

Total disc replacement alters the biomechanics of cervical spine based on sagittal cervical alignment: A finite element study

ABSTRACT

Introduction: The correlation between cervical alignment and clinical outcome of total disc replacement (TDR) surgery is arguable. We believe that this conflict exists because the parameters that influence the biomechanics of the cervical spine are not well understood, specifically the effect of TDR on different cervical alignments.

Methods: A validated osseo-ligamentous model from C2-C7 was used in this study. The C2-C7 Cobb angle of the base model was modified to represent: lordotic (-10°), straight (0°), and kyphotic ($+10^\circ$) cervical alignment. The TDR surgery was simulated at the C5-C6 segment. The range of motion (ROM), intradiscal pressure, annular stresses, and facet loads were computed for all the models.

Results: The ROM results demonstrated kyphotic alignment after TDR surgery to be the most mobile when compared to intact base model (41% higher in flexion-extension, 51% higher in lateral bending, and 27% higher in axial rotation) followed by straight and lordotic alignment, respectively. The annular stresses for the kyphotic alignment when compared to intact base model were higher at the index level (33% higher in flexion-extension and 48% higher in lateral bending) compared to other alignments. The lordotic model demonstrated higher facet contact forces at the index level (75% higher in extension than kyphotic alignment, 51% higher in lateral bending than kyphotic alignment, and 78% higher in axial rotation than kyphotic alignment) when compared among the three alignment models.

Conclusion: Preoperative cervical alignment should be an integral part of surgical planning for TDR surgery as different cervical alignments may significantly alter the postsurgical outcomes.

Keywords: Biomechanics, cervical alignment, cervical arthroplasty, cervical spine, finite element analysis, sagittal alignment, total disc replacement

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INTRODUCTION

Anterior cervical discectomy and fusion (ACDF) surgery has long been the customary surgical solution to radiculopathy, myelopathy, stenosis, and disc herniation/degenerative disc disease.^[1,2] ACDF surgery is becoming more common as the annual number of operations skyrocketed from 540 in 2006 to 1565 in 2013, a staggering 190% increase in just 7 years.^[3] As this procedure becomes more common, the average hospital bill of \$34,000 may become a significant stressor to even more patients.^[4] Due to complications associated with ACDF, it is estimated that the success of ACDF surgery is

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approximately 37%.^[5] ACDF itself is not a perfect solution as some patients may experience postsurgical complications such as adjacent segment degeneration (ASD) and lowered range of motion (ROM) at the operated segment and excessive motion at adjacent segments.^[6] The potential complications associated with ACDF have given rise to the creation and innovation of total disc replacement (TDR) implants that may offer similar benefits as ACDF with lower complication rates.^[7]

The indications for TDR include myelopathic or radiculopathy cervical disease. Benefits of TDR include discectomy, disc height restoration, near-physiologic motion preservation, indirect decompression, and removal of herniation.^[8] TDR is ideally suited for central and paracentral compression such as herniation and spur, with or without neck pain, for one or two levels. Patients with osteoporosis, sagittal imbalance, or advanced spondylitis disease are not good candidates for cervical TDR.^[9] The complications of TDR include device expulsion/dislocation/subsidence as well as focal kyphosis and heterotopic ossification (HO).^[8]

However, TDR surgery is estimated to be significantly more consistent than ACDF with 70% success rate.^[5] The incidence of revision surgery for TDR surgery is commonly lower than ACDF surgery.^[2,6,10] However, complications do occur even after TDR surgery and may be related to cervical alignment.^[11] The relationship between TDR and sagittal cervical spine alignment's biomechanics is not well understood. This is an area that needs clinical and experimental validation. We hypothesize that the sagittal alignment of the cervical spine may influence the outcome of TDR surgery. Thus, finite element (FE) analysis was used to model the cervical spine and measure the effects of different sagittal alignments on TDR surgery. Since TDR procedures are commonly performed at the C5-C6 segment, TDR surgery was simulated at this segment.^[12-14] An implant with simplified design of Mobi-C TDR implant was used in this study because of its FDA approval status [Figure 1].

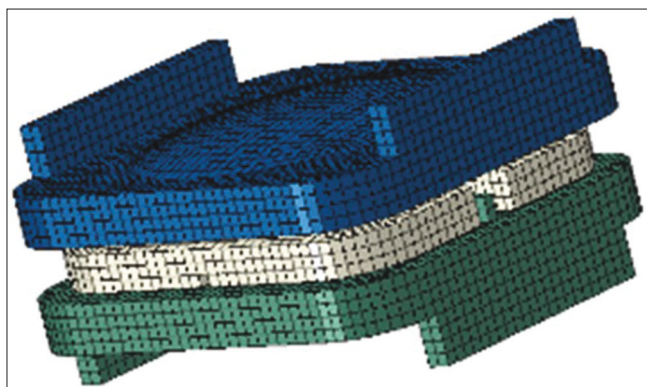


Figure 1: TDR implant. TDR - Total disc replacement

METHODS

Model development

A validated FE model of C2-C7 cervical spine was used in this study [Figure 2].^[15] In summary, the FE model was created based on the computed tomography (CT) scans of a healthy adult subject. The CT scans were used for three-dimensional (3D) reconstruction of cervical spine anatomy. The CT scans were exported to MIMICS software (Materialise, Belgium) to obtain the 3D geometry of bony structures (C2-C7). The geometry of bony structures was exported to IA-FE Mesh (Iowa, United States) for meshing. A similar approach was used for obtaining/meshing the intervertebral discs. Finally, the meshed model was exported to ABAQUS (Dassault Systèmes, Simulia Inc., Providence, RI). The vertebrae were modeled using hexahedral elements where the outer 0.5 mm layer represented cortical shell, and the inside of it represented cancellous bone. The intervertebral discs were composed of annulus fibrosus (50%) and nucleus pulposus (50%). The annulus consisted of ground substance along with embedded fibers oriented at $\pm 25^\circ$.^[16]

The FE model consists of anterior longitudinal ligament (ALL), posterior longitudinal ligament, interspinous ligament, supraspinous ligament, capsular ligament, and ligamentum flavum. All the ligaments were represented with tension-only truss elements in ABAQUS. The facet joints in the model were represented using surface-surface sliding contact, whereas the Luschka's joints in the lower cervical intervertebral discs were modeled using GAPUNI elements.^[17] The material properties for all the structures in the FE model were taken from literature and are summarized in Table 1.^[18-21]

Cervical alignments and total disc replacement surgery

The intact base model used for cervical validation had C2-C7 lordosis with a Cobb angle of -5° . This model was modified to represent three different alignments with the following Cobb angles (a) lordotic (-10°), (b) straight (0°), and (c) kyphotic ($+10^\circ$).

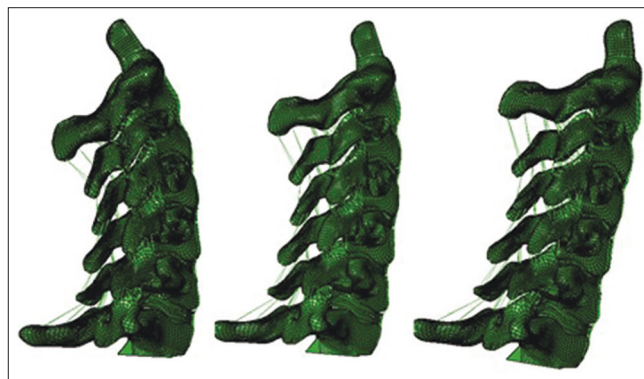


Figure 2: C2-C7 FE models: (a) Lordotic (C2-C7 Cobb angle = -10°), (b) Straight (C2-C7 Cobb angle = 0°), and (c) Kyphotic (C2-C7 Cobb angle = $+10^\circ$)

Table 1: Material properties assigned to the finite element model

Component	Material properties	Constitute relation	Element type	Cross sectional area (mm ²)
Bone ^[20]				
Vertebral cortical bone	E=10,000 Mpa v=0.3	Isotropic, elastic	C3D8	-
Vertebral cancellous bone	E=450 Mpa v=0.25	Isotropic, elastic	C3D8	-
Vertebrae-posterior	E=3500 Mpa v=0.25	Isotropic, elastic	C3D8	-
Intervertebral disc ^[18,19]				
Ground substance of annulus fibrosis	C10=0.7 C01=0.2	Hyper-elastic, Mooney-Rivlin	C3D8	-
Nucleus pulposus	C10=0.12 C01=0.03 D1=0	Incompressible hyper-elastic, Mooney-Rivlin	C3D8	-
Ligaments ^[20]				
ALL	15.0 (<12%), 30.0 (>12%) v=0.3	Nonlinear, hypoelastic	T3D2	6.1
PLL	10.0 (<12%), 20.0 (>12%) v=0.3	Nonlinear, hypoelastic	T3D2	5.4
CL	7.0 (<30%), 30 (>12%) v=0.3	Nonlinear, hypoelastic	T3D2	46.6
LF	5.0 (<25%), 10.0 (>25%) v=0.3	Nonlinear, hypoelastic	T3D2	50.1
ISL	4.0 (20%-40%), 8.0 (>40%) v=0.3	Nonlinear, hypoelastic	T3D2	13.1
Facet joints ^[20]				
Apophyseal joints	Nonlinear soft contact, GAPUNI elements	-	-	-
TDR implant ^[21]				
Core=UHMWPE	E=3 Mpa, v=0.3	-	-	-
Endplates=CoCr	E=210 Gpa, v=0.3	-	-	-

ALL - Anterior longitudinal ligament; PLL - Posterior longitudinal ligament; CL - Capsular ligament; LF - Ligamentum flavum; ISL - Interspinous ligament; TDR - Total disc replacement; UHMWPE - Ultra-high-molecular-weight polyethylene; CoCr - Cobalt chromium;

The TDR implant used in this study was modeled after the Mobi-C implant (Zimmer–Biomet, Warsaw, IN, USA). The TDR surgery was simulated in cervical alignment models (lordotic, straight, and kyphotic) at the C5–C6 segment without altering the lordosis of the index segment. The surgery was simulated by removing the ALL at the C5–C6 segment, anterior portion of the annulus, and complete removal of the nucleus. The interaction between the metal–polymer surfaces was simulated using surface-to-surface contact formulation in ABAQUS with a coefficient of friction of 0.1.^[21] The polymer core of the TDR implant was free to move in any direction unless stopped by the metal stoppers present on the inferior endplate of the implant. The endplates of the implant were tied to their respective vertebra to represent osteointegration and prevent subsidence of the implant.^[21]

Validation of intact base cervical spine model

The intact base C2–C7 model was validated by comparing the ROM, intradiscal pressure (IDP), and facet contact forces at each level in flexion/extension, lateral bending,

and axial rotations with the published *in vitro* data in the literature.^[22–24]

The intact base cervical spine model was subjected to pure moment of 1.5 Nm flexion/extension, lateral bending, and axial rotations. The caudal endplate of the C7 vertebra was fixed by suppressing all six degrees of freedom. A connector force of 100 N was applied to the model as per the follower load method to replicate effects of muscular contractures as well to simulate the weight of the skull.

Loads and boundary conditions

Finn *et al.*'s *in vitro* protocol was used for defining loads and boundary conditions in all the FE models.^[22] The bottom surface of the C7 vertebra was fixed with no active degrees of freedom, and the follower load of 100N was applied along the C2–C7 vertebral bodies using the connector elements in ABAQUS. The application of follower load simulated the effect of muscle contractions and the weight of the skull. After the follower load, a pure moment of 1.5 Nm was applied to the C2 vertebra to simulate the flexion/extension, lateral bending, and axial rotation.

Data analyses

The ROM, IDP, annular stresses, and facet contact forces were calculated for intact and instrumented alignment models (lordotic, straight, and kyphotic) of the cervical spine and compared. For calculation of facet forces, flexion was excluded as cervical facets are unloaded within the physiological ROM of the cervical spine. For extension, lateral bending, and axial rotations, facet forces were recorded for the left and right facet and averaged for each level.

$$\text{Percentage Difference} = \frac{\text{Instrumented} - \text{Intact}}{\text{Intact}} \times 100$$

RESULTS

Validation results for the intact base model

Range of motion

The intersegmental ROM for all the levels of intact base cervical spine model was within the range of experimental ROM reported by Finn *et al.*^[22] [Figures 3-5].

Intradiscal pressure

The IDP for all the segments of the intact base cervical spine model were also in good agreement with the *in vitro* IDP data reported by Pospiech *et al.* and Kretzer *et al.*^[23,24] [Table 2].

Facet contact forces

The facet contact force data for all the segments of the intact base cervical spine model were also in good agreement with the *in vitro* facet contact force data reported by Patel *et al.*^[25] [Table 3].

Instrumented models

Range of motion

The kyphotic model generally demonstrated the highest ROM at the index level of all models in flexion/extension (41.3% higher than the intact model), left/right lateral bending (50.9% higher than the intact model), and axial rotation (38.7% than the intact model) [Figures 6-8].

Conversely, the lordotic model had the least ROM across the models after TDR surgery at the index level across all loading scenarios (12.1%, 10.4%, and 1.7% reduction in ROM in flexion/extension, lateral bending, and axial rotation, respectively, when compared to the intact model).

A similar trend was observed for the cranial and caudal adjacent level segments when the ROMs of the three alignment models were compared to the intact base model.

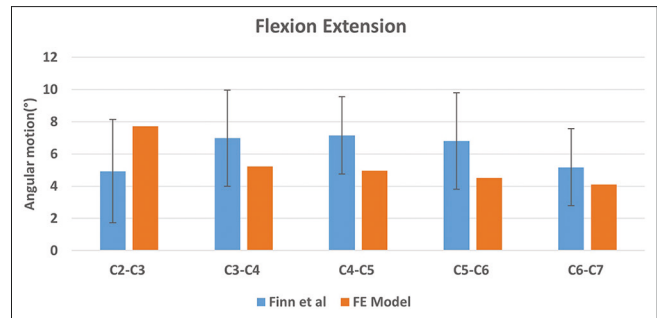


Figure 3: Comparison of flexion–extension range of motion under 1.5 Nm moment and 100N follower load for intact base model with *in vitro* data reported by Finn *et al.*^[22]

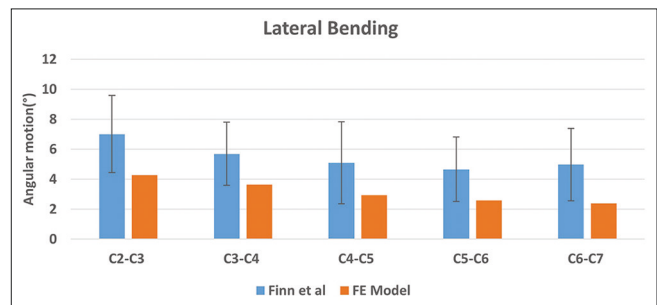


Figure 4: Comparison of lateral bending range of motion under 1.5 Nm moment and 100N follower load for intact base model with *in vitro* data reported by Finn *et al.*^[22]

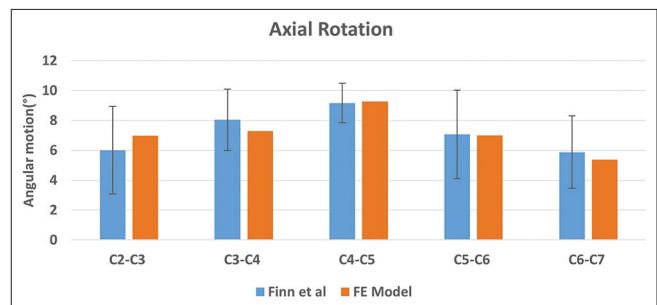


Figure 5: Comparison of axial rotation range of motion under 1.5 Nm moment and 100N follower load for intact base model with *in vitro* data reported by Finn *et al.*^[22]

Intradiscal pressure

The intact base model generally showed higher IDP than the three alignment models after TDR surgery for the cranial/caudal adjacent levels (except for flexion/extension where the kyphotic TDR model showed 3% higher IDP at the cranial adjacent level and lateral bending where the kyphotic TDR model showed 15% higher IDP at the caudal adjacent level) [Figures 9-11].

The kyphotic model generally demonstrated higher IDP than the straight and lordotic models in flexion/extension, left/right lateral bending, and axial rotation (except for axial rotation at the caudal adjacent level and lateral bending at the cranial adjacent level where lordotic TDR model showed the largest IDP among the three alignment models).

Table 2: Intradiscal pressure for C5-C6 segment for flexion-extension, right/left lateral bending, and right/left axial rotation under 1.5Nm moment along with 100N follower load

Segment	Flexion	Extension	Left bending	Right bending	Left rotation	Right rotation
IDP (MPa) - FE model						
C2-C3	0.26	0.35	0.23	0.22	0.27	0.26
C3-C4	0.17	0.14	0.14	0.15	0.19	0.24
C4-C5	0.21	0.16	0.11	0.17	0.22	0.21
C5-C6	0.17	0.12	0.1	0.14	0.18	0.18
C6-C7	0.11	0.14	0.09	0.11	0.1	0.13
IDP (MPa) - <i>In vitro</i>						
C2-C3	0.08-0.36	0.08-0.36	0.12-0.36	0.12-0.36	-	-
C3-C4	0.12-0.43	0.12-0.43	0.08-0.31	0.08-0.31	0.14-0.36	0.14-0.36
C4-C5	-	-	-	-	-	-
C5-C6	0.01-0.56	0.01-0.56	0.01-0.38	0.01-0.38	0.04-0.49	0.04-0.49
C6-C7	0.01-0.17	0.01-0.17	0.01-0.11	0.01-0.11	-	-

The IDP data for intact base model compared to the *in vitro* data reported by Pospiech et al.^[23] IDP - Intradiscal pressure; FE - Finite element

Table 3: Facet contact force for C3-C4 segment for flexion-extension, lateral bending, and axial rotation under 1.5Nm moment along with 100N follower load

Segment	Facet contact forces (N) - FE model			Facet contact forces (N) - <i>In vitro</i>		
	Extension	Lateral bending	Axial rotation	Extension	Lateral bending	Axial rotation
C2-C3	50.9	45.6	21.3	-	-	-
C3-C4	42.6	34.2	36.2	12.5-62.5	29.5-81.2	34.5-88.1
C4-C5	31.4	35.8	20.7	13.9-43.9	36.2-74.8	34.7-88.2
C5-C6	32.4	34.6	34.7	-	-	-
C6-C7	24.6	31.9	28.4	-	-	-

The facet contact force data for intact base model compared to the *in vitro* data reported by Patel et al.^[24] FE - Finite element

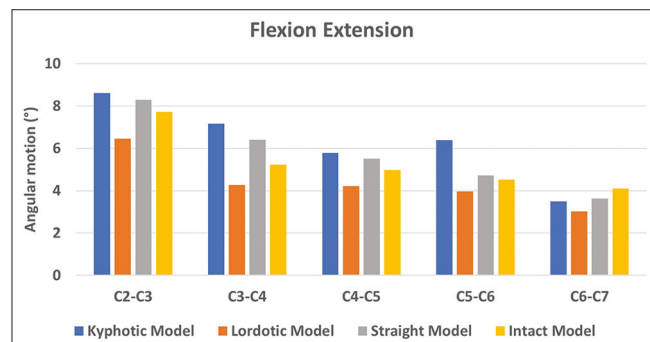


Figure 6: Comparison of flexion–extension range of motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

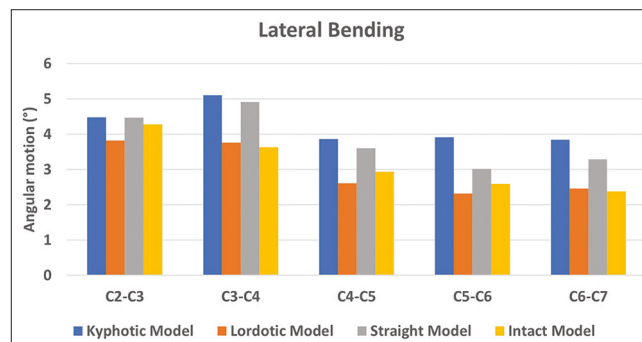


Figure 7: Comparison of lateral bending range of motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

The lordotic model showed the least IDP among all cases except at the C4-C5 level for lateral bending and the C6-C7 level for axial rotation.

Annular stresses

The kyphotic TDR model showed higher annular stresses among all the model at the index level in flexion–extension (33% higher than intact) and lateral bending (48% higher than intact), while the intact model demonstrated the highest annual stresses at the index level in axial rotation. A similar trend was observed when comparing annual stresses at the

cranial adjacent level, where the kyphotic TDR model showed higher stresses in flexion–extension (29% higher than intact) and lateral bending (14% higher than intact), while the intact model demonstrated the highest stresses in axial rotation. For the caudal adjacent level, the intact model showed the highest annular stress in flexion–extension and axial rotation, while the kyphotic TDR model showed higher stresses in lateral bending (19% higher than intact) [Figures 12-14].

When comparing among the three alignment models after TDR surgery, the kyphotic TDR model generally showed

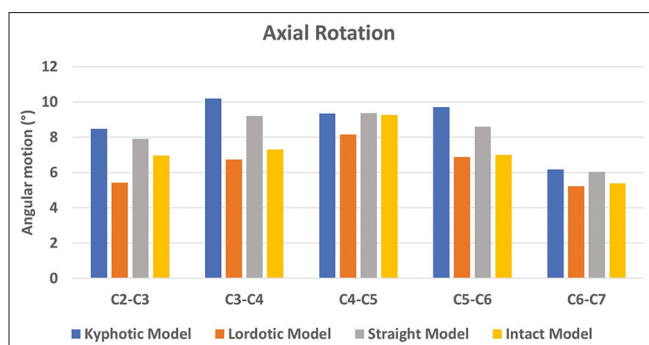


Figure 8: Comparison of axial rotation range of motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

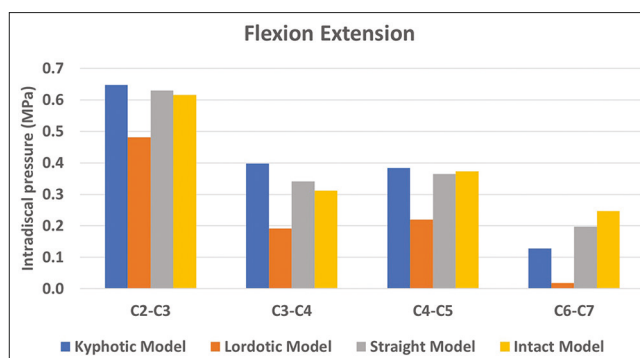


Figure 9: Comparison of intradiscal pressure for flexion/extension motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

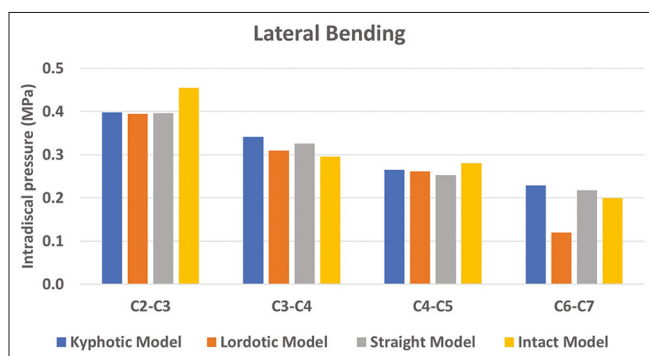


Figure 10: Comparison of intradiscal pressure for lateral bending motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

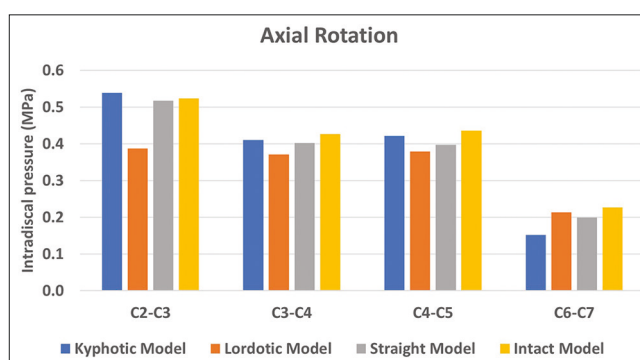


Figure 11: Comparison of intradiscal pressure for axial rotation motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

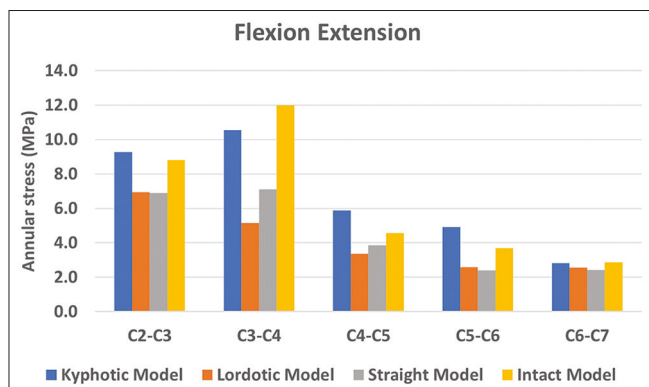


Figure 12: Comparison of annular stress for flexion/extension motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

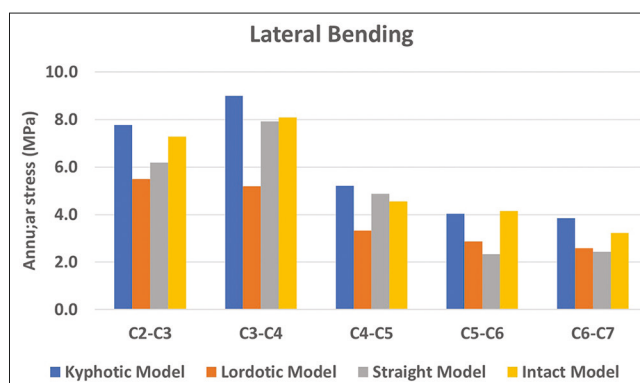


Figure 13: Comparison of annular stress for lateral bending motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

higher annular stresses at the index level. Similarly, the kyphotic TDR model demonstrated higher annular stress than the straight and lordotic models in flexion/extension and left/right lateral bending at the cranial and caudal adjacent levels. In axial rotation, the straight TDR model showed higher annular stresses at the cranial and caudal adjacent levels. The straight TDR model showed the lowest annular stresses

among the three alignment models at the index level, while the lordotic TDR model showed the lowest annular stresses at the cranial adjacent level.

Facet contact forces

The kyphotic TDR model showed the lowest facet contact forces among all the models at the index level in

extension (71% lower than intact), lateral bending (53% lower than intact), and axial rotation (75% lower than intact). A similar trend was observed at the cranial adjacent level (85% lower than intact in extension, 35% lower than intact in lateral bending, and 85% lower than intact in axial rotation) and caudal adjacent level (93% lower than intact in extension, 96% lower than intact in lateral bending, and 98% lower than intact in axial rotation) [Figures 15-17].

When comparing among the three alignment models after TDR surgery, the lordotic model generally demonstrated higher facet forces at the index level as well as the cranial and caudal adjacent levels than the straight and kyphotic models in left/right lateral bending and axial rotation except for extension where the straight model showed higher facet forces at the index level. The kyphotic TDR model showed the lowest facet forces among the three alignment models at the index level as well as cranial and caudal adjacent level.

DISCUSSION

TDR surgery has a potential to become the standard procedure for cervical degenerative disc diseases, so factors that may complicate clinical outcomes of the procedure need to be well understood. The cost of TDR surgery is comparable to ACDF surgery with an average cost of \$35,712, so the rising number of TDR surgeries can be attributed to its proposed ability to reduce the occurrence of side effects such as ASD while preserving/restoring better motion of the spine in comparison to ACDF surgery.^[4,10] In addition, the reoperation rates of TDR surgery are consistently lower than ACDF surgery.^[2,6,10] However, the outcome for TDR surgery is not always good. One of the possible causes of this is alignment. There are three common cervical spine alignments: lordotic, straight, and kyphotic alignments. As high as 64% of the population may have a lordotic spinal curvature.^[10,26] In a retrospective study, Been *et al.* found that straight alignment may be prevalent in up to 41% of the population, whereas <10% may have kyphotic alignment.^[27]

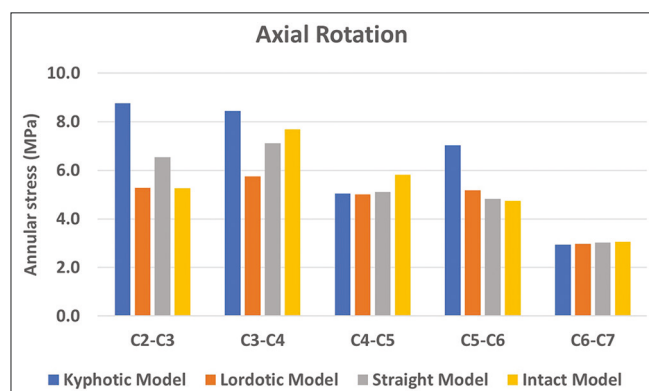


Figure 14: Comparison of annular stress for axial rotation motion between kyphotic, lordotic, and straight C2-C7 models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

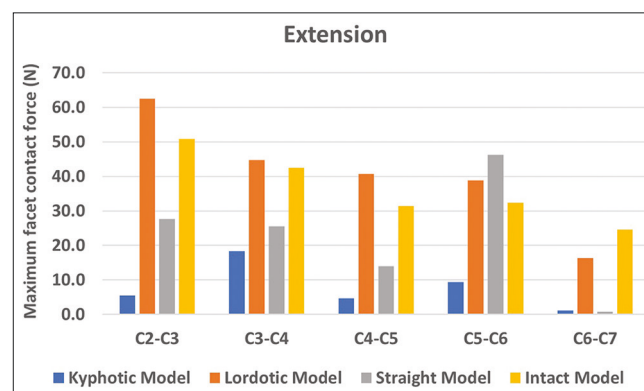


Figure 15: Comparison of facet contact force for extension motion between kyphotic, lordotic, and straight models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

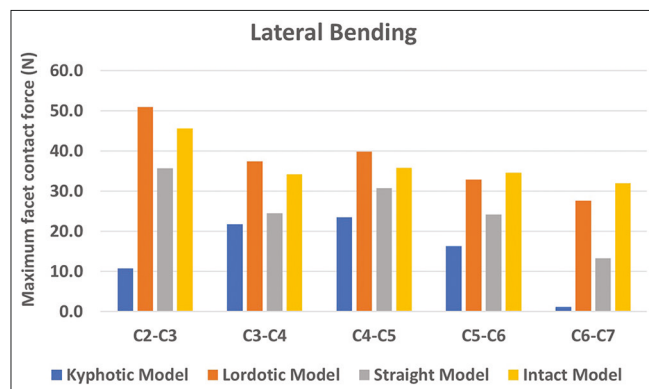


Figure 16: Comparison of facet contact force for lateral bending motion between kyphotic, lordotic, and straight models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

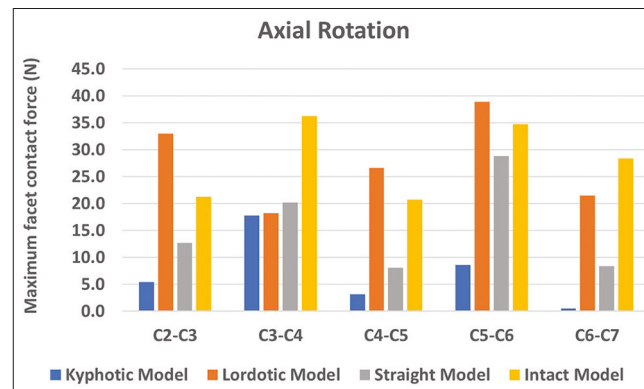


Figure 17: Comparison of facet contact force for axial rotation motion between kyphotic, lordotic, and straight models after TDR surgery at the C5-C6 level with the intact base model under 1.5 Nm moment along with 100 N follower load. TDR - Total disc replacement

The biomechanics of the cervical spine after TDR surgery has been analyzed using FE analysis, cadaveric (*in vitro*) studies, and clinical (*in vivo*) studies. There have been few studies analyzing biomechanical changes in cervical spine after Mobi-C implantation in published literature. Patwardhan and Havey performed a study on human cadaveric spines investigating the changes in segmental ROMs after TDR surgery. They observed an increase in the flexion + extension ROM at the index level post-TDR surgery.^[28] Purushothaman *et al.* conducted a FE study and computed the segmental ROM after TDR surgery using Mobi-C devices in cervical spine.^[21] They also observed an increase in the flexion + extension ROM post-Mobi-C implantation at the index level. In a second study, Purushothaman *et al.* compared the biomechanical effects of Mobi-C implantation with three other TDR devices. Here, they again observed an increase in the flexion + extension ROM post-Mobi-C implantation at the index level.^[29] Hisey *et al.* conducted a prospective, randomized clinical study comparing the biomechanical performance of Mobi-C with anterior discectomy and fusion surgery and reported clinical follow-up data. They observed an immediate postoperative increase in flexion + extension and left + right lateral bending ROM post-Mobi-C implantation at the index level.^[13,30,31]

These trends in ROM are very similar to what we observed with our FE model. An increase in the index level (C5-C6) ROM was observed for the normative (lordotic) alignment model in flexion + extension and left + right bending after TDR implantation with Mobi-C was performed with our FE model.

However, none of the studies in the literature have reported the sagittal parameters of the cadaveric spines/FE models used in their studies nor they have reported the biomechanical effects of different cervical alignments after TDR surgery. These aspects make it harder to compare their data with our findings.

Previous studies have investigated the response of artificial disc replacement without considering the alignment of the cervical spine. However, some clinical studies suggest that TDR surgery leads to a postoperative change in C2-C7 Cobb angle, and sagittal cervical alignment may affect clinical outcomes.^[32,33] For that purpose, a nonlinear cervical FE model representative of the 50th percentile of the adult male population was developed and validated. The model was validated for ROM, IDP, and facet contact forces. The validated model was modified to represent the lordotic, straight, and kyphotic alignments. For each alignment, ROM, IDP, annular stress, and facet contact forces were calculated to study the influence of sagittal cervical alignments on TDR surgery.

The investigation of different cervical sagittal alignment's ROM showed that the kyphotic model represents the most mobile alignment followed by straight alignment, whereas the lordotic alignment was associated with the stiffest response in all loading conditions except flexion motion. This trend in the ROM is consistent with the computational study of John *et al.*, in which they simulated cervical alignments to study the effect of a corpectomy.^[34] The stiff response of the lordotic alignment model could possibly be explained by the fact that facet joints get in proximity due to high lordosis angle in all motions except flexion. For the same reason, the authors believe that the high facet joint contact forces were observed in the lordotic alignment model compared to other alignment models under all loading conditions. The facet forces were higher at the index and superior adjacent segment compared to the inferior adjacent segment for all the alignment models under all loading conditions. Since the high magnitude of facet force has been associated with facet joint pain.^[35,36] Thus, our results imply that subjects with lordotic alignment might be at higher risk for experiencing pain in the facet joints. In addition, a postoperative increase in cervical lordosis has been reported in the literature.^[33,37] Thus, postoperative increase in lordosis may pose an additional risk of developing facet pain for a subject already having lordotic alignment preoperatively. Some studies link the change in postoperative alignment with the type/design of artificial disc.^[38] However, some studies do not consider postoperative alignment to be linked to the device type/design.^[37] Moreover, targets for restoration of cervical spine alignment are not as well defined as they are defined for the thoracolumbar spine.^[39] Setting the cervical spine restoration target could be challenging because of the fact that normal cervical alignment can be lordotic, straight, and kyphotic for different individuals.^[40] Thus, we suggest that the restoration targets should be set for the cervical spine the way they are set for the thoracolumbar spine.

On investigating the annular stress and IDP, we observed high annular stress in the kyphotic alignment followed by straight and lordotic alignment, respectively. However, the IDP was similar in all the alignment models under all the motions except extension. On average, the IDP in extension for lordotic, straight, and kyphotic alignment was 0.05 Mpa, 0.19 Mpa, and 0.21 Mpa, respectively. The possible reason for lower IDP in extension for lordotic alignment could be due to the large portion of the load being carried out by facet joints, as summarized in Tables 2-3. On the other hand, in kyphotic alignment, a significant portion of the load is being carried out by the intervertebral discs. The high ROM coupled with high annular stress at the superior adjacent segment poses a risk for the adjacent segment pathology for subjects with the

kyphotic alignment. Furthermore, as expected the straight alignment had all the biomechanical parameters: ROM, IDP, annulus stress, and facet contact forces in the median upon comparison with lordotic and straight alignment.

This computational study has certain limitations. The artificial disc was designed to fit the geometry of the current FE model, and an experienced surgeon confirmed the position of the TDR. However, the size of the artificial disc can lead to a change in the biomechanics of TDR surgery.

One other limitation of our study is that even though clinical presentation of kyphotic cervical alignment is often followed by degenerative disc disease, we have assumed healthy material behavior of the intervertebral discs in our model. Another limitation of our study was that the model did not include cervical spine musculature. However, this limitation was addressed by the addition of follower loads that mitigate the muscle contractions and has been used in other FE studies in literature.^[21,41,42] Other limitations of this FEA include the simplification of material properties and interactions between the different components of the model. Moreover, the results of this study need to be verified by the experimental and *in vivo* studies. In addition, we do not take into account the possibility and effects of spinal cord compression in straight and kyphotic alignments as the spinal cord was not included into our model. Furthermore, from a clinical perspective, multilevel TDR surgery has been performed for patients with kyphotic cervical alignment. However, in our study, we have only simulated one level TDR surgery. Future studies should explore the response of other FDA-approved artificial disc replacement implants as well and explore the effects of multi-level TDR surgeries on cervical alignment.

CONCLUSION

FE analysis was conducted to analyze the relationship between TDR and cervical alignment. The straight alignment may not be at higher risk for facet pain or disc degeneration. On the other hand, the lordotic model was associated with the highest facet loads, while the kyphotic model was associated with the highest annular stresses compared to straight model. Clinically, we recommend that care must be taken in the surgical management of patients with preexisting hyper kyphosis and signs of preexisting disc degeneration to mitigate the risk for ASD.

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Conflicts of interest

There are no conflicts of interest.

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