatment of degenerative cervical spine disease, and must be studied rigorously to ensure *in vivo* efficacy and safety.

Methods. A total of 20 patients underwent single or 2-level implantation of the Bryan® artificial cervical disc (Medtronic Sofamor Danek, Memphis TN) for treatment of cervical degenerative disc disease producing radiculopathy and/or myelopathy. Lateral neutral, flexion, and extension cervical radiographs were obtained before surgery and at intervals up to 24 months after surgery. Kinematic parameters, including sagittal rotation, horizontal translation, change in disc height, and center of rotation (COR), were assessed for each spinal level using quantitative motion analysis software.

Results. Motion was preserved in the operated spinal segments (mean range of motion 7.8°) up to 24 months following surgery. The relative contribution of each spinal segment to overall spinal sagittal rotation differed depending on whether the disc was placed at C5–C6 or C6–C7. Overall cervical motion (C2–C7) was moderately but significantly increased during late follow-up. Sagittal rotation, anterior and posterior disc height, translation, and COR coordinates did not change significantly following surgery. The COR was most frequently located posterior and inferior to the center of the disc space.

Conclusions. The Bryan® artificial cervical disc provided *in vivo* functional spinal motion at the operated level, reproducing the preoperative kinematics of the spondylotic disc.

Key words: biomechanics, cervical spine, spinal arthroplasty, cervical disc prosthesis, artificial disc. **Spine 2005;30:1949–1954**

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Cervical arthroplasty aims to restore normal spinal motion following anterior cervical discectomy and avoid the abnormal kinematic stresses produced by anterior cervical fusion. By converting a mobile, functional spinal unit into a fixed, nonfunctional one, arthrodesis results in increased strain at levels immediately adjacent to the fused segment,[1,2] and is thought to result in more rapid disc degeneration and/or segmental instability at these levels.[1,3–9] Such adjacent segment degeneration may be preventable if spinal motion can be maintained by a functional disc prosthesis. To achieve this goal, an artificial disc must mimic natural spinal kinematics as closely as possible, maintaining biomechanical parameters not only at the operated level but throughout the spine.

The Bryan® cervical disc prosthesis (Medtronic Sofamor Danek, Memphis TN) consists of a low friction polyurethane nucleus, surrounded by a polyurethane sheath, situated between 2 titanium alloy shells. The disc possesses elasticity and compressibility, and allows for unconstrained motion and translation through the normal range of motion (ROM). Early clinical results from European trials of single and 2-level implantation showed that sagittal plane motion was preserved in 88% of single-level and 86% of 2-level patients at 1 year, while clinical outcomes were rated as excellent, good, or fair in more than 90% of patients at 1 year.[10] We determine whether the Bryan® artificial cervical disc preserved the kinematic parameters of the preoperative spine in a prospectively enrolled cohort of patients. Quantitative Motion Analysis software (Medical Metrics, Inc., Houston, TX) was used to evaluate the *in vivo* biomechanical impact of the Bryan® disc.

Patients and Methods

There were 20 consecutive patients with cervical spondylosis at 1 or 2 levels, presenting with radiculopathy and/or myelopathy, who underwent anterior cervical discectomy, followed by implantation of the Bryan® cervical disc prosthesis. The operative technique has been described previously.[11] Static and dynamic digital radiographs were obtained before surgery at 1.5–3 months, and at additional times up to 6, 12, or 24 months after surgery. Experienced radiographers obtained all radiographs at a distance of 72 in. The neutral lateral image was obtained, and patients were then instructed to flex their neck as much as possible, bringing the chin down to the chest, to obtain the flexion image. Patients were then instructed to return to neutral and then to extend their neck as much as possible, raising the chin and looking to the ceiling, to obtain the extension view. A single ROM was performed.

Quantitative Motion Analysis software (Medical Metrics, Inc.) was used to analyze intervertebral motion. This validated radiographic motion analysis software uses advanced pattern recognition algorithms to generate accurate measurements of segmental sagittal rotation, anterior and posterior disc distraction (height displacement), and horizontal translation.[12,13] These values and the center of rotation (COR) were obtained for each spinal level from C2–C3 to C6–C7. The location of the center of the vertebral body was calculated by averaging the absolute (X,Y) coordinates of the 4 vertebral corners in a lateral view. The COR was then reported as (X,Y) offset from the center of the vertebral body.

The preoperative and postoperative biomechanics of each spinal level were examined for 3 operative groups, including disc implanted at C5–C6, disc implanted at C6–C7, and 2-level procedures. Times for postoperative radiographic follow-up were defined as early (1.5–3 months) and late (6 up to 24 months). Absolute values within groups were assessed, together with measures of change within individual patients. The Student *t* test and analysis of variance were used to assess statistical significance.

■ Results

A total of 24 discs were implanted in 20 patients, including 8 at C5–C6 alone, 8 at C6–C7 alone, while 4 patients underwent 2-level implantation. Table 1 presents observed sagittal rotation values for all patients at all spinal levels before surgery, and during early and late follow-up. Mean postoperative sagittal ROM at the operated disc space was 8.04° during early follow-up and 8.92° during late follow-up, not significantly different from the preoperative value of 8.89° (paired Student *t* test, $P = 0.45$ and 0.74, respectively). No significant change was observed in mean ROM at adjacent or more distant spinal levels (Table 1). The amount of rotation contributed by each spinal level to overall cervical rotation appeared to differ before surgery, depending on whether the patients had C5–C6 or C6–C7 disease (Figure 1), and these patterns did not change significantly postoperatively. Overall cervical sagittal motion from C2–C7 increased moderately but significantly during late follow-up, from a preoperative mean of 47.2° to 56.1° during late follow-up ($P = 0.027$). This increase in mobility (mean 8.9°) was distributed over all spinal levels. The vast majority of this increase occurred between the early and late times.

Measurements of horizontal translation did not change significantly at any level or time (Table 2). Mean preoperative translation was 1.5 mm at C5–C6 and 0.7 mm at C6–C7; during late follow-up, mean translation was 1.5 and 1.1 mm, respectively. Anterior and posterior disc distraction or compression also did not change significantly following surgery (Table 2). Translation, ROM, and anterior disc distraction were correlated: higher sagittal rotation at a given level was associated with higher translation as well as higher change in anterior disc height.

The preoperative and postoperative mean coordinates of the COR for each operated level and adjacent levels are presented in Figures 2, 3. The lack of motion introduces very large errors into the calculation of the COR, and, therefore, COR values from any spinal segment that showed a sagittal ROM <2° were censored. The preoperative window for the (X,Y) coordinates of the COR ranged from as high as 6.8 mm off the anteroposterior

Table 1. Sagittal Rotation (degrees) at All Levels for All Patients

Level	C2–C3	C3–C4	C4–C5	C5–C6	C6–C7
			Preop.		
C5/C6	3.7	11.0	13.7	13.9	16.7
C5/C6	8.1	8.2	10.1	13.3	13.9
C5/C6	4.8	6.9	6.4	2.4	6.7
C5/C6	1.2	15.0	20.1	19.8	13.2
C5/C6	4.9	8.6	11.4	12.6	7.4
C5/C6	7.4	12.3	15.6	3.6	0.5
C5/C6	8.2	13.8	15.6	9.8	11.5
C5/C6	8.6	9.2	10.0	13.7	5.7
C6/C7	7.1	9.5	10.5	6.0	5.2
C6/C7	7.7	8.6	13.7	10.8	7.8
C6/C7	5.3	10.7	13.8	17.3	12.6
C6/C7	3.2	5.4	12.2	14.0	4.5
C6/C7	7.8	13.4	19.3	21.9	11.9
C6/C7	3.0	7.0	12.0	14.0	7.2
C6/C7	3.9	8.3	12.4	9.6	7.1
C6/C7	4.3	9.8	11.1	10.8	8.0
C4/C5 + C5/C6	1.7	11.3	4.6	9.5	1.2
C5/C6 + C6/C7	8.5	12.0	14.4	8.8	2.3
C5/C6 + C6/C7	6.8	11.6	8.7	5.6	4.1
C5/C6 + C6/C7	3.3	6.6	11.1	16.2	8.8
Mean	5.5	10.0	12.3	11.7	7.8
			Early Postop.		
C5/C6	5.6	12.8	12.6	8.0	14.4
C5/C6	8.3	7.8	11.8	10.6	9.2
C5/C6	5.9	8.3	9.2	4.5	14.6
C5/C6	0.1	11.5	14.3	2.2	6.2
C5/C6	3.2	6.5	12.9	9.8	9.2
C5/C6	8.2	14.3	18.8	3.3	0.8
C5/C6	7.1	11.2	11.9	5.0	2.9
C5/C6	8.0	13.8	17.9	11.6	15.7
C6/C7	8.9	12.8	17.9	13.5	16.4
C6/C7	7.3	11.2	13.2	15.0	8.4
C6/C7	3.7	7.8	13.9	15.8	7.2
C6/C7	5.2	5.5	11.8	15.8	9.5
C6/C7	4.8	9.8	12.6	12.7	4.6
C6/C7	8.2	13.1	18.2	14.7	8.8
C6/C7	6.1	10.6	14.1	7.1	2.2
C6/C7	9.3	9.3	11.2	16.9	8.0
C4/C5 + C5/C6	9.4	4.0	9.7	8.9	1.0
C5/C6 + C6/C7	9.6	10.4	12.8	12.5	11.4
C5/C6 + C6/C7	9.4	13.6	10.9	6.5	7.2
C5/C6 + C6/C7	5.2	7.3	11.4	6.4	3.5
Mean	6.7	10.1	13.4	10.0	8.1
			Late Postop.		
C5/C6	6.3	14.4	17.0	8.1	16.6
C5/C6	9.6	6.0	9.8	11.7	9.4
C5/C6	6.5	10.3	9.8	6.0	15.7
C5/C6	1.0	14.0	19.4	8.7	15.2
C5/C6	6.3	10.4	13.3	10.8	5.4
C5/C6	7.6	16.3	22.6	14.8	13.3
C5/C6	7.5	15.1	18.1	2.0	12.7
C5/C6	8.0	14.8	21.0	13.6	16.8
C6/C7	5.6	9.5	12.1	14.4	5.4
C6/C7	4.0	5.6	13.7	15.8	7.6
C6/C7	6.8	10.6	16.2	14.2	3.0
C6/C7	6.8	10.3	15.2	13.5	8.4
C6/C7	7.8	12.6	17.7	16.3	8.2
C6/C7	9.0	9.4	10.7	16.4	9.6
C5/C6 + C6/C7	9.4	11.2	12.4	12.7	12.2
Mean	6.8	11.4	15.3	11.9	10.6

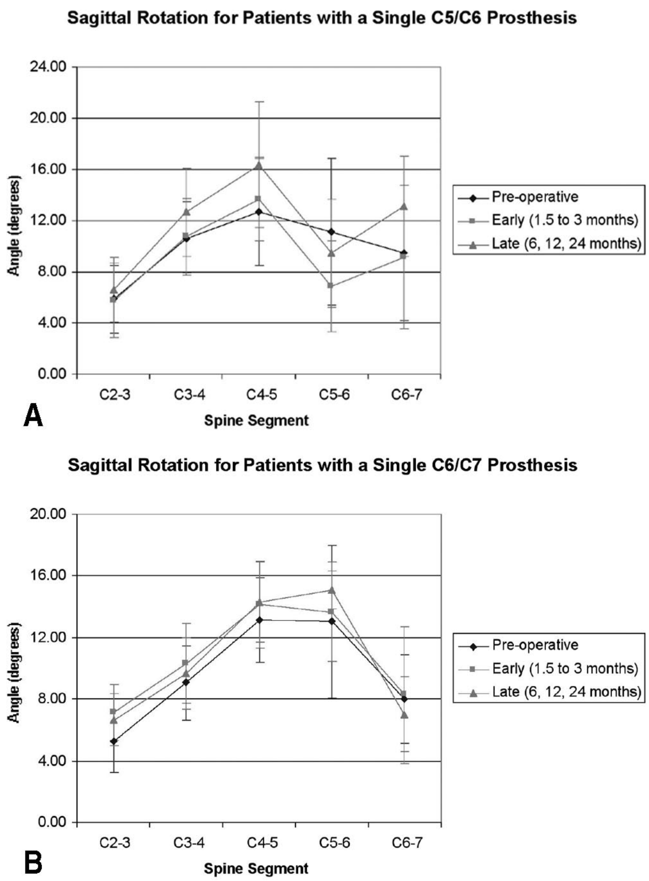

Figure 1. Sagittal plane rotation showing mean values before surgery, and during early and late follow-up. **A**, Disc placed at C5–C6. **B**, Disc placed at C6–C7.

center and 11.5 mm off the cephalad-caudad center of the disc space. COR values did not change significantly at the operated level or at any other spinal level during either early or late follow-up.

■ Discussion

A cervical disc replacement must adequately mimic the *in vivo* function and biomechanics of an intervertebral disc if it is to restore the functional spinal unit and avoid long-term consequences of fusion. Early results in this small group of patients found no significant change in sagittal rotation, translation, anterior and posterior distraction, or COR values following insertion of the Bryan® cervical disc prosthesis. This result indicates that the disc is able to provide equivalent ROM, translation, and disc compressibility as compared to the preoperative condition of the discs at the operated levels. Furthermore, no significant alterations of function occurred at adjacent or more distant spinal levels.

The nature and extent of the biomechanical stress produced by anterior cervical discectomy and fusion (ACDF) remains controversial. Fusion removes a functional motion segment, and, therefore, either the total cervical ROM must decrease in fused cases or else the nonfused segments must move more. Biomechanical analysis in cadaveric specimens has shown increased intradiscal pressures and increased segmental motion at levels adjacent to a fixation with anterior cervical plating during normal ROM.[2] Matsunaga *et al*[1] studied 96 patients following ACDF and showed increased strain at the adjacent-level intervertebral discs, particularly in cases in which degenerative changes were found at the adjacent levels before surgery. This result appeared clinically relevant because 85% of discs showing abnormal strain went on to herniate during follow-up.

Wigfield *et al*[5] reported a significant increase in flexion-extension movement at levels adjacent to ACDF and noted that such an increase was not seen in patients in whom an artificial cervical joint was placed. In contrast, computerized analysis using the same software used in this study found no consistent change in average junctional intervertebral flexion-extension motion at a mean of 13 months following ACDF.[12] Further follow-up of patients receiving cervical prostheses will determine the clinical significance of maintaining functional spinal motion and clarify the role of motion *versus* fusion in the development of adjacent segment degenerative disease.

Patients had a modest but significant increase in global cervical sagittal motion during late follow-up, as compared to preoperative values (mean increase 8.9°, $P = 0.027$). We chose to define late follow-up as 6

Table 2. Mean Horizontal Translation, Anterior and Posterior Disc Distraction at All Levels

	Translation (mm)			Anterior Distraction (mm)			Posterior Distraction (mm)		
Level	Preop.	Early	Late	Preop.	Early	Late	Preop.	Early	Late
Disc at C5–C6									
C2–C3	1.3	1.1	1.6	0.8	0.9	0.9	−0.7	−0.6	−0.8
C3–C4	1.7	1.6	2.1	1.5	1.7	1.7	−1.3	−1.2	−1.7
C4–C5	1.9	1.9	2.6	1.8	2.2	2.5	−1.6	−1.6	−2.1
C5–C6	1.3	0.8	1.2	1.6	1.2	1.3	−1.6	−0.8	−1.4
C6–C7	0.8	0.7	1.3	1.6	1.6	2.3	−1.2	−1.2	−2.1
Disc at C6–C7									
C2–C3	0.9	1.1	1.2	0.6	1.0	1.0	−0.7	−0.6	−0.7
C3–C4	1.4	1.5	1.5	1.3	1.4	1.3	−1.1	−0.8	−1.1
C4–C5	1.8	1.8	2.0	1.9	1.9	2.2	−1.7	−1.3	−1.6
C5–C6	1.8	1.6	2.0	2.0	1.9	2.3	−1.8	−1.3	−1.9
C6–C7	0.7	0.8	0.7	1.2	1.2	1.2	−1.2	−0.8	−0.7

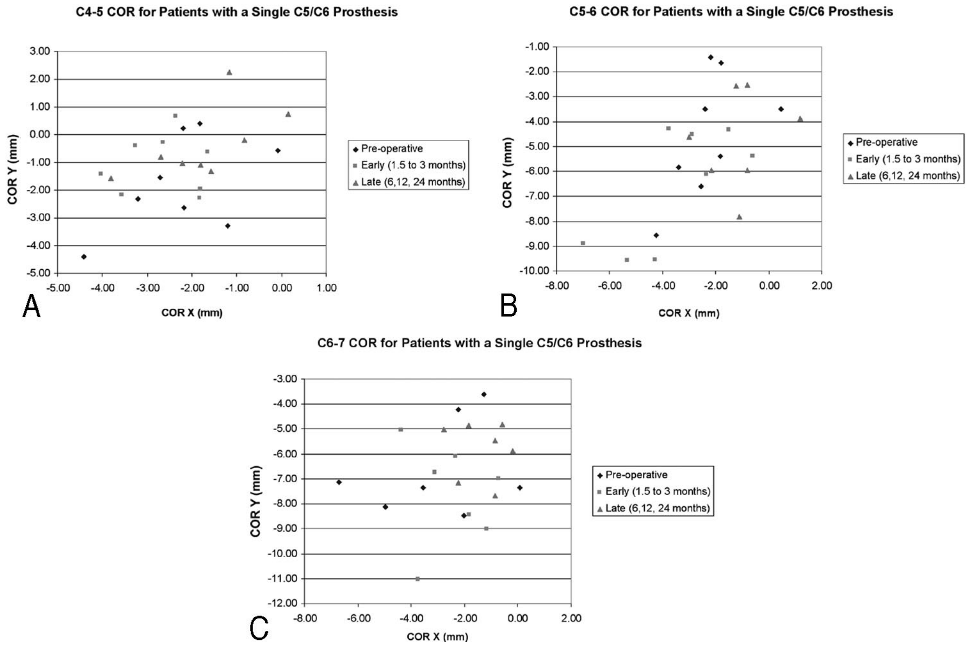

Figure 2. These scatter plots indicate the coordinates of the COR before surgery, and during early and late follow-up, plotted as (X,Y) pairs. Extensive variation and overlap among groups is present, indicating that the location of the COR varied widely both before and after surgery, and was not significantly changed following surgery. **A–C**, Patients who received a disc at C5–C6 had no significant change in the COR of C5–C6 or adjacent levels. The COR at C5–C6 is posterior (negative X) and superior (negative Y) to the center (0,0) of the C6 vertebral body.

months or later because we found in a separate pilot study that there was no significant difference in biomechanics between 6 and 12 months of follow-up (unpublished data, March 2004). This result likely reflects resolution of postsurgical neck and arm pain by 6 months, which may limit flexion and extension effort during earlier follow-up. With few exceptions, the increase in global cervical motion was distributed across all spinal levels, suggesting that the whole cervical spine is more mobile after implantation of a single-level prosthesis. Although the cause of this general increased mobility cannot be derived with certainty, we speculate that relief of neck pain during late follow-up allowed for increased neck movement in these patients who had been symptomatic before surgery. Motion at any given individual level, including those adjacent to the disc, was not significantly altered. However, our results should be interpreted with caution because this increase in motion at adjacent levels occurs over time, and our follow-up to date is fairly short.

A major limitation in the assessment of preoperative imaging is that all patients had symptomatic disc disease. Therefore, the preoperative parameters observed cannot be taken as "normal." As such, the lack of significant change in biomechanical parameters between preoperative and postoperative radiographs should not be interpreted as meaning that the artificial disc has restored the spine to "normal function." Rather, the disc was able to maintain the existing, preoperative biomechanical properties of the cervical spine. The prosthesis, being passive, will simply fit itself into the local biomechanical profile provided by adjacent vertebral bodies, ligaments, and facet joints. It assumes the kinematic characteristics of its predecessor, the natural disc, but it cannot alter or restore function.

Dvorak *et al*[14,15] have published biomechanical data derived from flexion and extension radiographs of the "normal" cervical spines of 44 healthy, asymptomatic volunteers, as well as similar data for patients with degenerative disease and radicular syndrome. They report much larger values for sagittal rotation at all levels in all patient conditions than those we observed. For instance, mean rotation at C5–C6 was 22.6° for normal volunteers, 19.1° for those with radicular pain, and 16.8 for those with degenerative disease, which was markedly different from our preoperative and late postoperative values of 12.5 and 10.8°, respectively. A review of the literature[15–20] reveals wide variability in reported ROM for each cervical level (Table 3). Bogduk and Mercer[21] point out that segmental ROM differs according to whether the motion is executed from flexion to extension or from extension to flexion, with differences of 5° to 15° possi-

Table 3. Historical Comparison of Reported Mean Values for Cervical ROM at Each Spinal Level From C2–C3–C6–C7*

Level	Dvorak *et al*[14,15]	Ordway *et al*[20]	Holmes *et al*[19]	Lind *et al*[18]	Penning[17]	Bhalla and Simmons[16]
C2–C3	12.0 ± 3.0	13 ± 5	7.7 ± 3.2	10 ± 4	12	9
C3–C4	17.2 ± 3.9	17 ± 4	13.5 ± 3.4	14 ± 6	18	14
C4–C5	21.1 ± 3.5	19 ± 4	17.9 ± 3.1	16 ± 6	20	22
C5–C6	22.6 ± 4.2	19 ± 3	15.6 ± 4.9	15 ± 8	20	18
C6–C7	21.4 ± 3.7	17 ± 5	12.5 ± 4.8	11 ± 7	15	19

*Mean ± standard deviation (degrees).

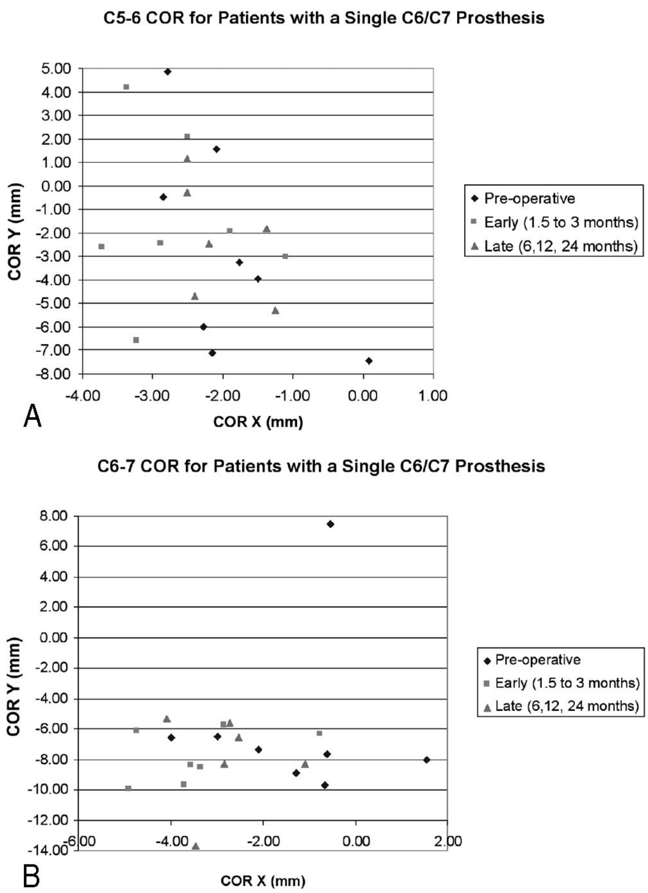

Figure 3. Patients who received a disc at C6–C7 had no significant change in the position of the COR. **A**, At C5–C6. **B**, At C6–C7. The COR at C6–C7 is posterior and superior to the center of the C7 vertebral body.

ble in a single segment at the same sitting in the same individual. Therefore, it is particularly important to standardize the radiographic technique within a single study so that such variables are at least minimized between time comparisons. The Bryan® disc is designed to permit sagittal rotation up to 15°, clearly adequate for the patients in this series.

In vivo COR values from young healthy asymptomatic volunteers have also been reported by Dvorak *et al.*[14] Using a specially designed computer program that calculated kinematic parameters from manually digitized landmarks, the investigators reported errors of 1.75 mm or less. Mean COR for all levels from C2–C3 to C6–C7 were noted to become more anterior and cephalad in the caudal motion segments.[14] In particular, the COR for C2–C3 was determined to be in the posterior third of C3 and approximately at the midpoint in the cephalad/caudad direction. In contrast, the COR for C6–C7 was noted to be approximately on the anterior/posterior midpoint of the cephalad endplate of C7.

Both this study and the work previously published by Dvorak *et al*[14,15] have shown level-to-level differences of the COR within patients and patient-to-patient differences of the COR at a given level. In our group of patients, we found a wide range of COR values both before and after surgery. The cephalad/caudad and anterior/posterior trends noted by Dvorak *et al* for the levels from C2–C3 to C6–C7 were confirmed in this study. The preoperative (X,Y) coordinates ranged up to 6.8 mm away from the anteroposterior center of the inferior vertebral body and up to 11.5 mm away from the cephalad-caudad center of the inferior vertebral body. For these same patients, the Bryan® disc was able to provide a clinically adequate range of COR, as postoperative COR was shown with maximal offsets of 7.9 and 11.5 mm, respectively. All points where the preoperative COR was measured were accommodated by the prosthesis after surgery.

Artificial disc prostheses with a ball and socket design provide a fixed COR located at the center of the ball. Therefore, they require precise device placement with the center of the ball at the location of the preoperative COR if they are to reproduce normal cervical kinematics. Artificial cervical prostheses that allow for a mobile COR, such as the Bryan® disc, have a theoretical advantage because they should provide normal kinematics over a range of device positions. With the location of the COR preserved, the facets and ligaments are not subjected to abnormal stresses. Abnormal shifting of the COR following spinal arthroplasty has been implicated in recent reports of facet pain associated with prosthesis positioning.[22]

The radiographic analysis software used has been highly accurate, reliable, and reproducible. The major source of potential error in this study lies in the quality of flexion-extension imaging analyzed. Patient discomfort, lack of effort, out-of-plane motion, and imaging technique may produce substantial variability in imaging of the same patient at different times. These factors can introduce significant inaccuracies into the calculation of all biomechanical parameters. In addition, adequate imaging of the lower cervical spine may be difficult in some patients because of their body habitus, rendering accurate identification of the margins of the vertebral bodies difficult. Care must be taken to ensure technically adequate, true lateral films, with the patient appropriately and consistently instructed as to positioning and movement. Finally, it should be noted that this study addresses only flexion-extension motion, incorporating sagittal rotation, horizontal translation, and disc compression. Axial rotation and lateral flexion have not been assessed in this analysis. However, the Bryan® prosthesis is axially symmetric, so a similar ROM is possible in lateral bending if allowed by the hard and soft tissue constraints. Axial rotation of the Bryan® disc is unconstrained and is not fixed to a central COR.

■ Conclusions

Computerized analysis of multiple kinematic parameters showed that the Bryan® cervical disc prosthesis provides *in vivo* functional spinal motion, not only at the operated level, but also throughout the cervical spine. Sagittal ROM, COR, translation, and disc distraction were not significantly altered at any level following surgery. Overall cervical spinal motion from C2–C7 increased moderately during late follow-up, with the increase in mobility distributed across all levels.

■ Key Points

- An artificial cervical disc prosthesis was able to duplicate the preoperative kinematics of the natural, spondylotic intervertebral discs up to 24 months postoperatively.
- Sagittal rotation, anterior and posterior disc height, and translation values did not change significantly after surgery.
- The location of the COR did not change significantly at the operated levels or at the adjacent levels.

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