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Kinematics of a cervical disc prosthesis implanted above or below one- and two-level fusions

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ABSTRACT

Background: The theoretical advantages of hybrid constructs over multi-level fusion have been illustrated in clinical and biomechanical studies. However, there is no biomechanical data on hybrid constructs using load control analyses. There is also no clear data on whether there is a biomechanical difference if the arthroplasty is below or above a 1- or 2-level fusion. This work investigated the effect on segmental motion of having a cervical total disc arthroplasty implanted above or below a 1- or 2-level fusion.

Methods: Segmental motions of 16 C2-T1 cervical spine specimens were measured as the specimens were tested to 1.5Nm in axial rotation and in flexion-extension under compressive preload. Tests were conducted on intact specimens, and then after arthroplasty with a 1-level and 2-level fusion. 8 specimens were in test Group 1, where the hybrid configuration had a total disc arthroplasty above a 1- or 2-level fusion. The arthroplasty was below the 1- and 2-level fusion in Group 2. Load control and displacement control analyses were conducted to determine the effect of the hybrid configurations on segmental motion.

Results: In load control, compensatory motion increases were found at all non-instrumented cervical spine segments in flexion-extension and axial rotation. Flexion-extension and axial rotation ranges of motion at the total disc arthroplasty level were less than 1° different than intact.

In displacement control, there was no consistent pattern of compensatory motion. Range of motion at the arthroplasty level was within 3.5° of intact.

Conclusions: The total disc arthroplasty segmental level in a hybrid construct has similar amounts of motion as intact. This may shield the arthroplasty level and adjacent levels from supra-physiological motion and loading. These results suggest that a hybrid construct may be protective of adjacent segments, whether the total disc arthroplasty is above or below the fusion.

Background

Hybrid surgery, defined as a combination of cervical total disc arthroplasty and anterior cervical discectomy and fusion, is used to treat multilevel cervical spondylosis and disc degenerative disease. This allows a tailored approach to treatment, with the less degenerative or more mobile segment or segments being treated with arthroplasty [1,2].

In the decade from 2009 to 2018, there were several publications of short to medium term clinical results of hybrid surgery compared to anterior cervical discectomy and fusion (**ACDF**) [1–5]. Ji et al. and Shin et al. presented 2-year and 5-year follow-up on a cohort of patients treated either with 2-level ACDF or hybrid surgery [1,4]. The 20 hybrid surgery patients had a more rapid C2-C7 range of motion (**ROM**) recovery than ACDF and, unlike the 20 ACDF patients, had recovered pre-operative ROM by 2 years [1]. The difference in ROM between the cohorts reduced at 4-5 years [4]. In their 5-year follow-up data, Wang et al. showed no difference in pre- and post-op C2-C7 ROM in the 30 patients in the 2-level hybrid surgery group but an average reduction of 10° of C2-C7 ROM in 33 patients treated with 2-level ACDF [2]. Similarly, Xiong et al. at 6 years of follow-up found lower C2-C7 ROM in

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the 22 2-level ACDF patients than in the 20 hybrid surgery patients [5]. In the last of the list of clinical studies in this time period, Kang et al. looked at 3-level ACDF versus a 3-level hybrid construct consisting of total disc arthroplasty (**TDA**) above and below an ACDF [3]. As with the 2-level data, at 2 years there was a more rapid recovery of C2-C7 ROM in the 12 hybrid surgery patients. They also found an increase over pre-operative values of superior and inferior adjacent segment ROM in the 12 3-level ACDF patients at 1 year. The increased adjacent segment ROM persisted at the 2-year follow-up.

Several biomechanical studies of hybrid constructs have also been published over the same 10-year period from 2009. Cunningham et al., Lee et al. and Gandhi et al. found that range of motion increased at the TDA level in the hybrid configuration [6–8]. In contrast, Barrey et al. found that segmental motion at the TDA in the hybrid configuration was no different from intact, while Martin et al. found reduced motion at the TDA level [9,10]. All studies found compensatory increases in motion in the unfused segments [6–10]. These experiments used a form of displacement control, where the total ROM of the specimen is maintained.

These clinical and biomechanical results illustrate the theoretical advantages of hybrid constructs over ACDF that have been proposed. Namely, maintenance of cervical spine range of motion and reduction in demand from segments adjacent to the construct, thereby preventing or slowing progression of cervical spondylosis and disc degeneration [7]. The biomechanical studies all used displacement control analysis for their results. However, the biomechanical studies did not always indicate if the TDA was placed above or below fusion. How the results would differ if a load control analysis was used is unknown. In addition, it is not known if a single- versus a 2-level fusion in the hybrid construct would produce a different response.

Therefore, in this study we investigated the effect of 1- or 2-level fusion on the motion of a TDA implanted above or below the fused segment(s). Both load control and displacement control analyses were used to calculate results. Our hypotheses were: 1) motion at the TDA segment is no different from intact and the TDA being above or below the fusion will not matter, and 2) motion at the TDA segment will be no different from intact regardless of whether the fusion is 1-level or 2-level.

Methods

A total of 16 C2-T1 cervical spine specimens were tested soon after thawing, with 8 specimens in each test group. In test Group 1, the hybrid configurations had a TDA above a 1- or 2-level ACDF (age 47.4 ± 13.7 years; 4 Male, 4 Female) (**Fig. 1**). Test Group 2 specimens had the TDA below a 1- or 2-level ACDF (age 47.4 ± 14.2 years; 4 Male, 4 Female) (**Fig. 2**). Specimens were assigned to groups after testing of the intact/native state. The primary grouping criterion was to match mean segmental flexion-extension range of motion at C4-C5, C5-C6 and C6-C7 (**Table 1**). The quality of the match between segmental flexion-extension ranges of motion was calculated using a t-test. Secondary criteria for grouping were age and gender.

Preparation of specimens and experimental setup

Specimens were prepared for testing by dissecting muscle tissues while keeping the discs, ligaments, and posterior bony structures in-

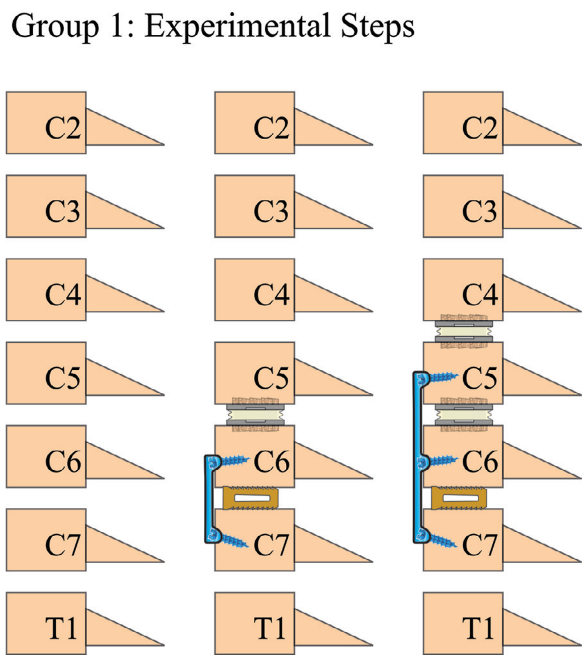

Fig. 1. Schematic showing the Group 1 hybrid configurations with the 1-level and 2-level fusions below the total disc arthroplasty.

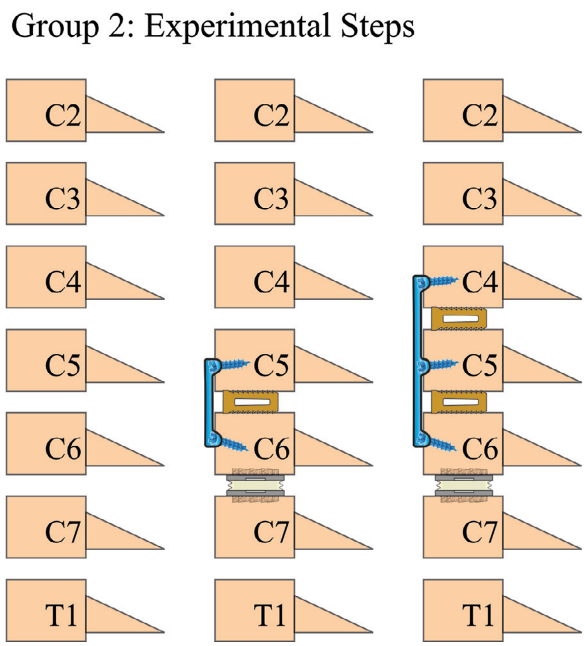

Fig. 2. Schematic of the Group 2 hybrid configurations with the 1-level and 2-level fusions above the C6-C7 total disc arthroplasty.

Table 1
Intact segmental flexion-extension range of motion values (mean ± standard deviation) in degrees. Segments to be instrumented are denoted by shading.

	Intact State Flexion-Extension Range of Motion, degrees					
	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7	C7-T1
Group 1, Proximal to ACDF	7.6 ± 1.7	13.4 ± 2.6	14.1 ± 2.8	10.6 ± 2.9	9.0 ± 4.2	7.0 ± 2.8
Group 2, Distal to ACDF	7.4 ± 2.6	9.4 ± 2.9	12.0 ± 3.7	12.4 ± 3.6	10.1 ± 4.6	6.8 ± 3.7
Group Difference (T-test)	0.90	0.01	0.23	0.31	0.63	0.87

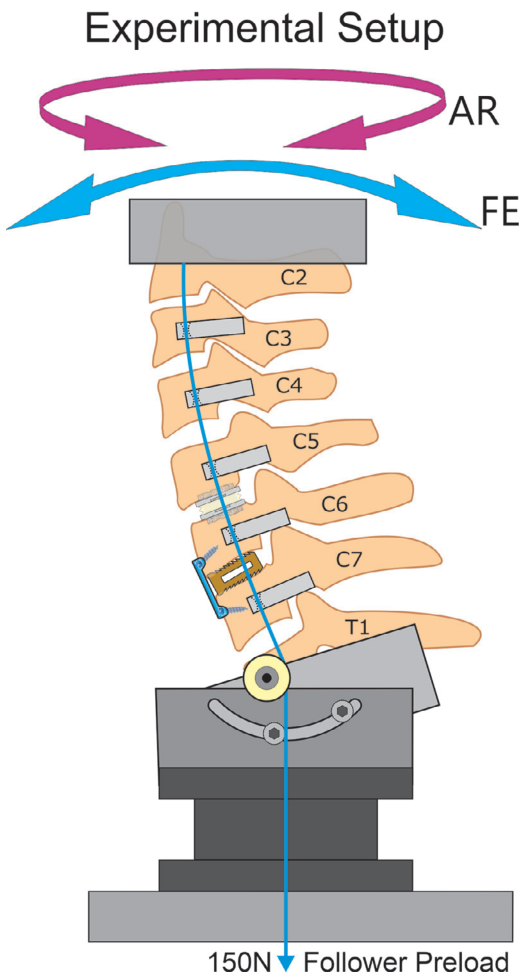

Fig. 3. Schematic showing the experimental setup. Axial rotation (AR) and flexion-extension (FE) motion was generated by applying moments to C2 through the top cup. 150N follower preload was only applied during flexion-extension testing.

tact and in place. A fine slice (0.3 mm interslice distance) axial CT scan was obtained after the specimens were dissected and prepared. CT based specimen-specific anatomic models for kinematic analysis were then built for each specimen [11].

The C2 and T1 vertebrae were anchored in aluminum cups using bone cement and pins. The specimens were wrapped in saline soaked towels to prevent dehydration of the soft tissues. 3-D motion of the cervical vertebrae were measured using infra-red light-emitting targets and an optoelectronic motion measurement system (Optotrak Certus, Northern Digital Inc., Waterloo, Ontario, Canada). A 6-component load cell (Model MC3A-6-250, AMTI Multi-component transducers, AMTI Inc., Newton, MA) placed under the specimen measured applied compressive preload and moments (Fig. 3).

The follower load technique was used to apply compressive preloads to the cervical spine during the range of motion (ROM) experiments in flexion and extension [12]. In vivo the cervical spine is always under some level of compressive preload because of muscle tone, muscle activity and weight bearing. In the experiment, 150N of compressive preload was applied using bilateral loading cables attached to the cup holding the C2 vertebra, the cable passed through guides anchored to each vertebra and followed the lordotic curve of the cervical spine. By applying a compressive load along the follower load path, the segmental bending moments and shear forces due to the preload application were minimized. This allowed the cervical spine to support physiologic compressive preloads without damage or instability while maintaining its mobility in flexion-extension. Follower load was not applied during axial rotation range of motion experiments.

Surgical protocols

A discectomy was performed using standard instruments after testing of the intact spine. The endplates were preserved but scraped clean. Plated ACDF using a polyetheretherketone (PEEK) cage and artificial cervical disc prosthesis (M6-C, Orthofix Medical Inc., Lewisville, TX) were implanted using the manufacturer's instruments and guidelines. Trial sizes were used to gauge the correct cage and disc footprint sizes. 2-level ACDF was simulated by converting TDA to a fusion using an anterior cervical plate (Fig. 4). Fluoroscopic imaging (9900 Elite, GE OEC Medical Systems, Inc., Salt Lake City, UT) was used during surgery for sizing and implant placement. All surgeries were performed under the guidance of an attending spine surgeon.

Experimental protocol

Segmental range of motion was measured during flexion-extension and axial rotation motion for each specimen state (intact, TDA and 1-level ACDF, and TDA and 2-level ACDF). Flexion-extension (**FE**) testing was performed in load control to a moment limit of 1.5Nm with an applied compressive preload of 150N. 1.5Nm was also used as the moment limit for axial rotation but without an applied compressive preload.

Analyses

A mean and standard deviation was computed for the range of motion data. Load control and a modified Panjabi displacement control were used to analyze the data (Details of the modified Panjabi displacement control analysis are in the Results under Range of Motion - Displacement Control). The effect size was not known a priori therefore; similar studies were used to choose the number of specimens in each group.

The Lilliefors test was used to test for normality of the range of motion data. Repeated measures ANOVA of segmental ranges of motion was used to test for the effects of independent categorical variables of group membership and type of motion (flexion-extension and axial rotation). The repeated measurement was the range of motion recorded for each of the three specimen states. Bonferroni corrections were used for post-hoc comparisons. A p-value of less than 0.05 was considered statistically significant.

Results

Equivalence of the two test groups

By design (performing group assignment after intact state testing) there was no difference between groups in flexion-extension range of motion at the 3 targeted intervertebral disc levels C4-C5, C5-C6 and C6-C7 (T-test: $p \geq 0.23$, Table 1). Coincidentally, there was no difference between groups in axial rotation range of motion at those same 3 intervertebral disc levels (T-test: $p \geq 0.12$, Table 2).

Range of motion - load control

Range of motion data was determined from a single extension to flexion load cycle (-1.5Nm to +1.5Nm). Between specimen there was no statistically significant effect detected of type of motion (axial rotation: **AR** vs flexion-extension: **FE**) or group membership (Group 1 vs Group 2) or the interaction of group membership and type of motion on segmental range of motion. Multivariate repeated measures analysis found a statistically significant effect of specimen state (intact, TDA and 1-level ACDF, and TDA and 2-level ACDF) on segmental range of motion ($p < 0.01$). There were also statistically significant interactive effects of specimen state and type of motion ($p < 0.01$); specimen state and group membership ($p = 0.02$); and specimen state, type of

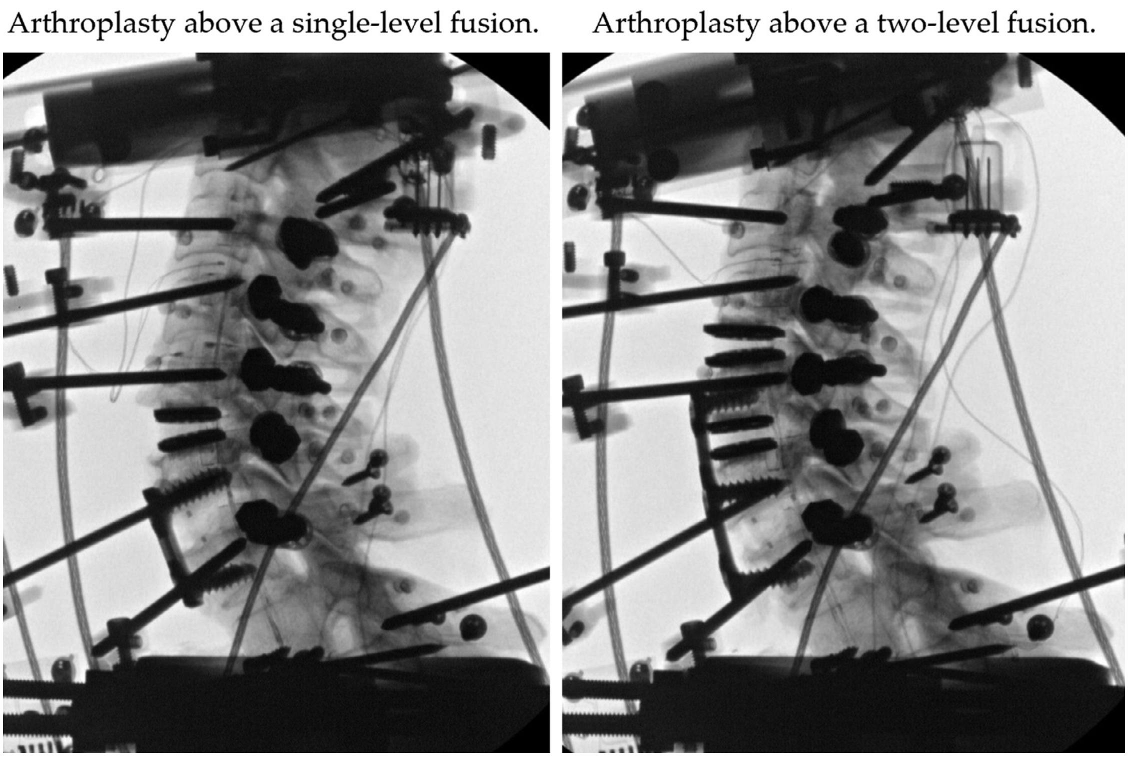

Fig. 4. Radiograph of a Group 1 specimen with an arthroplasty above a single-level fusion (left), and above a 2-level fusion (right).

Table 2
Intact segmental axial rotation range of motion values (mean ± standard deviation) in degrees. Segments to be instrumented are denoted by shading.

	Intact State Axial Rotation Range of Motion, degrees					
	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7	C7-T1
Group 1, Proximal to ACDF	9.9 ± 3.7	14.7 ± 2.8	16.3 ± 5.8	8.7 ± 5.3	7.6 ± 3.4	7.2 ± 2.0
Group 2, Distal to ACDF	8.6 ± 2.9	12.4 ± 1.6	12.6 ± 2.0	10.5 ± 4.1	7.7 ± 3.5	6.4 ± 2.4
Group Difference (T-test)	0.46	0.07	0.12	0.46	0.93	0.49

Table 3
Range of motion in axial rotation for specimens where the total disk arthroplasty is above the fusion (Group 1). The data is presented as mean ± standard deviation. Instrumented segments are denoted by shading. The numbers in bold font are for the level with a total disk arthroplasty. The symbol (§) denotes significantly different from intact ($p < 0.05$).

	State	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7	C7-T1
Load Control	Intact	9.9 ± 3. 7	14.7 ± 2.8	16.3 ± 5.8	9.5 ± 3.5	7.6 ± 3.4	7.2 ± 2.0
	1-level ACDF	6.2 ± 3.1	11.0 ± 2.1	12.7 ± 3.7	**8.1 ± 2.2**	5.5 ± 2.9	7.7 ± 2.3
	2-level ACDF	5.6 ± 2.1	9.9 ± 2.5	**8.8 ± 4.7 §**	5.5 ± 2.9	4.8 ± 2.5	8.1 ± 2.5
Displacement Control	Intact	5.5 ± 2.3	5.1 ± 1.1	12.2 ± 3.5	6.6 ± 4.0	2.4 ± 1.7	5.1 ± 2.2
	1-level ACDF	5.3 ± 2.3	9.7 ± 2.5	8.0 ± 3.4	**4.7 ± 2.1**	4.5 ± 2.5	7.6 ± 2.1
	2-level ACDF	4.6 ± 2.2	8.5 ± 2.3	**6.4 ± 3.1 §**	7.9 ± 2.9	5.4 ± 3.1	7.3 ± 2.1

motion and group membership ($p < 0.05$). The results of Bonferroni-corrected post-hoc paired comparisons, used to determine if these effects were true of the TDA segment adjacent to a fusion, are detailed below.

Group 1: Proximal to 1-level ACDF (C5-C6 TDA above an C6-C7 ACDF) (Tables 3 and 5)

The axial rotation range of motion at C5-C6 reduced from 9.5 ± 3.5° in the intact state to 8.1 ± 2.2° after implantation of a TDA C5-C6 above an C6-C7 ACDF ($p = 0.89$) (**Table 3**). Flexion-extension ROM at C5-C6 was 11.4 ± 4.3° after TDA implantation above an ACDF compared to 10.6 ± 2.9 in the intact/native state ($p = 1.0$) (**Table 5**).

Group 1: Proximal to 2-level ACDF (C4-C5 TDA above C5-C7 ACDF) (Tables 3 and 5)

The axial rotation range of motion of C4-C5 reduced from an average of 12.7 ± 3.7° in the intact state to 8.8 ± 4.7° after TDA implantation at C4-C5 above a 2-level ACDF ($p = 0.02$). Similarly, the flexion-extension range of motion of C4-C5 reduced from an average of 15.4 ± 2.9° to 10.5 ± 3.8° ($p < 0.01$).

Group 2: Distal to 1-level ACDF (C6-C7 TDA below a C5-C6 ACDF) (Tables 4 and 6)

Axial rotation range of motion at C6-C7 increased from 7.7 ± 3.5° in the intact state to 8.0 ± 3.6° after implantation of a C6-C7 TDA below

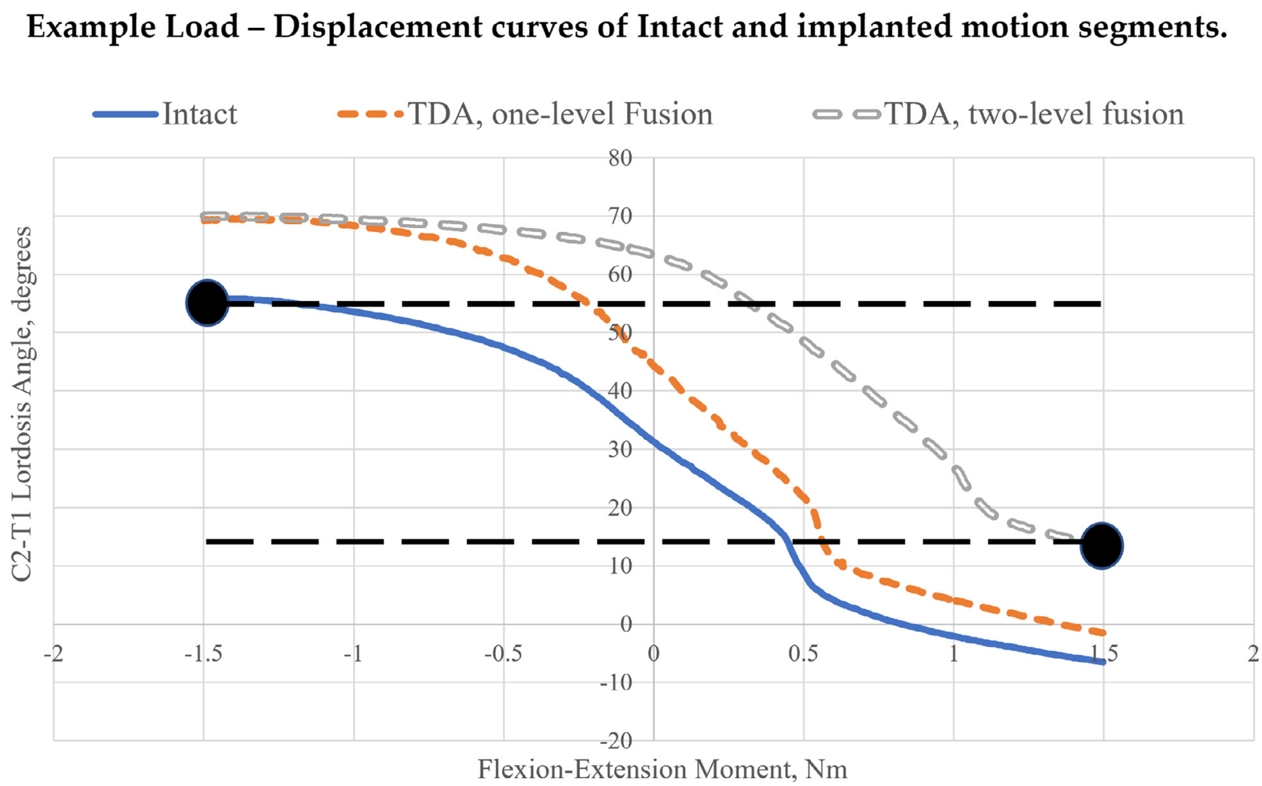

Fig. 5. C2-T1 displacement control limits using the modified Panjabi method. Data from Specimen 1 (Group 1). Black dots indicate the intersection of the data and the applied moment limits.

a 1-level ACDF ($p = 0.01$). C6-C7 flexion-extension range of motion increased slightly from 10.1 ± 4.6° in the intact state to 10.2 ± 5.2° with a C6-C7 TDA below a 1-level ACDF ($p = 1.0$).

Group 2: Distal to 2-level ACDF (C6-C7 TDA below C4-C6 ACDF) (Tables 4 and 6)

Axial rotation range of motion at C6-C7 decreased from 7.7 ± 3.5° in the intact state to 6.0 ± 2.8° with a C6-C7 TDA below a 2-level ACDF ($p < 0.01$). Compared to intact, C6-C7 flexion-extension range of motion increased slightly from 10.1 ± 4.6° to 10.2 ± 4.8 with a C6-C7 TDA below a 2-level ACDF ($p = 1.0$).

Range of motion - displacement control

Displacement control range of motion was calculated using a variation on the Panjabi hybrid test method [13].. In the Panjabi hybrid test method, the motion endpoints are set to those measured in a load control test of the intact specimen. In the variation, the displacement control range of motion is extracted from load control data from all the specimen states. The C2-T1 motion endpoints for each of the states under load control were examined. The lowest value of C2-T1 motion at 1.5Nm and -1.5Nm was then chosen as the displacement control limits. Segmental ranges of motion were then calculated from the load control data using segmental angles at the corresponding C2-T1 displacement control limits.

For example (**Fig. 5**), the lowest C2-T1 angle at -1.5Nm was from the intact specimen test and at 1.5Nm from the TDA with 2-level fusion test. These two states provide us with the C2-T1 angular displacement control limits of 56° and 13°. Therefore for displacement control analysis of Specimen 1, segmental angles were extracted and analyzed for each state when C2-T1 angle was 13° and 56°. Similar analyses were performed for the other specimens based on their own specific flexion and extension endpoints.

By multivariate repeated measures analysis, there was a statistically significant effect of state on segmental range of motion ($p < 0.01$). There were also statistically significant interactive effects of specimen state and type of motion ($p < 0.01$); specimen state and group membership ($p < 0.01$); and specimen state, type of motion and group membership ($p < 0.01$). Results of Bonferroni-corrected post-hoc paired comparisons, used to determine if these effects were true of the TDA segment adjacent to a fusion, are detailed below.

Group 1: Proximal to 1-level ACDF (C5-C6 TDA above a C6-C7 ACDF) (Tables 3 and 5)

The axial rotation range of motion of C5-C6 reduced from 6.6 ± 4.0° in the intact state to 4.7 ± 2.1° after TDA implantation at C5-C6 above an C6-C7 ACDF ($p = 0.67$). Flexion-extension ROM at C5-C6 was 6.2 ± 3.9° after implantation of a C5-C6 TDA above an ACDF compared to 6.8 ± 4.0 in the intact/native state ($p = 1.0$).

Group 1: Proximal to 2-level ACDF (C4-C5 TDA above C5-C7 ACDF) (Tables 3 and 5)

The axial rotation range of motion of C4-C5 reduced from an average of 12.2 ± 3.5° in the intact state (note that the 1-level ACDF data is being used for this comparison) to 6.4 ± 3.1° after C4-C5 TDA above a 2-level ACDF ($p < 0.01$). Similarly, the flexion-extension range of motion of C4-C5 reduced from an average of 10.1 ± 4.2° to 9.0 ± 3.6° ($p = 0.98$).

Group 2: Distal to 1-level ACDF (C6-C7 TDA below an C5-C6 ACDF) (Table 4 and 6)

Axial rotation range of motion at C6-C7 decreased from 4.3 ± 3.1° in the intact state to 3.9 ± 2.7° after TDA implantation at C6-C7 below a 1-level ACDF ($p = 1.0$). C6-C7 flexion-extension range of motion also

Table 4
Range of motion in axial rotation for specimens where the total disk arthroplasty is below the fusion (Group 2). The data is presented as mean ± standard deviation. Instrumented segments are denoted by shading. The numbers in bold font are for the level with a total disk arthroplasty. The symbol (§) denotes significantly different from intact ($p < 0.05$).

	State	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7	C7-T1
Load Control	Intact	8.6 ± 2.9	12.4 ± 1.6	12.6 ± 2.0	10.5 ± 4.1	7.7 ± 3.5	6.4 ± 2.4
	1-level ACDF	7.5 ± 2.5	11.5 ± 1.5	12.1 ± 2.0	6.0 ± 3.2	**8.0 ± 3.6 §**	6.7 ± 2.5
	2-level ACDF	4.6 ± 2.0	7.9 ± 1.8	6.0 ± 1.4	6.7 ± 3.2	**6.0 ± 2.8 §**	6.9 ± 2.6
Displacement Control	Intact	4.3 ± 1.4	3.7 ± 1.2	8.3 ± 1.3	7.0 ± 2.6	4.3 ± 3.1	3.3 ± 2.0
	1-level ACDF	4.7 ± 1.6	4.1 ± 0.7	9.3 ± 1.1	4.6 ± 2.9	**3.9 ± 2.7**	5.4 ± 2.5
	2-level ACDF	4.8 ± 2.0	8.5 ± 1.1	2.6 ± 1.1	5.9 ± 3.0	**6.0 ± 2.4**	6.8 ± 2.5

Table 5
Flexion-extension range of motion for specimens where the total disk arthroplasty is above the fusion (Group 1). The data is presented as mean ± standard deviation. Instrumented segments are denoted by shading. The numbers in bold font are for the level with a total disk arthroplasty. The symbol (§) denotes significantly different from intact ($p < 0.05$).

	State	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7	C7-T1
Load Control	Intact	7.6 ± 1.7	13.4 ± 2.6	14.1 ± 2.8	10.6 ± 2.9	9.0 ± 4.2	7.0 ± 2.8
	1-level ACDF	8.5 ± 2.1	14.4 ± 3.0	15.4 ± 2.9	**11.4 ± 4.3**	3.6 ± 1.5	7.4 ± 2.8
	2-level ACDF	9.0 ± 1.9	14.8 ± 2.7	**10.5 ± 3.8 §**	2.3 ± 1.3	2.9 ± 2.2	7.8 ± 2.8
Displacement Control	Intact	5.1 ± 2.5	8.3 ± 2.4	10.2 ± 3.8	6.8 ± 4.0	1.1 ± 0.5	4.8 ± 3.3
	1-level ACDF	4.9 ± 2.6	9.5 ± 3.1	10.1 ± 4.2	**6.2 ± 3.9**	1.4 ± 0.9	4.5 ± 2.5
	2-level ACDF	6.6 ± 3.0	11.5 ± 4.8	**9.0 ± 3.6**	1.6 ± 0.9	2.4 ± 2.2	5.4 ± 1.9

Table 6
Flexion-extension range of motion for specimens where the total disk arthroplasty is below the fusion (Group 2). The data is presented as mean ± standard deviation. Instrumented segments are denoted by shading. The numbers in bold font are for the level with a total disk arthroplasty. The symbol (§) denotes significantly different from intact ($p < 0.05$).

	State	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7	C7-T1
Load Control	Intact	7.4 ± 2.6	9.4 ± 2.9	12.0 ± 3.7	12.4 ± 3.8	10.1 ± 4.6	6.7 ± 3.7
	1-level ACDF	8.2 ± 3.2	10.5 ± 3.5	12.7 ± 4.3	5.0 ± 2.6	**10.2 ± 5.2**	6.8 ± 3.1
	2-level ACDF	8.6 ± 3.3	10.8 ± 3.6	1.2 ± 0.6	3.6 ± 2.6	**10.2 ± 4.8**	7.2 ± 3.3
Displacement Control	Intact	5.4 ± 2.9	6.2 ± 2.7	7.1 ± 2.8	1.4 ± 0.9	5.8 ± 5.1	4.6 ± 4.6
	1-level ACDF	5.0 ± 3.2	6.9 ± 3.4	8.2 ± 3.8	2.2 ± 1.7	**4.7 ± 3.7**	4.2 ± 4.0
	2-level ACDF	5.4 ± 3.7	7.7 ± 4.2	0.8 ± 0.6	2.6 ± 2.0	**9.2 ± 4.8**	5.3 ± 4.0

decreased slightly from 5.8 ± 5.1° in the intact state to 4.7 ± 3.7° with a C6-C7 TDA below a 1-level ACDF ($p = 1.0$).

Group 2: Distal to 2-level ACDF (C6-C7 TDA below C4-C6 ACDF) (Tables 4 and 6)

Axial rotation range of motion at C6-C7 increased from 4.3 ± 3.1° in the intact state to 6.0 ± 2.4° with a C6-C7 TDA below a 2-level ACDF ($p = 0.09$). Compared to intact, C6-C7 flexion-extension range of motion increased from 5.8 ± 5.1° to 9.2 ± 4.8 with a C6-C7 TDA below a 2-level ACDF ($p = 0.06$).

Compensatory motion

From the load control analysis, all segments above instrumentation had reduced axial rotation range of motion (**Tables 3** and **4**). This result was the same for 1-level and 2-level fusions in Group 1 and Group 2 specimens. Similarly, all non-instrumented segments had increased flexion-extension range of motion (**Tables 5** and **6**).

No consistent pattern of compensatory motion in non-instrumented cervical spine segments was found in displacement control analysis.

Summary of 1-level ACDF results

There was a small change in axial rotation and flexion-extension range of motion when the intact state was compared to the specimen instrumented with a C5-C6 TDA above a 1-level ACDF (Group 1). The reduction in mean axial rotation range of motion between intact C5-C6 and C5-C6 TDA was 1.4° using load control analysis ($p = 0.89$) and 1.9° using displacement control analysis ($p = 0.67$). The mean C5-C6 TDA flexion-extension range of motion was 0.8° higher than in the intact C5-C6 using load control analysis ($p = 1.0$) and 0.6° lower using displacement control analysis ($p = 1.0$).

Similarly, there were small changes in axial rotation and flexion-extension ranges of motion after implantation of a C6-C7 TDA below a 1-level ACDF (Group 2). Mean C6-C7 axial rotation range of motion after TDA was 0.3° higher than intact using load control analysis ($p = 0.01$) and 0.4° lower using displacement control analysis ($p = 1.0$). In flexion-extension, using load control analysis the average C6-C7 range of motion increased by 0.1° after TDA ($p = 1.0$) and decreased 1.1° using displacement control analysis ($p = 1.0$).

Summary of 2-level ACDF results

Placing a TDA above a 2-level ACDF (Group 1) reduced the mean C4-C5 axial rotation range of motion by 3.9° in load control analysis ($p = 0.02$) and 5.8° using displacement control analysis ($p < 0.01$). Mean C4-C5 flexion-extension range of motion was 4.9° less after TDA using load control analysis ($p < 0.01$) and 1.2° less using displacement control analysis ($p = 0.98$).

Compared to intact, C6-C7 TDA below a 2-level ACDF (Group 2) reduced the mean C6-C7 axial rotation range of motion by 1.7° in load control analysis ($p < 0.01$) and increased the mean axial rotation range of motion by 1.7° by displacement control analysis ($p = 0.09$). Mean

C6-C7 flexion-extension range of motion was 0.1° higher than intact using load control analysis after TDA ($p = 1.0$) and 3.4° higher using displacement control analysis ($p = 0.06$).

Discussion

In this work we investigated 2 different hybrid construct configurations. The TDA was below the fusion in one configuration and the TDA was above the fusion in the other configuration. 1- and 2-level fusions were tested in both hybrid configurations. The data was analyzed in load control and, to allow comparison to previous studies, displacement control. A feature of the experimental design is that the TDA segment is the same for 1- and 2-level fusions for the hybrid configuration where the TDA is below the fusion, i.e. the TDA is at C6-C7. Whereas the TDA is at C5-C6 and C4-C5 for one and 2-level fusions respectively when the hybrid configuration has the TDA above the fusion.

Load control: Hybrid with C6-C7 TDA below the fusion

In load control, segmental flexion-extension range of motion at the TDA segment was not different from intact when the TDA was below the fusion. C6-C7 was the segment with the TDA in the 1-level and 2-level fusion cases. In both fusion cases, the mean change from intact in C6-C7 flexion-extension range of motion was a non-significant increase of 0.1°. C6-C7 segmental axial rotation range of motion was 0.3° higher than intact with 1-level fusion and 1.7° lower with 2-level fusion. Although these C6-C7 axial rotation ranges of motion were statistically different from intact: 1) 0.3° difference (1-level fusion) is not clinically significant, and 2) the 1.7° of reduced range of motion (2-level fusion) may be protective of the implanted segment and those segments adjacent to the hybrid construct. In this study, fusion was not very effective at controlling axial rotation motion and it is not clear what the effect would have been of a more effective fusion. Nevertheless, these results suggest that there is no additional motion demand in adding an additional fused level (a proxy for stress) on the C6-C7 TDA in flexion-extension and that there is a reduced motion demand in axial rotation.

Load control: Hybrid with TDA above the fusion

In load control, mean segmental flexion-extension range of motion at the TDA segment was significantly lower than intact in the hybrid configuration with a 2-level fusion and higher than intact (0.8°, $p = 1.0$) with the 1-level fusion. In the hybrid configuration with a 2-level fusion, the mean flexion-extension range of motion at the TDA segment was 4.9° less than intact motion.

In axial rotation, the motion at the TDA segment was less than intact in both 1-level and 2-level fusion hybrid configurations. The reduction in segmental motion was 1.4° with the 1-level fusion and a statistically significant 3.9° with the 2-level fusion hybrid configuration.

In the hybrid configuration with the TDA above the fusion, motion was always lower than intact when statistically significant differences in segmental range of motion at the TDA segmental level were found. These significant reductions in segmental motion, 4.9° in flexion-extension and 3.9° in axial rotation, occurred at C4-C5 when testing the hybrid configuration with a 2-level fusion.

Displacement control: Hybrid with TDA below the fusion

In the hybrid configuration with a 1-level fusion, C6-C7 segmental flexion-extension range of motion decreased by 1.1° ($p = 1.0$). C6-C7 axial rotation range of motion decreased by 0.4° ($p = 1.0$). These changes in range of motion were not statistically or clinically significant. Compared to intact, Lee et al. found that the PCM TDA level, C5-C6, had a slightly increased flexion-extension range of motion with the TDA below a 1-level fusion ($p > 0.05$) [7]. Gandhi et al. found increased flexion-extension and axial rotation motion at the Bryan and Prestige TDA level with the TDA below a 1-level fusion [8]. The increase in flexion-extension range of motion was significant for the Bryan TDA (2°). Our data and that of Lee et al. and Gandhi et al. show that changes in segmental flexion-extension range of motion were not clinically significant in a hybrid configuration with the TDA below a 1-level fusion.

In the 2-level fusion hybrid configuration, both flexion extension and axial rotation range of motion increased at C6-C7. Axial rotation range of motion by 1.7° ($p = 0.09$) and flexion-extension by 3.4° ($p = 0.06$). This increase in axial rotation motion was neither clinically nor statistically significant. In flexion-extension, however, the increase in motion was clinically significant. This data suggests that the TDA segmental level was less stiff than the intact segment and, therefore, was preferentially recruited to provide motion.

Displacement control: hybrid with TDA above the fusion

With the TDA above a 1-level fusion, we found reductions in C5-C6 axial rotation and flexion-extension ranges of motion that were neither clinically nor statistically significant (AR: 1.9°, $p = 0.67$; FE: 0.6°, $p = 1.0$). Lee et al. found a non-significant increase in segmental flexion-extension ROM at the TDA level in a hybrid configuration with the PCM TDA above a 1-level fusion ($p > 0.5$) [7]. Testing a PCM TDA above a 1-level fusion, Cunningham et al. found significantly increased axial rotation and flexion-extension range of motion increased at the TDA level [6]. The data in Cunningham et al. were presented as percentage of intact motion making it hard to deduce if the changes were clinically significant. The TDA in the Lee et al. and Cunningham et al. hybrid configurations was the PCM. The difference in their results may be because Cunningham et al. ran specimens back to global intact motion (Panjabi method) while Lee et al. used a modified Panjabi method. Barrey et al. found reductions in C4-C5 flexion-extension and axial rotation range of motion after implantation of a Discocerv TDA above a 1-level fusion [9]. The change in axial rotation range of motion of approximately 10° was statistically and clinically significant.

In this study, flexion-extension and axial rotation ranges of motion reduced at the TDA level in the hybrid with the TDA above a 2-level fusion. The reduction in axial rotation range of motion of six° was clinically and statistically significant. With a ProDisc-C TDA above a 2-level kyphotic or lordotic fusion, Martin et al. found a significant reduction in flexion-extension range of motion at the TDA level (C3-C4) [10].

Displacement control: compensatory motion

A consistent pattern of compensatory motion was not found in this study when using displacement control analysis. Lee et al. found compensatory increases in flexion-extension motion at all unfused levels in hybrid configurations with the TDA either above or below the fusion [7]. Barrey et al. found contribution to C3-C7 flexion-extension range of motion increased in the upper adjacent and significantly increased in lower adjacent segments levels in the hybrid configuration with TDA above a 1-level fusion [9]. Gandhi et al. studied TDA below a 1-level fusion and found that non-instrumented segments increased compensatory motion by about 20% with the Bryan TDA, while increased motion primarily occurred at C6-C7 below the Prestige TDA [8]. Martin et al. found a significant increase in compensatory motion at the level above the ProDisc-C TDA (C2-C3) in kyphotic and lordotic hybrid configurations [10].

Summary and conclusions

Biomechanical studies have shown increased motion at the segment adjacent to one and 2-level fusions [7–10]. In this study, compensatory increases in motion were found at all non-instrumented cervical spine segments in flexion-extension and axial rotation when data were analyzed using the load control method. No such pattern was found when data were analyzed using a modified Panjabi displacement control method. These differences may be because in load control the analysis was performed on data acquired when the specimen was under the peak moment of ±1.5Nm. In the modified Panjabi displacement control analysis method, the data from each specimen state was collected at an applied moment that may be different from ±1.5Nm.

Using a load control analysis, flexion-extension and axial rotation ranges of motion at the TDA segmental level were either less than a degree higher than intact or lower than intact. Range of motion was higher than intact by, at most, three and a half°° or was lower than intact when data was analyzed using the displacement control method. That the TDA segmental level has similar amounts of motion or reduced motion as compared to intact may shield the TDA segmental level and levels adjacent to the TDA from supra-physiological motion and loading that can occur adjacent to fusion.

Clinical relevance

Our results suggest that a hybrid construct may be protective of adjacent segments, regardless of whether the total disc arthroplasty is above or below the fusion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Shin DA, Yi S, Kim KN, et al. Artificial disc replacement combined with fusion versus two-level fusion in cervical two-level disc disease. Spine 2009;34(11):1153–9.
[2] Wang KF, Duan S, Zhu ZQ, et al. Clinical and radiologic features of 3 reconstructive procedures for the surgical management of patients with bilevel cervical degenerative disc disease at a minimum follow-up period of 5 years: a comparative study. World Neurosurg 2018;113:e70–6.
[3] Kang L, Lin D, Ding Z, et al. Artificial disk replacement combined with midlevel ACDF versus multilevel fusion for cervical disk disease involving 3 levels. Orthopedics 2013;36(1):e88–94.
[4] Ji GY, Oh CH, Shin DA, et al. Artificial disk replacement combined with fusion versus 2-level fusion in cervical 2-level disk disease with a 5-year follow-up. Clin Spine Surg 2017;30(5):E620–7.
[5] Xiong Y, Xu L, Yu X, et al. Comparison of 6-year follow-up result of hybrid surgery and anterior cervical discectomy and fusion for the treatment of contiguous two-segment cervical degenerative disc diseases. Spine 2018;43(20):1418–25.
[6] Cunningham BW, Hu N, Zorn CM, et al. Biomechanical comparison of single- and two-level cervical arthroplasty versus arthrodesis: effect on adjacent-level spinal kinematics. Spine J 2010;10(4):341–9.
[7] Lee MJ, Dumonski M, Phillips FM, et al. Disc replacement adjacent to cervical fusion: a biomechanical comparison of hybrid construct versus two-level fusion. Spine 2011;36(23):1932–9.
[8] Gandhi AA, Kode S, DeVries NA, et al. Biomechanical analysis of cervical disc replacement and fusion using single level, two level, and hybrid constructs. Spine 2015;40(20):1578–85.
[9] Barrey C, Campana S, Persohn S, et al. Cervical disc prosthesis versus arthrodesis using one-level, hybrid and two-level constructs: an in vitro investigation. Eur Spine J 2012;21(3):432–42.
[10] Martin S, Ghanayem AJ, Tzermiadianos MN, et al. Kinematics of cervical total disc replacement adjacent to a two-level, straight versus Lordotic fusion. Spine 2011;36(17):1359–66.
[11] Havey RM, Goodsitt J, Khayatzadeh S, et al. Three-dimensional computed tomography-based specimen-specific kinematic model for ex vivo assessment of lumbar neuroforaminal space. Spine 2015;40(14):E814–22.
[12] Patwardhan AG, Havey RM, Ghanayem AJ, et al. Load-carrying capacity of the human cervical spine in compression is increased under a follower load. Spine 2000;25(12):1548–54.
[13] Panjabi MM. Hybrid multidirectional test method to evaluate spinal adjacent-level effects. Clin Biomech 2007;22(3):257–65.