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BIOMECHANICS

Disc Replacement Adjacent to Cervical Fusion

A Biomechanical Comparison of Hybrid Construct Versus *Two-Level Fusion*

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Study Design. A cadaveric biomechanical study.

Objective. To investigate the biomechanical behavior of the cervical spine after cervical total disc replacement (TDR) adjacent to a fusion as compared to a two-level fusion.

Summary of Background Data. There are concerns regarding the biomechanical effects of cervical fusion on the mobile motion segments. Although previous biomechanical studies have demonstrated that cervical disc replacement normalizes adjacent segment motion, there is a little information regarding the function of a cervical disc replacement adjacent to an anterior cervical decompression and fusion, a potentially common clinical application.

Methods. Nine cadaveric cervical spines (C3–T1, age: 60.2 ± 3.5 years) were tested under load- and displacement-control testing. After intact testing, a simulated fusion was performed at C4–C5, followed by C6–C7. The simulated fusion was then reversed, and the response of TDR at C5–C6 was measured. A hybrid construct was then tested with the TDR either below or above a single-level fusion and contrasted with a simulated two-level fusion (C4–C6 and C5–C7).

Results. The external fixator device used to simulate fusion significantly reduced range of motion (ROM) at C4–C5 and C6–C7 by 74.7 ± 8.1% and 78.1 ± 11.5%, respectively ($P < 0.05$). Removal of the fusion construct restored the motion response of the spinal segments to their intact state. Arthroplasty performed at C5–C6 using the porous-coated motion disc prosthesis maintained the total flexion-extension ROM to the level of the intact controls when used as a stand-alone procedure or when implanted adjacent to a single-level fusion ($P > 0.05$). The location of the single-level fusion, whether above or below the arthroplasty, did not significantly affect the motion response of the arthroplasty in the hybrid construct. Performing a two-level fusion significantly increased the motion demands on the nonoperated segments as compared to a hybrid TDR-plus fusion construct when the spine was required to reach the same motion end points. The spine with a hybrid construct required significantly less extension moment than the spine with a two-level fusion to reach the same extension end point.

Conclusion. The porous-coated motion cervical prosthesis restored the ROM of the treated level to the intact state. When the porous-coated motion prosthesis was used in a hybrid construct, the TDR response was not adversely affected. A hybrid construct seems to offer significant biomechanical advantages over two-level fusion in terms of reducing compensatory adjacent-level hypermobility and also loads required to achieve a predetermined ROM.

Key words: adjacent level, cervical, hybrid construct, PCM, total disc arthroplasty. **Spine 2011;36:1–8**

Radiculopathy and myelopathy from degenerative cervical disc disease have been successfully treated with anterior cervical decompression and fusion (ACDF).[1,2] Despite clinical success with fusion procedures, there are concerns regarding the effects of fusion on the adjacent mobile segment and long-term sequelae of fusion in the cervical spine. Hilibrand *et al*[3] have reported adjacent segment disease occurring at a rate of 2.9% per year for 10 years after anterior cervical fusion. There is consensus that fusion disturbs the biomechanics of the cervical spine and likely predisposes to the development of adjacent segment disease. In cadaveric models, intradiscal pressures adjacent to a fused level have been shown to increase by as much as 73%.[4] In addition, the motion segment adjacent to a fusion experiences increased shear strains as well as increased motion when compared to the native spine.[4–6] Cervical disc replacement has emerged as a surgical alternative to fusion with the potential to avoid the deleterious effects of fusion on adjacent-level kinematics. Primary cervical disc replacement has been reported to produce

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The device(s)/drug(s) that is/are the subject of this manuscript is/are not FDA-approved for this indication and is/are not commercially available in the United States.

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excellent short-term clinical outcomes with maintenance of motion.[7–9]

The use of disc replacement adjacent to an ACDF is an attractive reconstructive option for a common clinical problem, obviating the need for a multilevel fusion surgery. A recent prospective study has reported that the early clinical results of disc replacement adjacent to an earlier fusion using the porous-coated motion (PCM) device (Nuvasive, San Diego, CA) are comparable with the outcomes after primary disc replacement surgery.[10] In addition to performing total disc replacement (TDR) adjacent to a prior ACDF, some have proposed the concept of a hybrid construct in the setting of symptoms attributable to two adjacent cervical segments. In this scenario, the severely spondylotic segment is fused whereas the less involved, more mobile level is treated with a TDR.

When implanting a TDR adjacent to an ACDF, one must be aware of the kinematic alterations imposed on the level adjacent to the fusion. Although numerous biomechanical studies have demonstrated that cervical disc replacement as an index procedure normalizes adjacent segment motion,[11,12] there is a dearth of information regarding the function of a cervical disc replacement adjacent to an ACDF.[13] We hypothesized that (1) the behavior of disc replacement adjacent to fusion was comparable with that of a stand-alone disc replacement, (2) its behavior would not be affected by the location of the fusion (cephalad *vs.* caudad), and (3) the nonoperated segments in a hybrid construct would experience significantly less motion and forces than the other surgical alternative: a two-level fusion. The hypotheses were tested using the PCM cervical disc prosthesis of polyethylene-on-metal design with a large radius ultra high-molecular-weight polythylene-bearing surface attached to the caudal end plate. The large radius of the articulating surface prescribes coupled rotational and translational motion during the flexion-extension cycle.

MATERIALS AND METHODS

Specimens and Experimental Setup

Nine fresh-frozen, human cadaveric cervical spines from C3 to T1 were used (seven men, two women; age: 60.2 ± 3.5 years). Radiographic screening was performed to exclude specimens with fractures, metastatic disease, bridging osteophytes, or other conditions that could significantly affect the biomechanics of the spine. The specimens were thawed at room temperature 24 hours before testing. The paravertebral muscles were dissected, while keeping the discs, ligaments, and posterior bony structures intact. The C3 and T1 vertebrae were anchored in cups using polymethylmethacrylate and pins.

The specimen was mounted on a six-component load cell (Model MC3A-6-250, AMTI Multicomponent transducers, AMTI Inc., Newton, MA) at the caudal end and was free to move in any plane at the proximal end. The apparatus allowed continuous cycling of the specimen in either load-control or displacement-control modes. In the load-control tests, the specimen was cycled between specified moment end points in flexion-extension using the load cell for feedback. Conversely, the specimen was tested in a displacement-control mode in flexion-extension using the angular motion of the top cup for feedback.

The motions of C3, C4, C5, C6, and C7 vertebrae relative to T1 were measured using an optoelectronic motion measurement system (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada). In addition, biaxial angle sensors (Model 902–45, Applied Geomechanics, Santa Cruz, CA) were mounted on each vertebra to allow real-time feedback for the optimization of the preload path.

A compressive preload was applied to the cervical spine using the follower load technique described by Patwardhan *et al.*[14] The compressive preload was applied along a path that followed the lordotic curve of the cervical spine. This allowed the cervical spine to support physiologic compressive preloads without damage or instability.

The preload was applied using bilateral loading cables attached to the cup holding the C3 vertebra. The cables passed freely through guides anchored to each vertebra and were connected to a loading hanger under the specimen. The cable guide mounts allowed anterior-posterior adjustments of the follower load path within a range of about 10 mL. The preload path was optimized by adjusting the cable guides to minimize changes in cervical lordosis when the compressive preload is applied to the specimen beginning in its slightly forward-flexed posture.[15,16] Application of the compressive load along an optimized follower load path has been shown to minimize the segmental bending moments and shear forces because of the preload application.[15]

Experimental Protocol

Specimens were tested using a combination of load-control and displacement-control test modes depending on the protocol step (Table 1). The load-control test simulated a clinical scenario in which the patient's spine would be subjected to the same loads (moment and preload) before and after a surgical procedure. The displacement-control test simulated a postoperative clinical scenario in which the patient would attempt to reproduce the preoperative flexion and extension end points of the cervical spine. Two sets of displacement-control conditions (flexion and extension end points) were simulated in this study: one corresponding to a single-level fusion at C4–C5 (DC-1) and the other corresponding to a single-level fusion at C6–C7 (DC-2). We did not use the flexion-extension end points of the intact spine as a displacement-control condition for two reasons. First, it would have required substantially larger moments, particularly for the two-level fusion conditions and would have increased the risk of specimen damage. Second, the scenario being simulated was a patient with a prior single-level fusion and, therefore, was the control for any subsequent surgery (arthroplasty or a second fusion).

First, the baseline range of motion (ROM) for the intact specimen was determined in flexion-extension under a load-control test protocol (Protocol step 1). The specimens were subjected to flexion-extension moments of ±1.5 Nm. These moment values are within the range of moments

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TABLE 1. Test Protocol

Protocol Step	Surgical Procedure	Test Mode		Outcome Measures
		LC	DC	
1	Intact Spine	X		Segmental motions
2	C4–C5 FUSION	X		F/E endpoints (DC-1)
3	C6–C7 FUSION	X		F/E endpoints (DC-2)
4	C5–C6 PCM (Stand-alone)	X	DC-1 & DC-2	Segmental motions
5	C4–C5 FUSION + C5–C6 PCM	X	DC-1	Segmental motions, Flex-Ext moments
6	C6–C7 FUSION + C5–C6 PCM	X	DC-2	Segmental motions, Flex-Ext moments
7	C4–C6 FUSION		DC-1	Segmental motions, Flex-Ext moments
8	C5–C7 FUSION		DC-2	Segmental motions, Flex-Ext moments

DC indicates displacement-controlled; LC, Load-controlled.

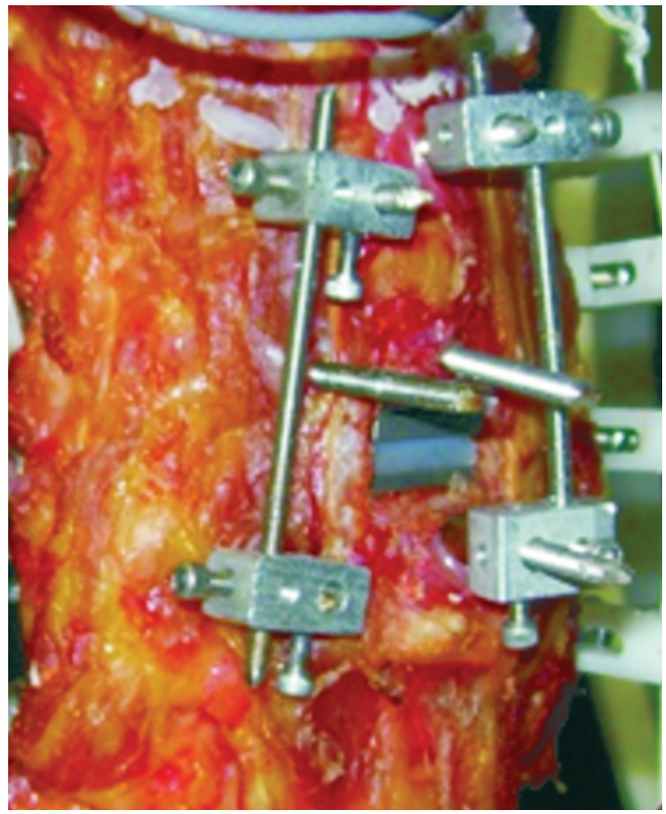

Figure 1. Anterior view of the external fixator-styled stabilization apparatus for the fusion simulation.

used in previous biomechanical studies of human cervical spine segments.[16] Flexion-extension was tested under 75 N compressive follower preload to simulate loading because of the weight of the head. Load-displacement data were collected until two reproducible load-displacement loops were obtained.

After intact testing, a simulated single-level fusion at C4–C5 followed by C6–C7 was performed (Protocol steps 2 and 3) using an external fixator-styled stabilization apparatus (Figure 1).[17] The apparatus consisted of four metal rods: two in the upper and two in the lower vertebrae of the motion segment to be stabilized. The metal rods were inserted in the anteroposterior direction, passing through the vertebral body and lamina of each vertebra, without causing any damage to the disc, facet joints, and ligamentous structures. Four longitudinal members were used to rigidly connect the left and right pairs of rods across the motion segment, both anteriorly and posteriorly, resulting in a 360°-stabilization construct. The longitudinal members could be disconnected from the rods to allow easy interchangeability between the stabilized and intact conditions. This technique allowed us to simulate a single-level fusion at two different segmental levels in the same spine specimen. The ROM of the specimen with a single-level fusion was determined in flexion-extension under a load-control test protocol as described earlier. The flexion and extension end points corresponding to the two single-level fusions formed the basis for the subsequent displacement-control testing conditions: (1) a single-level fusion at C4–C5 (DC-1) and (2) a single-level fusion at C6–C7 (DC-2).

[AQ2]

Next, the stabilization apparatus was removed and the response of a stand-alone PCM disc replacement was determined. After complete discectomy at C5–C6 and resection of the posterior longitudinal ligament, an appropriate-sized PCM cervical disc prosthesis was inserted (Protocol step 4). The specimen was tested with the TDR alone in load-control mode as described earlier. Subsequently, the specimen was retested under two displacement-control conditions, reaching the flexion and extension end points corresponding to those obtained for the spine with (1) a single-level fusion at C4–C5 (DC-1) and (2) a single-level fusion at C6–C7 (DC-2).

Next, a hybrid construct was simulated with a single-level fusion either below or above the TDR (Protocol steps 5 and 6). With the TDR in place at C5–C6, a single-level fusion was simulated at C4–C5 using the stabilization apparatus. The specimen was tested under both the load-control and displacement-control (DC-1) protocols as described earlier. The stabilization apparatus was removed from C4–C5 and the fusion was then simulated at the C6–C7 level. The specimen was again tested under both the load-control and displacement-control (DC-2) protocols as described earlier. The two hybrid construct tests were performed in random order.

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The final two steps of the protocol were designed to allow a comparison between a hybrid construct and a two-level fusion. Testing was performed with a two-level fusion simulated at either the C4–C6 or C5–C7 levels in random order (Protocol steps 7 and 8). With the C4–C6 fusion, the specimen was tested under a displacement-control condition with flexion and extension end points defined for the C4–C5 fusion (DC-1). With the C5–C7 fusion, the specimen was tested under a displacement-control condition with flexion and extension end points defined for the C6–C7 fusion (DC-2).

The testing order was randomized whenever possible to ensure tissue viability throughout the entire testing sequence. The fusion testing was performed directly after intact testing because the displacements produced under load-control testing with the fusion in place were required as inputs for all subsequent displacement-control tests. The hybrid construct was tested before the two-level fusion constructs to preserve the mechanical properties of the soft-tissues because of the potential for applying substantially higher loads to the spine under displacement control with a two-level fusion than a hybrid TDR-fusion construct. The high loads applied to the spine with a two-level fusion have the potential to damage the disc and ligamentous structures, in turn potentially skewing the results of any subsequent tests. After insertion of the PCM device into the C5–C6 level, all testing steps with the hybrid and two-level fusion constructs were randomized in regard to which levels were fused to reduce any potential effects of the testing order on the results.

Segmental ROM was measured at all levels using optoelectronic instrumentation and monitored using digital fluoroscopy. Flexion and extension moments were measured using the six-component load cell at the base of the test apparatus.

DATA ANALYSIS

The load-displacement curves were analyzed to obtain the angular ROM in flexion and extension at each cervical segment in each tested condition. The statistical analysis was performed using repeated-measures analysis of variance (Systat Software Inc., Richmond, CA). *Post hoc* tests were done where indicated by analysis-of-variance results using Bonferroni correction for multiple comparisons. The level of significance was set as Bonferroni-adjusted two-tailed $P \leq 0.05$.

Validation of the Fusion Construct

The following ROM comparisons were made to assess the adequacy of the method used in this study to simulate a reversible fusion with the use of the stabilization apparatus: [AQ3]

1. C4–C5 in the intact spine *versus* C4–C5 stabilized; both conditions were tested in the load-control test mode to ± 1.5Nm moments and
2. C6–C7 in the intact spine *versus* C6–C7 stabilized; both conditions were tested in the load-control test mode to ±1.5 Nm moments.

To assess whether the removal of the stabilization apparatus restored the spine's motion response to its intact state, we compared the following:

3. C4–C5 in the intact spine *versus* C4–C5 after the fusion construct was removed and applied across C6–C7. Both conditions were tested in load-control where all segments experienced the same ±1.5 Nm moment. The motion response of a segment under load-control should remain unaffected in the absence of any alteration to the disc, facet joints, and ligamentous structures of the segment.[18] Therefore, because no such alterations were made at C4–C5, the ROM of this segment in the load-control experiment should not be affected by the presence of a fusion at C6–C7.

Assessment of C5–C6 TDR Performed Alone *Versus* in a Hybrid Construct

The following pair-wise comparisons were made to assess the response of the PCM arthroplasty when performed alone *versus* in a hybrid construct:

1. intact C5–C6 segment *versus* C5–C6 arthroplasty alone,
2. intact C5–C6 *versus* C5–C6 arthroplasty, both adjacent to C4–C5 fusion,
3. intact C5–C6 *versus* C5–C6 arthroplasty, both adjacent to C6–C7 fusion,
4. C5–C6 arthroplasty alone *versus* C5–C6 arthroplasty adjacent to C4–C5 fusion, and
5. C5–C6 arthroplasty alone *versus* C5–C6 arthroplasty adjacent to C6–C7 fusion.

These comparisons were made separately for the data obtained in the load-control and displacement-control tests. For the load-control tests, the various comparisons were made on the C5–C6 ROM data. For the displacement-control tests, both the C5–C6 ROM and the flexion and extension moments were compared.

The effect of the location of the fusion (above or below) relative to the arthroplasty in a hybrid construct on the motion response of the arthroplasty was assessed by using the following comparison: C5–C6 arthroplasty above C6–C7 fusion *versus* C5–C6 arthroplasty below C4–C5 fusion. This comparison could be made only for the arthroplasty responses measured in the load-control test mode because the displacement-control conditions (flexion and extension end points) were different for the two single-level fusions. Only the C5–C6 ROM data were assessed across the various comparisons.

Finally, the following comparisons were made to assess the effect of a two-level fusion *versus* a hybrid construct on the response of the remaining cervical spine segments:

1. C5–C6 arthroplasty below C4–C5 fusion *versus* C4–C6 fusion, both tested under the DC-1 displacement-control condition and
2. C5–C6 arthroplasty above C6–C7 fusion *versus* C5–C7 fusion, both tested under the DC-2 displacement-control condition.

Comparisons were made on the flexion and extension moments and also for the ROM values at each cervical segment.

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RESULTS

Single-Level Fusion Using the Stabilization Apparatus

Motion Restriction at the Fusion Level

The stabilization apparatus allowed adequate reduction of segmental motion when tested under ±1.5 Nm moments. In the single-level fusion simulation at C4–C5, the C4–C5 ROM in flexion-extension was reduced from 10.5 ± 4.2° to 2.6 ± 1.2° ($P < 0.05$). In the single-level fusion simulation at C6–C7, the C6–C7 ROM in flexion-extension was reduced from 8.0 ± 4.4° to 1.5 ± 0.9° ($P < 0.05$).

Effect of Removal of Fusion Construct

The removal of the stabilization apparatus restored the motion response of the spinal segments to their intact state, validating the reversibility achieved with this technique from the stabilized condition to intact condition. This was verified for the C4–C5 level by comparing the total flexion-extension ROM at the C4–C5 segment in the intact state to that measured after removing the stabilization apparatus at that level. The C4–C5 ROM increased by 0.7 ± 0.5°; however, the increase in motion was well within the specimen variability in the samples used in this study.

C5–C6 Arthroplasty: Stand-Alone *Versus* Adjacent to a Single-Level Fusion

Arthroplasty performed at C5–C6 using the PCM disc prosthesis maintained the total flexion-extension ROM to the level of the intact controls when used as a stand-alone procedure or when implanted adjacent to a single-level fusion ($P > 0.05$). This was true whether the specimens were subjected to the same loads (Figures 2 and 3) or when they were tested to the same flexion-extension motion end points ($P > 0.05$, Figure 4). The location of the single-level fusion, whether above or below the arthroplasty, did not significantly affect the motion response of the arthroplasty in the hybrid construct.

Implantation in a stand-alone *versus* a hybrid construct did not affect the TDR motion when the specimens were subjected to the same loads ($P > 0.05$, Figure 3). However, in the displacement-control test where specimens were required to achieve the same flexion and extension motion end points, the presence of a single-level fusion above or below the prosthesis increased motion demands on the adjacent prosthesis in flexion-extension as compared to when the prosthesis was implanted as a stand-alone arthroplasty. The TDR adjacent to the fusion could not make up for the entire motion lost as a result of the single-level fusion and, as a consequence, there was compensatory increase in motion at the other segments as well (Figure 5A and B).

Two-Level Fusion *Versus* a Hybrid Construct

Performing a two-level fusion significantly increased the motion demands on the adjacent, nonoperated segments as compared to a hybrid construct (single-level fusion plus arthroplasty) when the spine was required to reach the same flexion and extension motion end points. The increase in motion was significant at all nonoperated segments ($P < 0.05$, Table 2). The spine with a hybrid construct required less moments than the spine with a two-level fusion to reach the same flexion and extension motion end points ($P < 0.05$, Figure 6).

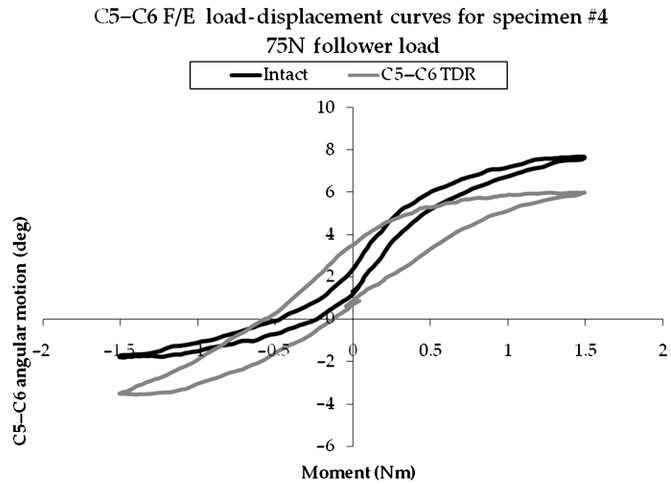

Figure 2. Load *versus* displacement response of a C5–C6 segment—intact and after total disc replacement.

DISCUSSION

This study demonstrated that the motion response of the PCM arthroplasty adjacent to a fused level is comparable with that of a stand-alone prosthesis. This study did not find a significant difference in the response of the prosthesis when the fused level was caudad or cephalad to the TDR. Furthermore, after a TDR plus fusion hybrid construct, we observed reduced compensatory adjacent-level hypermobility and forces required to achieve a predetermined ROM when compared to two-level fusion.

This study employed two distinct loading modes to simulate postoperative behavior of the cervical spine: load control and displacement control. In the load-control setting,

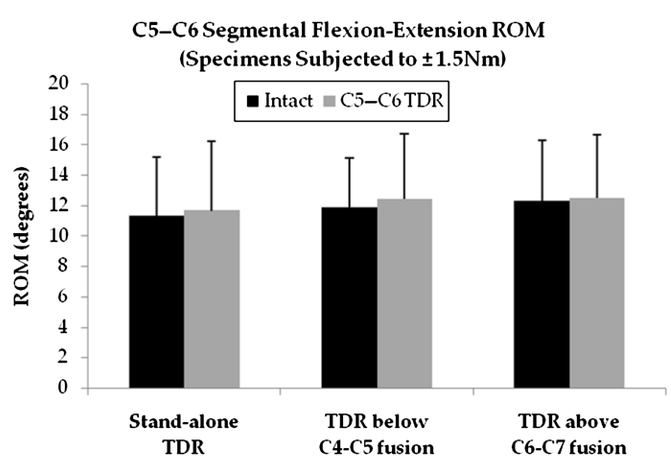

Figure 3. Range of motion of the C5–C6 total disc replacement (TDR) compared to the intact segment in the load-control test: Stand-alone TDR, TDR below a C4–C5 fusion, and TDR above a C6–C7 fusion. ROM indicates range of motion.

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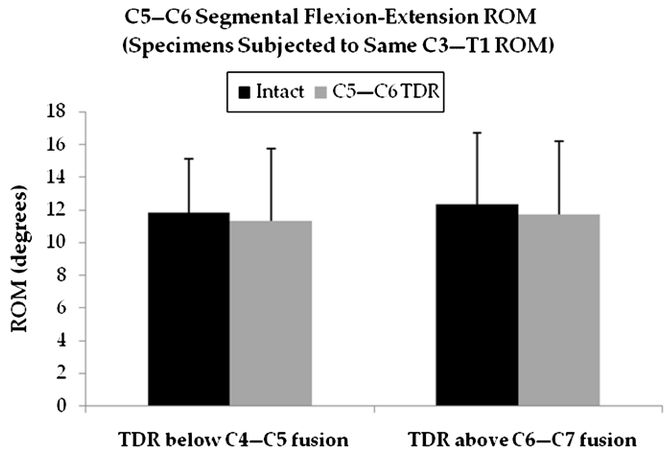

Figure 4. Range of motion of the C5–C6 total disc replacement (TDR) compared to the intact segment in the displacement-control test: TDR below a C4–C5 fusion and TDR above a C6–C7 fusion.

the flexion-extension moments and preload applied are the same, pre- and postintervention, thus allowing measurement of segmental and total cervical spine ROM under same loads. In the displacement-control setting, the overall ROM of the cervical spine is the same pre- and postintervention, allowing measurement of segmental ROMs and moments required for the specimen to reach the predetermined motion end point.

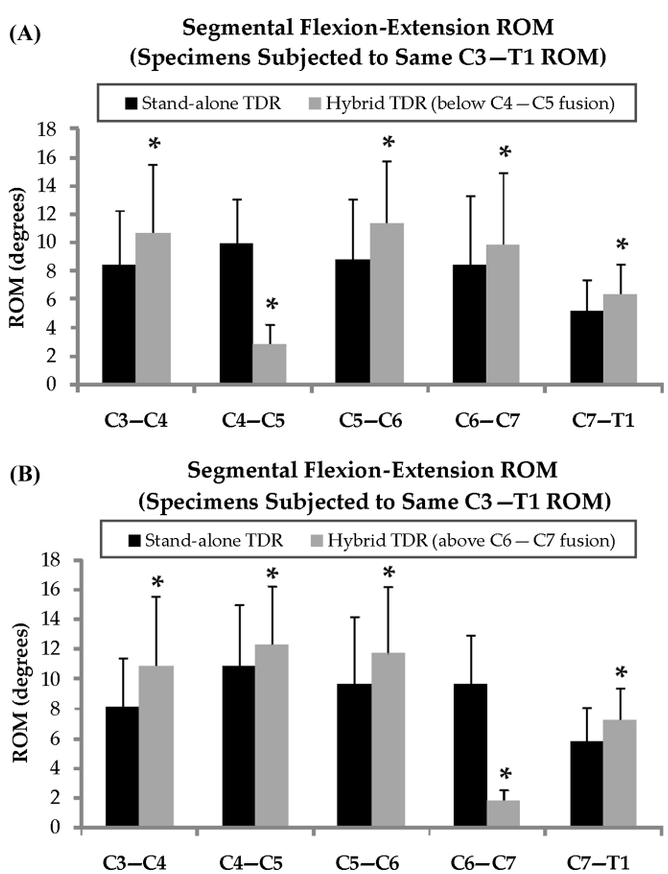

Figure 5. Segmental motions in the cervical spine in the displacement-control test: stand-alone total disc replacement (TDR) *versus* TDR adjacent to a fusion. **(A)** C5–C6 TDR below C4–C5 fusion. **(B)** C5–C6 TDR above C6–C7 fusion. Asterisk (*) indicates a statistically significant difference ($P < 0.05$).

Initially, the load-control testing mode may appear more physiologically representative as the weight of the head and muscle forces in the neck presumably do not change before and after surgery. If postoperative motion was primarily determined by muscle forces and avoidance of increased moments during motion, the motions observed under this loading mode would represent the *in vivo* motion patterns. It appears, however, that patients in fact attempt to restore the overall range of cervical motion after surgery, so that increased mobility may develop at segments adjacent to immobile ones (such as after fusion).[10] The displacement-control model implies that overall cervical spine ROM is similar pre- and postsurgery. If a simulated fusion is performed, the displacement model will invariably demonstrate increased motion and forces at nonoperated levels as the spine is forced to replicate its preoperative ROM. Although this is not likely to be physiologically representative in the immediate postoperative period, it may be representative of the cervical spine with longer follow-up. The actual *in vivo* loading is likely to be some combination of the two loading types, as the patient adapts over time to his or her postoperative condition. Thus, the results reported in this study for both the load-control and displacement-control testing modes provide a more comprehensive understanding of the TDR behavior than either test mode alone.

Biomechanically, it is intuitive that a two-level fusion will affect the adjacent motion segments more severely than a single-level fusion. Ragab *et al*[19] examined the effect of a one- and two-level fusion on the adjacent segments in a displacement-control setting. With a C4–C6 fusion, flexion-extension was increased by 37% at the C3–C4 level and by 46% at the C6–C7 level as compared to the intact specimen. Park *et al*[4] examined motion and pressure patterns in a cadaveric cervical model and noted that intradiscal pressure in the adjacent segment increased 73.2% after a single-level arthrodesis, whereas it increased 164% after a two-level procedure.[5]

This study confirmed that a two-level fusion increased motion demands at all mobile cervical levels when compared to the hybrid construct in a displacement-control test. In addition, greater moments were required to achieve the same motion end points after a two-level fusion. This implies that *in vivo* greater muscular effort will be required to achieve motion after the two-level fusion when compared to the hybrid construct. This potentially could lead to muscle fatigue and pain as well as potentially impact the adjacent levels that are also subject to the effects of increased muscle forces *in vivo*.

Although the kinematic effects of fusion on the immediately adjacent segments have been studied, this study suggests that a two-level fusion may have biomechanical consequences for the entire cervical spine beyond just the immediate adjacent levels. After two-level fusion, significantly increased motion compared to the hybrid (TDR plus fusion) construct was observed not only at the segments immediately adjacent to the fusion but also at two levels removed from the fusion (C3–C4 after C5–C7 fusion and C7–T1 after C4–C6 fusion). The effect of

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TABLE 2. Distribution of Motion (in Degrees) at Nonoperated Levels: Hybrid Construct *Versus* Two-Level Fusion*

	C3–T1	C3–C4	C4–C5	C5–C6	C6–C7	C7–T1
C4–C5 Fusion + C5–C6 TDA	42 ± 8.8	10.7 ± 4.8	2.9 ± 1.4	11.3 ± 4.4	9.8 ± 5.1	6.3 ± 2.1
C4–C6 Fusion	42 ± 8.8	15.2 ± 7.3	2.3 ± 1.3	2.1 ± 1.3	12.3 ± 5.2	8.4 ± 2.5
P (*)	>0.05	<0.05		<0.05	<0.05	*P* <0.05
C5–C6 TDA + C6–C7 Fusion	45 ± 10.8	10.8 ± 4.7	12.3 ± 4.0	11.7 ± 4.5	1.8 ± 0.7	7.2 ± 2.2
C5–C7 Fusion	44 ± 11.1	14.2 ± 6.1	14.5 ± 4.1	2.6 ± 1.1	2.2 ± 1.1	9.2 ± 2.5
P †	>0.05	<0.05	<0.05	<0.05		<0.05

[AQ6] *Mean and one standard deviation values are shown. The highlighted cells denote fused segments.

†Statistical comparison between the hybrid construct and two-level fusion.

fusion beyond the immediate adjacent segments has also been suggested in the lumbar spine where Hambly *et al*[20] reported the development of degenerative changes to occur with comparable frequency at a segment adjacent to a fusion as compared to the segment two levels removed from a fusion.

This study has some limitations. First, the biomechanical nature of this study allows only for evaluation of immediate results of the interventions. The fusion simulated using the external-fixator device also did not completely eliminate motion at the fused levels, instead of reducing the motion to a mean of 2.6°, which may be representative of immediate postsurgical results. *In vivo*, it is expected that as the fusion mass matures the residual motion at the fused segment will further reduce. A radiostereometric analysis of ACDF 12 months after surgery showed a motion of 1.3 ± 1.4°.[21] The discrepancy between the residual motion in the simulated fusion and the solid fusion ultimately seen *in vivo* is reflective of a cadaveric study wherein it is not possible to mimic the biologic healing response and may also be attributed to the less rigid nature of the external-fixator construct used to create a "reversible" fusion. A further reduction in the residual motion at the fused segment may increase the motion demand on the adjacent mobile segments if the patient attempts to reproduce preoperative neck motion.

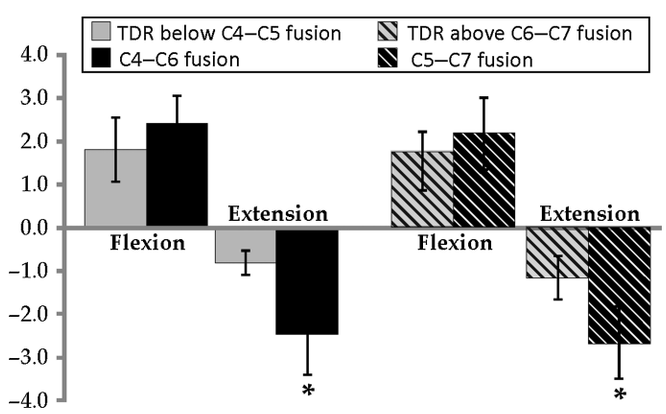

Figure 6. Peak flexion and extension moments required to bring the cervical spine to similar C3 motion endpoints: total disc replacement (TDR) adjacent to a single-level fusion compared with a two-level fusion. Asterisk (*) indicates a statistically significant difference ($P < 0.05$).

Clinical trials with long-term follow-ups are required to assess if a protective value against adjacent segment disease from TDR is realized. Second, this study evaluated only flexion and extension motions. Lateral bending and rotation were not included in this study and would be useful for evaluation of this prosthesis. It is also important to point out that the model simulated a TDR plus fusion hybrid construct performed in a single-surgical setting. The biomechanics of this situation may not be analogous to implanting a TDR adjacent to a prior ACDF where chronic adjacent-level hypermobility may have already developed.[10] This distinction is significant in terms of the clinical implications of this study.

In conclusion, the PCM arthroplasty restored the ROM of the treated level in flexion-extension to the intact state motion. When the TDR was used as a hybrid construct, the PCM response was not adversely affected. The location of the fusion (cephalad or caudad) did not affect the behavior of the disc replacement. A hybrid construct seems to offer significant advantages over a two-level fusion in terms of reducing compensatory adjacent-level hypermobility and also forces required to achieve a predetermined ROM. This study provides a biomechanical rationale for a hybrid TDR plus fusion construct.

➢ Key Points

- ❑ The behavior of the PCM arthroplasty adjacent to a fused level was comparable with that of a stand-alone prosthesis.
- ❑ This study did not find a significant difference in the behavior of the prosthesis when a fused level was caudad or cephalad to the TDR.
- ❑ We observed significantly increased motions and loads on the remaining mobile segments after a two-level fusion as compared to a hybrid (TDR plus fusion) construct.

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AUTHOR QUERIES

TITLE: Disc Replacement Adjacent to Cervical Fusion: A Biomechanical Comparison of Hybrid Construct *Versus* Two-Level Fusion

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[AQ1]: Please review your disclosure information and confirm that it is correct.
[AQ2]: A-P has been written out as "anteroposterior". OK?
[AQ3]: Is "reversible" the correct term being used?
[AQ4]: Ref. 1 is modified per the Internet. Please verify.
[AQ5]: Ref. 17 has been updated per PubMed. Please verify.
[AQ6]: Please highlight cells as shown in the first footnote of this table.