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Basic Science

Biomechanical effects on the intermediate segment of noncontiguous hybrid surgery with cervical disc arthroplasty and anterior cervical discectomy and fusion: a finite element analysis

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Abstract

BACKGROUND CONTEXT: Surgery for cervical degenerative disc disorder (CDDD) at two noncontiguous segments is infrequent. Few studies have explored the biomechanical effects on the intermediate adjacent segment of anterior cervical discectomy and fusion (ACDF) or cervical disc arthroplasty (CDA) in this situation. No study has examined biomechanical differences between ACDF and hybrid surgery (HS) constructs for noncontiguous CDDD. Differences in the biomechanical changes between the intermediate and adjacent segments are unknown.

PURPOSE: This study was conducted to compare the biomechanical changes resulting from noncontiguous ACDFs and HS.

STUDY DESIGN: A finite element analysis study.

METHODS: A finite element model of a healthy cervical spine (C2−C7) was constructed. Three surgical models were developed: (1) ACDF at C3/4 and C5/6 (FF), (2) ACDF at C3/4 and CDA at C5/6 (FA) and (3) CDA at C3/4 and ACDF at C5/6 (AF). A 75-N follower load with 1.0 N·m moments was applied to the top of the C2 vertebra in the intact model to simulate flexion, extension, lateral bending, and axial rotation. Surgical models achieved identical motion angles of the intact model in each direction following the displacement-control protocols.

RESULTS: The FF model required much higher moments than did the AF and FA models to achieve the same amount of motion. In the FF model, the motion contributions of the unfused segments were unevenly increased. The magnitude of the increased motion in the intermediate segment was larger than those in the supra- or infra-adjacent segments. The facet contact force (FCF) and intradiscal pressure (IDP) at the intermediate segment were also more susceptible to impact. In the FA and AF models, the motion contributions of the untreated levels were evenly changed, and the intermediate segment did not experience additive motion, FCF, or IDP. The segment adjacent to the level of ACDF had greater FCF and IDP than did the segment adjacent to the level of CDA in the two HS constructs.

CONCLUSIONS: HS constructs resulted in less altered biomechanics and kinematics of the untreated levels and showed no additive biomechanical effects on the intermediate segments compared with ACDF at noncontiguous levels. However, the effects were associated with the relative location of the ACDF and CDA levels.

FDA device/drug status: Not applicable

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CLINICAL SIGNIFICANCE: This study provides a biomechanical rationale for the use of HS to treat patients with noncontiguous CDDD.

Keywords: Anterior cervical discectomy and fusion; Biomechanics; Finite element analysis; Hybrid surgery; Intermediate segment; Noncontiguous cervical degenerative disc disease

Introduction

Symptomatic cervical degenerative disc disorder (CDDD) is a common condition causing pain and/or neurological deficit secondary to compression of the spinal cord or nerve roots [1,2]. Although multilevel CDDD is not uncommon in clinical practice [3], surgeons are occasionally confronted with a patient who has two noncontiguous levels requiring surgical treatment. Due to a paucity of data regarding noncontiguous CDDD, the optimal management of this disorder remains controversial and case dependent. While anterior cervical discectomy and fusion (ACDF) for multilevel CDDD has long been advocated, there is evidence supporting more substantial biomechanical effects on adjacent segments in multilevel fusion compared to single-level fusion [4,5]. In a cadaveric study, Finn et al. found that infra- and suprajacent levels experienced a marked increase in strain with a contiguous three-level fusion procedure, whereas the intermediate, supra-, and infra-adjacent segments of a noncontiguous two-level fusion experienced modest strain relative to that in the intact spine [6]. Cervical disc arthroplasty (CDA) was developed to preserve motion and potentially reduce the incidence of adjacent segment degeneration (ASD). Unfortunately, no study regarding the biomechanical effect on an intermediate segment after level two, noncontiguous CDA has been presented.

Several clinical studies have reported the incidence of degeneration at the intermediate segment after noncontiguous (also known as skip-level) ACDF, ranging from 6.25% to 20% at 2-year follow-up [7,8]. Kan et al. [9] found that degeneration of the intermediate segment was more accelerated after skip-level fusion than was degeneration of the supra- or infra-adjacent segments. Additionally, the authors confirmed a higher rate of ASD in the skip-level fusion group 3 years after surgery. In previous work, we reported a case of collapse of the intermediate segment 3 months after skip-level HS [10]. These observations raise some questions for surgeons: (1) Does an intermediate segment experience additive biomechanical effects after noncontiguous surgery when compared with the supra- or infra-adjacent segments? (2) Does HS have the potential to protect the intermediate segment? (3) Does the relative location of CDA and HS affect the biomechanical stressors on the intermediate segment? Although several biomechanical studies have investigated the kinematic response to hybrid constructs [11−13], conclusions based on contiguous HS may not be applicable to noncontiguous HS because the mechanism is different. To our knowledge, no study has examined the biomechanics of HS for noncontiguous CDDD in the cervical spine. We tried to address these questions and aimed to compare the biomechanical changes resulting from skip-level fusion and HS of the cervical spine in the current study.

Methods

A nonlinear three-dimensional finite element (FE) model of cervical spine segments (C2−C7) was developed and validated in our previous study [14]. The model was constructed based on computed tomography (CT) images from a young male volunteer without cervical degeneration (28 years, 165 cm, 65 kg) with a resolution of 0.75 mm and interval 0.69 mm, which were obtained using a CT scanner (SOMATOM Definition AS+, Siemens, Germany).

Construction of the cervical spine model and instruments

Mimics 17.0 (Materialize Inc., Leuven, Belgium) software was used to reconstruct the geometric structure of the C2−C7 cervical vertebrae by importing into the CT scans. Next, the primary geometry was embedded into Geomagic Studio 12.0 (3D System Corporation, Rock Hill, South Carolina, USA) to construct a symmetrical model. Then, the model was processed using CATIA v5r21 (Dassault systems Corporation, Velizy-Villacoublay Cedex, France) and imported into Hypermesh 12.0 (Altair, Troy, MI, USA) to prepare the model. Finally, the boundary conditions of the prepared model were set using ABAQUS 6.9.1 (Dassault Systems Corporation).

The cancellous bone regions of the vertebrae were set as solid elements. A 0.4-mm-thick shell consisting of cortical bone and endplates covered the cancellous bone [15]. The intervertebral disc was divided into the annulus fibrosus and nucleus pulposus with a volume ratio of 6:4 [15]. Annulus fibers surrounded the ground substance with an inclination to the transverse plane between 15° and 30°, accounting for approximately 19% of the entire annulus fibrosus volume [15]. A tie connection was defined between the intervertebral disc and endplates. The facet joint space was 0.5 mm and was covered by a cartilage layer with nonlinear surface-to-surface contact. Frictionless contact was defined between the articular surfaces of the facet joints [14,16]. Five groups of ligaments, including the anterior longitudinal ligament, posterior longitudinal ligament, ligamentum flavum, interspinous ligament, and capsular ligament were developed using tension-only rod elements and attached to the corresponding vertebrae. The numbers of nodes and elements of the cervical spine model are shown in Supplemental File 1.

The Zero-P system (Synthes, Oberdorf, Switzerland) and the Prestige-LP artificial cervical disc (Medtronic Sofamor Danek, Memphis, Tennessee) were adopted in the current study. The width, length, and height of the Prestige-LP and cage were 15, 16, and 6 mm, respectively. The self-tapping screws were 6.5 mm long (Fig. 1). The cancellous bone that fills the Zero-P cage frame was defined as frictionless [17]. A nonbonded contact was applied between the supra- and infra-adjacent surfaces of the cage and the relevant vertebral surfaces with a contact friction coefficient of 0.3 [18]. The graft-vertebrae and screw-vertebrae interfaces were defined as tie constraints to simulate rigid fusion and sufficient osseointegration. To simplify the model, shared nodes at the screw-plate interfaces were used, thus not allowing relative motion between the components. The implant-implant interfaces of the artificial cervical disc were defined as surface-to-surface sliding contact with a fraction coefficient of 0.07 [19]. The material properties and mesh types are listed in Supplemental File 2 [14,15,20,21].

Biomechanical testing

The FE model of intact C2−C7 segments was fixed at the inferior endplate of C7. Follower loads of 75 N were used to simulate muscle force and head weight. A 1.0-N·m moment and a 75-N follower load were applied to the odontoid of the C2 vertebrae to produce flexion, extension, lateral bending, and axial rotation.

According to the hybrid control proposed by Panjabi [22], the corresponding movement angles of all directions in the intact cervical model were applied to the subsequent surgical constructs, including (1) FF: skip-level ACDF at C3/4 and C5/6 segments, (2) FA: ACDF at C3/4 and CDA at C5/6 segments, and (3) AF: CDA at C3/4 and ACDF at C5/6 segments (Fig. 1). Based on our previous study and literature data, we chose C3/4 and C5/6 as the implanted levels because they are the most frequently involved levels in clinical practice [8,23−26].

Results

Validation of the intact cervical spine model

The predicted range of motion (ROM) of the intact cervical spine model fell within one standard deviation of previous experimental data [27−29] (Fig. 2). This finding indicates that the level of spinal kinematics of the current model can represent a statistically healthy individual. The overall ROMs of flexion, extension, lateral bending, and axial rotation were 30.61°, 23.61°, 24.24°, and 15.43°, respectively. The corresponding angles were applied to all surgical models under the displacement-control test.

Predicted moment

The FF model required much higher moments than did the two HS models to achieve the same motion in all directions. Compared with that in the intact model, the flexion moment required to drive the FF, FA, and AF models to produce the same motion angle increased by 92%, 27%,

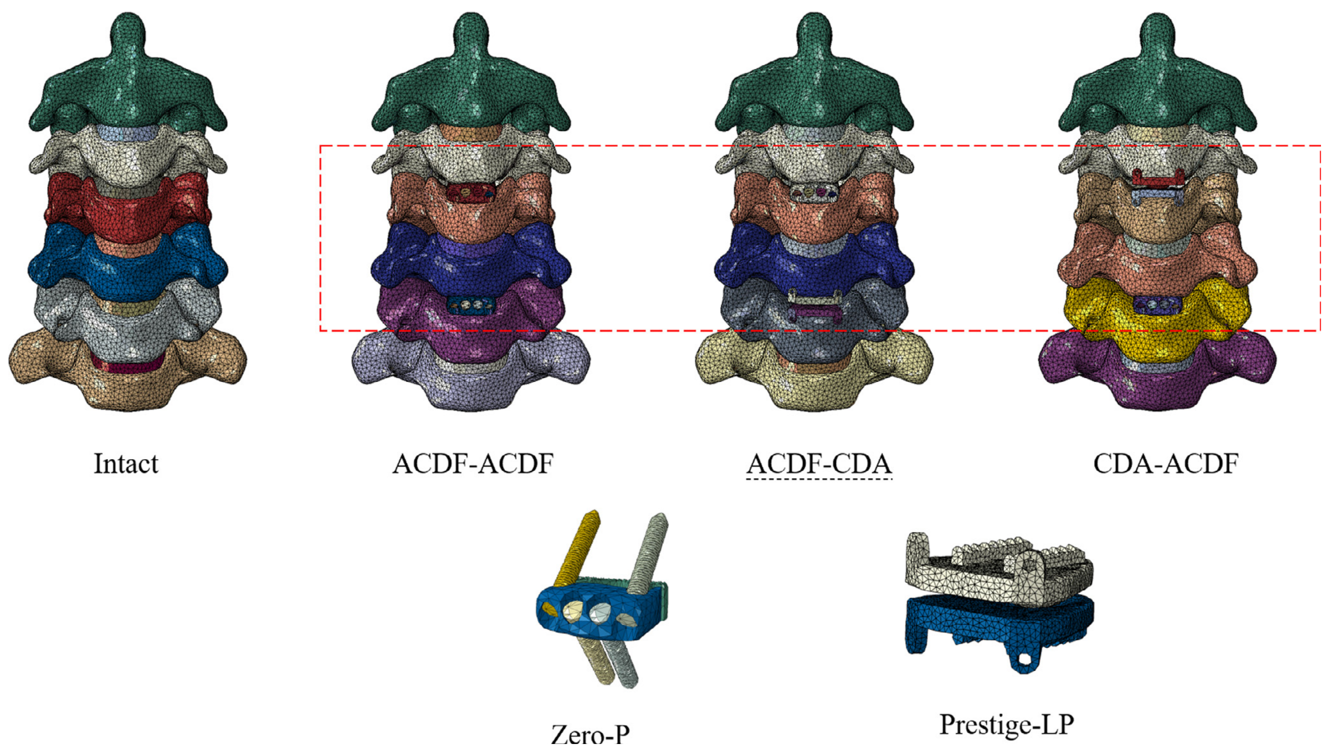

Fig. 1. Finite element of a healthy cervical spine (C2−C7) and three surgical models.

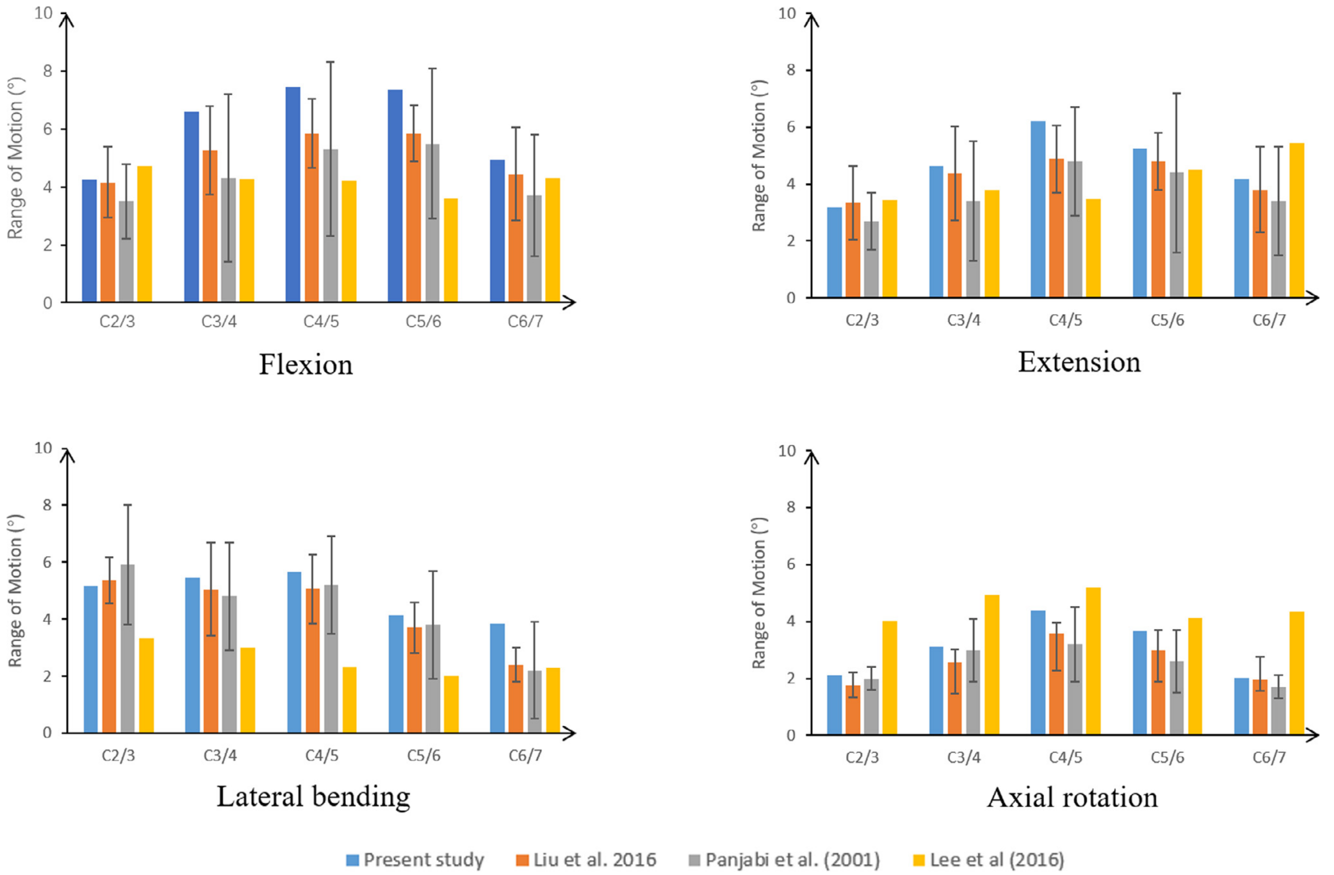

Fig. 2. The predicted ranges of motion (ROMs) of the intact model are validated by previous published studies.

and 34%, respectively. In extension, the moments increased by 85%, 24%, and 29% in the FF, FA, and AF models, respectively. In lateral bending, the moments increased by 74%, 31%, and 39% in the FF, FA, and AF models, respectively. In axial rotation, the moments increased by 86%, 25%, and 23% in the FF, FA, and AF models, respectively (Fig. 3).

Distribution of spinal motion

The ROMs of each segment during flexion, extension, lateral bending, and axial rotation are shown in Fig. 5. For all motions, the ROMs of the fused levels in the FF, FA, and AF models were nearly zero, resulting in an increase in the contribution of unfused levels, especially in the FF model. In contrast, the ROMs of the arthroplasty levels in the FA and AF models were increased by 12.6%−75.5% for all motions when compared with ROM of the intact model. The unfused levels that exhibited increased motions fulfilled a compensatory function to maintain normal movement (Fig. 4).

In the FF model, the contributions of the superior (C2/3), intermediate (C4/5), and inferior (C6/7) segments to the overall ROM in all motions were unevenly increased, with the magnitude of increased motion in the intermediate segment being larger than those in the supra- or infra-adjacent segments. In contrast to the FF model, the contributions of the untreated levels to the global ROM in all motions were more evenly changed in the HS models, irrespective of the relative location of the fusion and arthroplasty. For example, under the flexion moment, the contributions to the global ROM increased from 13.9% to 24.6% at the C2/3 segment, from 24.4% to 42.2% at the C4/5 segment, and from 16.1% to 26.3% at the C6/7 segment in the FF model. For the FA model, the corresponding segmental contributions were 19.7%, 26.7%, and 21.0%, respectively. In the AF model, the contributions of the corresponding segmental motion were 17.0%, 28.0%, and 20.97%, respectively. In the extension, lateral bending and axial rotation conditions, the contributions of the untreated levels showed a trend similar to those in the flexion condition. The results indicated that skip-level ACDF had a substantial effect on the intermediate segment, while the intermediate segment was less influenced by the skip-level HS constructs.

Facet contact force at the adjacent and intermediate segments

Compared to the intact model, the maximum increases of the facet contact force (FCF) in the FF model were

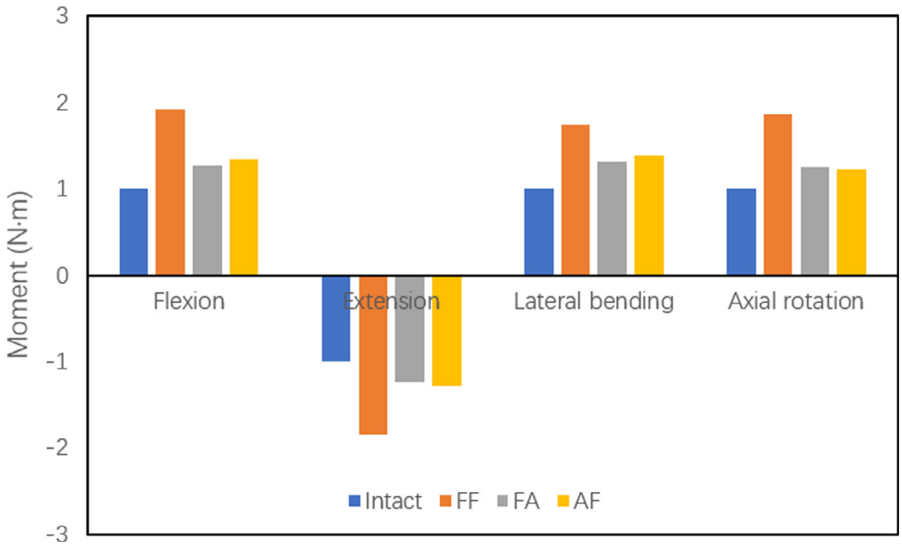

Fig. 3. Predicted moments in flexion, extension, lateral bending, and axial rotation.

50.7%, 54.3%, and 37.6% in the supra-adjacent, intermediate and infra-adjacent segments, respectively, occurring under the extension moment. The FCF at the untreated levels was apparently affected by the relative location of the fusion and arthroplasty (Fig. 5). In the FA model, the FCF of the supra-adjacent segment to the fusion level increased by 35.7% from the intact model, whereas changes in the infra-adjacent segment to the arthroplasty level decreased by 2.5% compared with the intact model under the extension moment. A similar trend was observed in the AF group, in which the FCF transmitted superior to the arthroplasty level modestly increased by14.6%, whereas the force

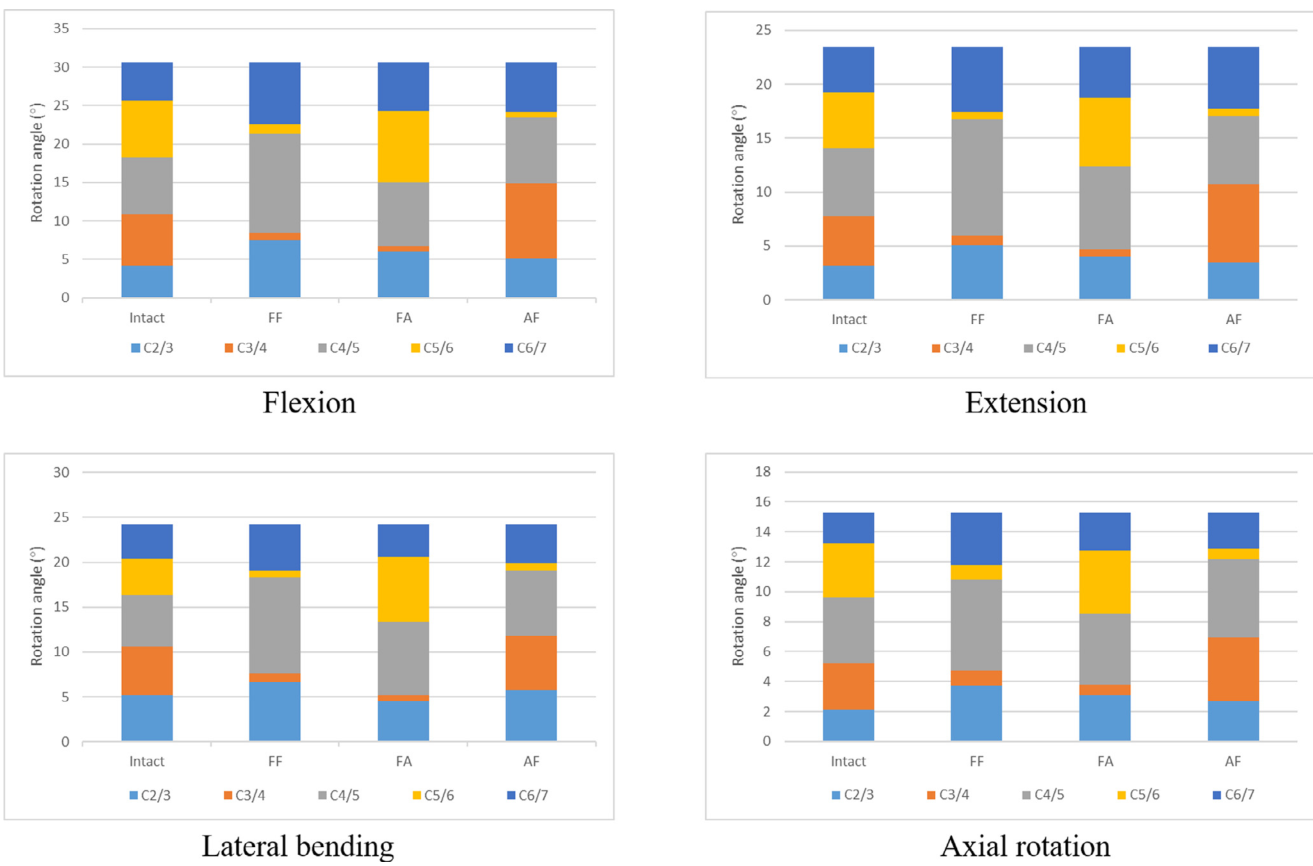

Fig. 4. Spinal motion distribution in flexion, extension, lateral bending, and axial rotation.

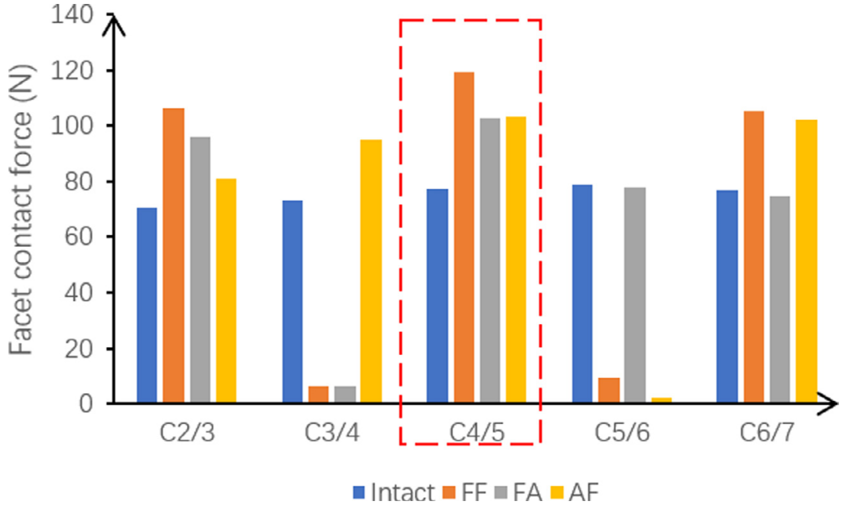

Fig. 5. Facet contact force in extension.

increased by 33.4% at the level infra-adjacent to the fusion level compared with the intact model. However, the FCF of the intermediate segment similarly increased in the FA and AF groups (32.8% and 33.6%, respectively).

Intradiscal pressure

Intradiscal pressure (IDP) measures at the supra-adjacent (C2/3), intermediate (4/5), and infra-adjacent (C6/7) segments are presented in Figs. 6 and 7. The maximum IDPs were noted at the end of the axial rotation moment. As expected, the IDPs at the untreated levels were substantially more sensitive to the skip-level fusion construct. Compared with that in the intact model, the IDP increased by 62.9% at C2/3, 69.0% at C4/5, and 72.5% at C6/7 in the FF model. In the FA model, the IDP at C2/3, C4/5, and C6/7 increased by 52.6%, 57.1%, and 15.0%, respectively.

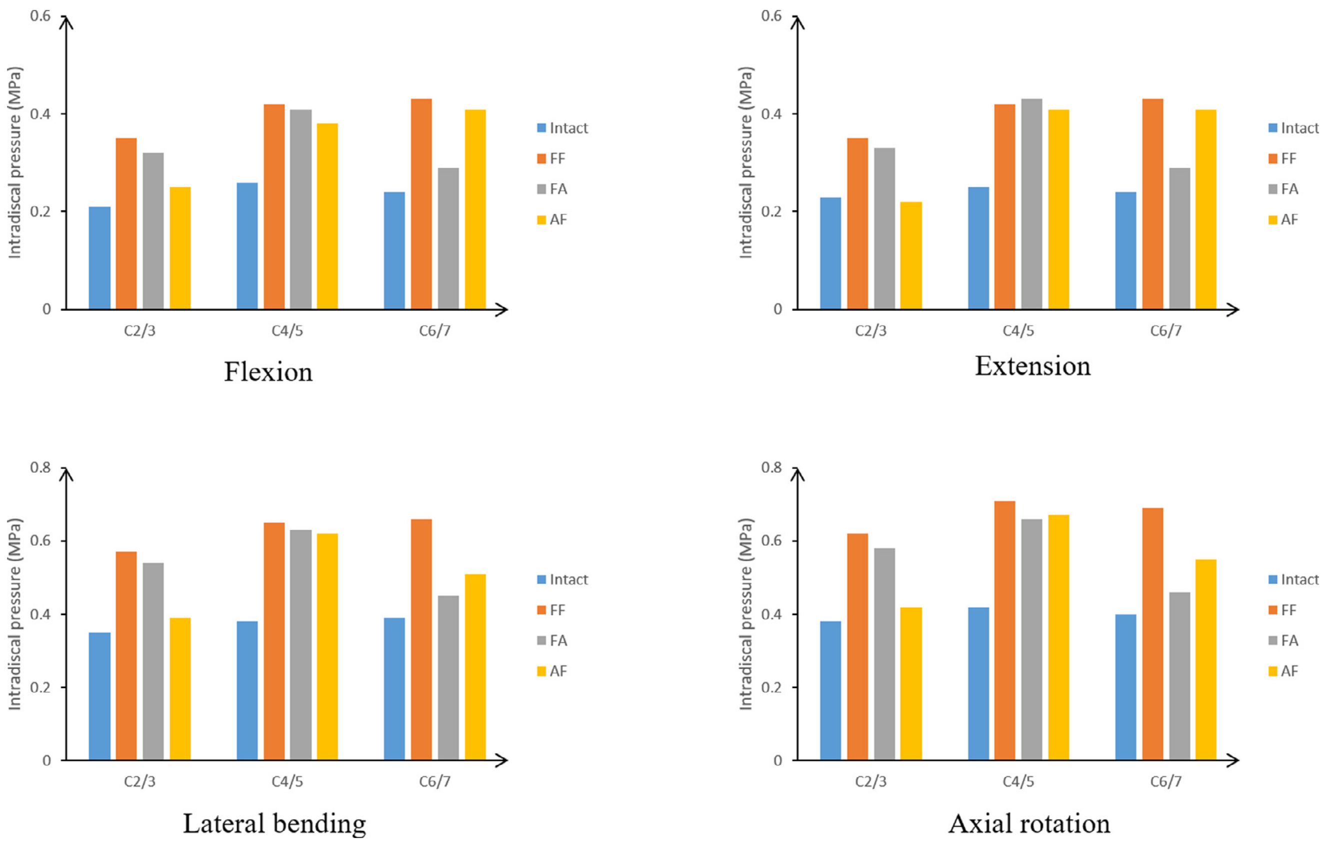

Fig. 6. Intradiscal pressure at the intermediate segment and adjacent segments.

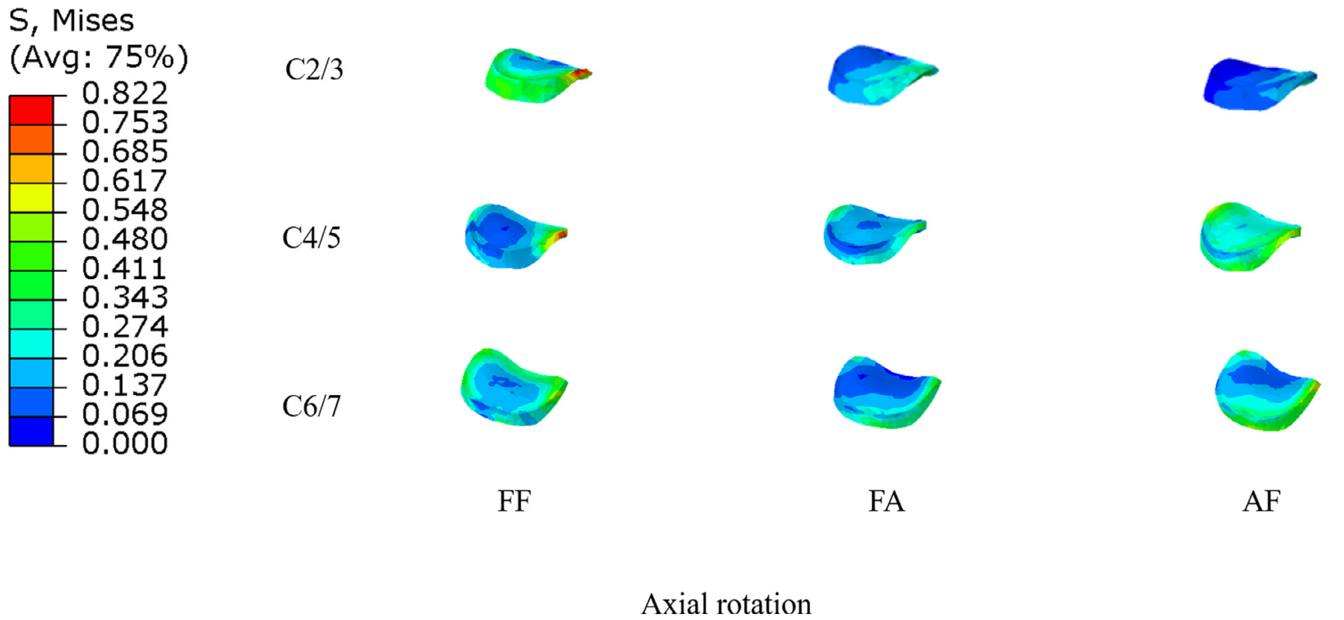

Fig. 7. Stress distribution on the intervertebral disc in axial rotation.

In the AF model, the corresponding IDP increased by 10.5%, 59.5%, and 37.5%, respectively.

Discussion

ACDF has been widely accepted as a gold standard for multilevel CDDD due to its excellent clinical outcomes. However, substantial loss of mobility at the fused level after ACDF has been suggested to lead to accelerated ASD [30,31]. In addition, long-segment fusion may sacrifice the normal structure and function of the intermediate segment in noncontiguous CDDD, as surgeons fear a remarkable effect of additive biomechanical forces on the intermediate segment. Although Finn et al. [6] initially compared the differences between the biomechanical effects of three-level fusion and skip-level fusion constructs on the adjacent and intermediate segments, many questions remained. HS may latently provide a tradeoff in stiffness and motion preservation. Recently, some authors have reported clinical experience of HS at two or three levels with outcomes comparable to those of ACDF and CDA [32−35]. Furthermore, biomechanical studies have noted that HS is beneficial in maintaining cervical mobility and does not decrease the stiffness of the cervical spine [36,37]. Based on these results, HS may have the potential to be an alternative treatment for noncontiguous CDDD.

In the current investigation, the kinematic changes at the adjacent segments were highlighted under a hybrid test protocol, which allows for the redistribution of biomechanical kinematic parameters throughout the multilevel segments of the cervical spine and accounts for the observed changes in adjacent-level motion [22]. One of the valuable findings in the FF model was that the adjacent segments produced larger motions to compensate for the motion lost at the fused levels due to the increased stiffness of the construct, but the intermediate segments responded for more compensatory motions than did the supra- or infra-adjacent segments under all motion conditions, indicating that the intermediate segment may be overly burdened. This result is contradictory to that reported in a previous study by Finn et al., in which skip-level cervical fusion exhibited a similar magnitude of increased motion across all three unfused levels [6]. The difference may be due to the use of different test protocols and the selection of the treated segments. In contrast, regardless of the hybrid strategy, the compensatory motion increased more evenly, although the ROMs of the untreated levels were greater than those of the intact model under all motions except for lateral bending at C2/3 and C6/7 in the FA model. This result is partly because the artificial cervical disc preserved the motion at the arthroplasty level and compensated for the lost motion at the fused level to some degree. However, the placement of ACDF and CDA is an essential factor for the kinematics of the adjacent segments. The ROM at the level adjacent to ACDF increased more than that of the level adjacent to CDA. This result suggests that the compensatory motion was unevenly spread across the unfused levels and that the kinematics of the immediate adjacent segment were more susceptible to impact in the hybrid strategy. The observation also indicates that the immediate adjacent level to fusion may be most at risk for degeneration.

FCF tends to decrease at the ACDF level due to rigid fusion without relative motion between the two adjacent segments. This phenomenon has been confirmed by several FE studies [19,27,38]. In the current study, we detailed the differences in the changes in facet loading between the supra-adjacent, infra-adjacent, and intermediate segments in the FF model. The changes in FCF agreed with the changes in the ROM. Under the extension condition, all unfused levels exhibited substantial increases in FCF. The loading at the intermediate segments increased the most. For the two HS models, compared with the FF model, the FCF increase was attenuated. Interestingly, the magnitude of overloading in the facet joints was also associated with the location of ACDF and CDA. As previously mentioned, Lee et al. [27] found that the facet joint loading at the CDA level increased, while it decreased at the adjacent levels. Faizan et al. [38] found that the facet joint loading tended to increase at the disc implant level but not overload at adjacent level facets in two-level CDA model, indicating that CDA has the potential to protect the facet joints in the adjacent segments. This phenomenon was also observed in the current study. The level adjacent to CDA had a weaker impact on the facet joints. Increases in contact force and pressure in the facet joints at the treated or adjacent levels may cause microinjury to the facet joints and eventually accelerate degeneration of the facet joints [14,39,40]. This hypothesis may explain why patients suffer from neck pain after ACDF or CDA at long-term follow-up.

Measurement of IDP is essential to evaluating changes in internal stresses at adjacent levels [41].Increases in IDP at adjacent levels after surgery may correlate with discogenic pathology and subsequent pain [42]. Previous studies found that the IDP examined at the adjacent level following HS at two contiguous levels was lower than that for contiguous bilevel fusion [38,41]. We made similar observations in noncontiguous ACDF and HS constructs. The adjacent IDP for the two HS models was less than that of the FF model, indicating that these reconstructions had the ability to alter or delay the accelerated degeneration at adjacent discs. Three implanted models predicted substantially higher IDP than did the intact model at the adjacent levels mainly because higher moments were applied to the implanted models to achieve the same overall angle as that of the intact C2−C7 model. The untreated level of IDP in the HS models followed trends similar to those of the motion and FCF. The IDPs of the untreated levels were highly associated with the relative location of ACDF and CDA. The level adjacent to CDA exhibited a lower increase in the IDP than did the adjacent level to ACDF, indicating that CDA had a protective effect against untreated levels.

In the current study, although the changes in ROM, FCF, and IDP on the adjacent segments were associated with the location of ACDF and CDA in the HS model, the FA model resulted in a lower increase in FCF and maximum IDP on the intermediate segment than that in the AF model. Furthermore, the FA model altered the moments at all directions except axial rotation to a lower extent than did the AF model. These results may serve as a guide for surgeons when deciding one CDA on the top or bottom of an ACDF. If both segments were suitable for CDA, ACDF/CDA was recommended for altering the biomechanical environment in the cervical spine to a lower extent. This recommendation is consistent with previous views indicating that CDA should be placed on a highly flexible segment to achieve lower compensation from other segments [32,43]. If the stage of degeneration was different in segments, a milder degenerative level was recommended for CDA. Skip-level ACDF was recommended if no level was suitable for CDA.

FE analysis is an effective method for predicting the tendency for change after different surgical strategies and thereby providing certain guidance for therapy. However, several limitations of current study should be taken into account. First, similar to previous studies, some acceptable idealized conditions were used. The frictionless contact between the articular surfaces of the facet joints may create potential inaccuracies [16,19]. The bone-implant and cage/screw interface were modeled as a tie, thus neglecting any possible micromotion [18,19]. However, osteointegration has not been achieved, especially in the immediate postoperative time. Additionally, we assumed that the artificial cervical disc could be fully functioning, thus ignoring abnormal motion observed in clinical examples. Second, comparisons of biomechanical effects on adjacent levels between the intact and implanted models were made possible using a hybrid control loading protocol. However, load conditions are much more complex with the function of muscles in vivo, possibly resulting in different motion and load-sharing behavior. Third, although we tried to reflect the actual surgical procedures by resecting the anterior longitudinal ligament, posterior longitudinal ligament, nucleus pulposus, and annulus fibrosus at C3/4 and C5/6 while preserving the lateral structures, we simplified the surgical insertion procedure of vertebral distraction before inserting a device in the surgical models. Simplified models may not simulate the actual biomechanical environment, particularly for endplates at the implanted levels and ligaments. Fourth, a healthy cervical model rather than a degenerative one was constructed, and only C3/4 and C5/6 (most commonly involved in noncontiguous CDDD) were implanted for analysis. Thus, the model may not be a perfect representative of the real word clinical scenario. However, the current study aimed to provide a trend instead of actual data. In addition, various designs of artificial cervical discs have different characteristics and biomechanical features, and the results of the current study may not be applicable to other devices.

Conclusion

The FE results suggest that skip-level ACDF substantially alters kinematics, FCF, and IDP at the unfused levels, possibly accounting for a higher risk of degeneration. The ROMs were unevenly redistributed across the unfused levels, and the intermediate segment exhibited additive biomechanical effects compared with the supra- and infra-adjacent segments. The biomechanics and kinematics of the untreated levels were less altered by HS constructs.

Although the intermediate segment did not experience additive biomechanical effects compared with the supra- and infra-adjacent segments, the biomechanical effects on the adjacent segments were associated with the relative location of ACDF and CDA. Overall, based on the results of this FE study, a noncontiguous HS construct has a reduced biomechanical impact on the intermediate segments compared with noncontiguous two-level fusion. This study provides a biomechanical rationale for the use of HS to treat patients with noncontiguous CDDD.

Supplementary materials

Supplementary material associated with this article can be found in the online version at https://doi.org/10.1016/j.spinee.2019.02.004.

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