Biomechanical Effect of Plate-to-Disc Distance on Surgical and Adjacent Segment in C5/C6 Anterior Cervical Discectomy and Fusion - A Finite Element Analysis

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Research article

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Abstract

Background: The PDD is an important factor affecting the degeneration of adjacent segments after ACDF. However, the most suitable PDD is controversial. This study examined the adjacent intervertebral disc stress, bone graft stress, titanium plate stress and screw stress to evaluate the biomechanical effect of different Plate-to-Disc Distance (PDD) on surgical segment and adjacent segment following C5/C6 anterior cervical discectomy and fusion (ACDF).

Methods: We constructed 10 preoperative finite element models (FEM) of intact C4–C7 segments and validated them in the present study. We simulated ACDF surgery based on the 10 intact models in software. We designed three different distance of Plate-to-Disc titanium plates: L, long PDD (10 mm); S, short PDD (0 mm); and N, PDD (5 mm). The changes in C4/C5 and C6/C7 intervertebral disc stress, bone graft stress, titanium plate stress and screw stress were analyzed.

Results: The von Mises stress of C4/C5 and C6/C7 intervertebral discs have no significant differences (P>0.05) in three different PDD groups. Titanium plate stress increased as the PDD decreased. The bone graft stress and screws stress decreased as the PDD decreased. The maximum stress of each part occurred was mostly in the conditions of rotation and lateral bending.

Conclusions: The PDD has no effect on adjacent intervertebral disc stress, but it is an important factor that affecting the bone graft stress, titanium plate stress and screws stress after ACDF. Shorter PDD plate can provide better stability to reduce stress on screws and bone graft, that may be helpful to prevent cage subsidence, pseudarthrosis and instrument failure. This can serve as a reference for clinical choice of plate.

Background

Anterior cervical discectomy and fusion (ACDF) with plate has been the most popular surgical approach for treating symptomatic cervical disc herniation. Previous studies have reported that patients can achieve significant neurologic recovery and improvement in quality of life after ACDF[1–5]. However, it has been reported that the cervical arthrodesis with plate can change the biomechanical environment of cervical spine, eventually result in adjacent segment degeneration (ASD)[6–8].

ASD is defined as the degeneration of adjacent level of spine arthrodesis. Previous studies have been reported that the repeat surgery rate of ACDF patients was 17.4% due to symptomatic ASD[9], which seriously affected the patient's satisfaction with the surgery and increased the economic burden on society. There have been studies that suggested plate-to-disc distance (PDD)[6], graft type[10], and post-operative cervical alignment[11] are factors that affect the incidence of ASD. Among them, PDD is considered to be an important factor affecting the development of ASD. However, the biomechanical effect of different PDD on adjacent and surgical segments has not been reported.

Finite element analysis (FEA) has the ability to simulate a variety of complex body structures in a computer and calculate the pressure and stress of each component without any invasion[12, 13]. FEA also provide time- and cost- effective means to address various what if scenarios, thereby reducing the need for costly experimental animal and cadaveric studies. Hence, the objective of the present study is to analyze the biomechanical effect of different PDD on adjacent intervertebral disc stress, bone graft stress, titanium plate stress and screw stress precisely using quantitative FEA.

Material/methods

Construction of the C4-C7 finite element models

We built 10 nonlinear three-dimensional finite element (FE) models based on computed tomography (CT) scans with interval 0.625 mm of the cervical spine of 10 healthy volunteers without cervical degeneration. MIMICS 21.0 (Materialise, Leuven, Belgium) software was used to construct the primary geometric structures of the C4-C7 cervical vertebraes based on the CT images. Then, the primary geometries were imported into Geomagic Studio 14.0 (Geomagic, Research Triangle Park, North Carolina, USA) to generate smooth surface models. The 10 models were processed using Solidworks 2019 (Solidworks, Massachusetts, USA) and imported into Hypermesh 14.0 (Altair, Troy, MI, USA) to construct structures such as intervertebral discs, annulus fibrosus, annulus fibers, nucleus pulposus, endplates, ligaments and so on, and mesh. At this point, the three-dimensional finite element models have been created. Finally, the boundary conditions and loading conditions of the prepared models were set using ABAQUS 6.9.1 (Dassault Systems Corporation).

The bony structures of the vertebral body include cortical bone, cancellous bone and posterior structure. The cancellous bone region of the vertebrae was set as solid element. The thick of the cortical bone was 1.5 mm. We created the nucleus pulposus and annulus fibrosus with a volume ratio of 4:6[14]. Annulus fibers surrounded the ground substance with an inclination to the transverse plane between 15° and 45°, accounting for approximately 19% of the entire annulus fibrosus volume[14]. A bond connection was defined between the intervertebral disc and endplates. The cartilages were inserted into the spaces of the bony articular process joints. All cartilages of the articular processes were subjected to a face-to-face frictionless contact with each other[14, 15]. Five groups of ligaments, including the anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), ligamentum flavum, interspinous ligament and capsular ligament were established using tension-only spring elements and attached to the corresponding vertebrae.

The preoperative C4-C7 FE models and structural details were shown in Fig. 1. The information of ten volunteers was shown in Table 1. The material properties of the FE models are listed in Table 2 and Table 3[16, 17].

Validation of the model

The range of motion (ROM) of the C4-C7 FE models were predicted with a pure bending moment of 1 N m for flexion, extension, axial rotation, and lateral bending with 73.6 N of axial compression superior to C4, and compared to previous experimental results as shown in Fig. 2. The predicted ROM from the established models showed good agreement with published experimental results[18].

Surgery simulation

During the actual surgery, the C5/C6 anterior longitudinal ligament, C5/C6 disc, inferior endplate of C5, superior endplate of C6 and C5/C6 posterior longitudinal ligament were resected. We deleted the corresponding structures to simulate the surgery more precisely. In the present study, three different PDD plates: 0 mm, 5 mm, 10 mm plates and self-tapping screws were simulated. The screws were fixed in parallel to the endplates in all postoperative models. The 10 postoperative models was loaded in flexion, extension, axial rotation, and lateral bending by imposing a pure moment of 1.0 N·m on C4 with 73.6 N of axial precompression superior to the upper endplate of C4. The lower endplate of C7 was firmly fixed in all degrees of freedom. The postoperative C4-C7 FE models with different PDD plates were shown in Fig. 3. We choose the Mises stress of adjacent intervertebral disc, the titanium plate, bone graft and screws as the parameters to evaluate mechanical effect of three different PDD plates.

Statistical Analysis

Differences between groups were calculated by one-way analysis of variance (ANOVA) or chi-squared test in SPSS Version 25.0, (SPSS Inc., Chicago, IL). A P value of less than 0.05 was considered significant. Results are presented as mean ± standard deviation.

Results

The Mises stress of adjacent intervertebral disc, bone graft, titanium plate and screw under different load in different PDD titanium plate groups are shown in Table 3

The Mises stress of adjacent intervertebral disc

The Mises stress distribution diagram of adjacent intervertebral discs with different PDD titanium plates in different loading conditions are shown in Fig. 4. For the upper adjacent segment (C4/C5), no significant differences were found in the Mises stress of adjacent intervertebral disc among the three different PDD groups in flexion, extension, axial rotation, and lateral bending loading conditions. (P > 0.05). Additionally, for the lower adjacent segment (C6/C7), there was also no statistical difference among the three groups in different loading conditions. (P > 0.05).

The Mises stress of bone graft

The Mises stress distribution diagram of bone graft with different PDD titanium plates in different loading conditions are shown in Fig. 5. The Mises stress of bone graft in the three groups were statistically different (P < 0.05). The bone graft stress decreased as the PDD decreased in all different loading conditions.

The Mises stress of titanium plate

The Mises stress distribution diagram of titanium plate with different PDD titanium plates in different loading conditions are shown in Fig. 6. A significant difference was found in the Mises stress of titanium plates among the three different PDD groups (P < 0.05). The stress of titanium plate increased as the PDD decreased in all different loading conditions.

The Mises stress of screw

The Mises stress distribution diagram of screws with different PDD titanium plates in different loading conditions are shown in Fig. 6. A significant difference in the Mises stress of screws was found in the three different PDD groups (P < 0.05). The screw stress decreased as the PDD decreased in all different loading conditions.

Discussion

Anterior cervical discectomy and fusion has been an effective procedure for treating symptomatic cervical spondylotic myelopathy since it was initially described by Robinson and Smith[19]. It has produced good results in the treatment of many degenerative cervical lesions[20–22]. With the development of surgical instruments and surgical techniques, titanium plate has been routinely used in ACDF surgery. Reasonable use of titanium plate can provide immediate stability in early postoperative period, which can prevent bone graft subsidence, bone graft extrusion and improve fusion rates, and reduce the need for external immobilization[22–24]. However, it has been reported that the use of short PDD plate will accelerate the degeneration of adjacent segments, eventually result in symptomatic ASD[25].

ASD as a complication of ACDF has been reported to cause 17.4% of ACDF patients to have to undergo a second surgery[9], which has seriously affected patient's quality of life and increased the economic burden on families and society.

Various scholars have different opinions regarding PDD in ACDF. Chung et al.[6] reported that 177 patients who underwent anterior cervical discectomy and fusion using cervical plates, with follow-up periods of at least 10 years. They found most clinical adjacent-segment degeneration appeared on the patients with a PDD less than 5 mm. So they considered that to prevent adjacent segment degeneration, the PDD should be 5 mm or more if possible. In addition, Yu et al.[25] agreed that PDD < 5 mm is a risk factor for ASD by the logistic regression analysis based on 138 patients. However, Yang et al.[26] retrospectively reviewed 218 patients who underwent anterior cervical arthrodesis with plating and considered that there is no correlation between PDD and the incidence of ASD, but PDD > 5 mm could avoid the development of adjacent segment ossification. In a cadaver study, Raj D found that there was no statistical difference at intervertebral disc and intervertebral motion of adjacent segments with plate or not. Therefore, it remains controversial whether different PDD plate will affect the incidence of ASD.

FEA have been widely used for a biomechanical analysis of the cervical spine because they can analyze various results quantitatively without any invasion. In the present study, we constructed 10 three-dimensional finite element C4-C7 models based on cervical CT images of 10 volunteers. Considering that cervical disc lesions mostly occur in the C5/C6 segments, we selected the C5/C6 segment as the surgical segment so that the results could be suitable for more patients.

In our study, no significant differences were found in the adjacent intervertebral disc stress in the three different PDD groups. This result indicates that PDD does not affect the adjacent intervertebral disc stress. It has been reported that excessive loading can induce degeneration of intervertebral discs. So, we can conclude that the titanium plates of different PDD will not promote the degeneration of adjacent segments by increasing the intervertebral disc stress of adjacent segments. This can further validate the clinical findings of Yang et al.[26] that there is no correlation between PDD and the incidence of ASD.

As for the bone graft stress, we found that the bone graft stress decreased as the PDD decreased. This may be related to the fact that the short PDD plate increases the stiffness of the surgical segment and provides better stability. Although the most appropriate stress on bone graft is not clearly, excessive stress on the bone graft may result in fusion failure because of graft dislodgement and endplate fracture[27]. Furthermore, non-fusion is an important reason for the failure of instruments[28]. Considering bone graft stress and fusion rate, shorter PDD plate is safer because that shorter PDD is helpful to prevent bone graft subsidence and instrument failure from a biomechanical point of view.

The stress of titanium plate increased as the PDD decreased, which shows that as the length of the plate increases, the stress increases accordingly. This is due to the longer torque of the long plate. Of course, this result also explains that long titanium plates can carry more stress, which provides better stability. Although the increase of stress of the plate may cause the plate to break, the increase of the plate stress among different PDD groups is not obvious in the average value.

The screw stress decreased as the PDD decreased. As the length of the steel plate increases, the screw stress decreases. This may be caused by that the most of the overall stress is mostly carried by the plate. Screw loosening and breakage are associated with metal fatigue via pseudarthrosis, which were most dangerous complications in cervical anterior plating fixation. So shorter PDD plate plays an important role in preventing screws breakage and loosening. Yang et al.[26] found when the end point of plate violates the adjacent space, the incidence of ASD is the lowest among different PDD groups. They considered that this may be because the formation of ossification improves the stability of adjacent segments. However, they do not advocate the use of plates that can invade adjacent space. Considering that the strength of the screw is weaker than that of the plate[28], we believe that choosing a slightly shorter PDD plate is more conducive to postoperative recovery. Of course, we also don't recommend that the PDD is too small to violate the adjacent space.

In addition, we find that the maximum stress of each part occurred was mostly in the conditions of rotation and lateral bending, so we recommend that patients should avoid excessive rotation and lateral bending during early postoperative period to prevent screws breakage, fusion failure, endplate fracture and other complications.

The present study has a number of limitations: 1) Muscles and other soft tissue were not constructed in the models, however, these structures are extremely important for spine biomechanics research; 2) In addition, the screws were designed as solid cylinders bound to the cage or plate, and the threads on the screws were not modeled; 3) The model was based on only 10 persons, which may limit the present study’s applicability to a wider population; 4) Some simplifications were carried out in the prosthesis geometry, for example, we simplify the Cancellous bone as a solid structure which may affect the distribution and geometric deformation of the load. Although completely duplicating the result of in vivo studies in FE analysis was impossible, this study effectively shows the biomechanical differences among different PDD plate groups.

Conclusions

The PDD has no effect on adjacent intervertebral discs stress, but it is an important factor that affecting the bone graft stress, titanium plate stress and screw stress after ACDF. Shorter PDD does not affect the incidence of ASD through the increase of the adjacent intervertebral discs stress, but it can provide better stability to reduce stress on screws and bone graft which may be helpful to prevent bone graft subsidence, pseudarthrosis and instrument failure. This can serve as a reference for clinical choice of plate.

Abbreviations

ACDF: anterior cervical discectomy and fusion; ASD: adjacent segment degeneration; PDD: plate-to-disc distance; FEA: finite element analysis; FE: finite element; CT: computed tomography; ROM: the range of motion; ALL: anterior longitudinal ligament; PLL:

posterior longitudinal ligament: CL: capsular ligament; LF: ligamentum flavum; ISL: interspinous ligament; SL: supraspinous ligaments

Declarations

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Authors' contributions

YX and JMZ participated in the design of this study. XG, YYT, LK, RZ carried out the studies and performed the statistical analysis. XG, JMZ, YYT, and YX drafted the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to individual privacy but are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

This article contains a study with human participants, and the study protocol was approved by the Investigation and Ethics Committee of the Tianjin Medical University General Hospital (reference number IRB2019-WZ-145). Informed consent for this study was obtained from all patients by both written and verbal.

Consent for publication

Applicable. Written informed consent was obtained from the participants for the publication of this report and any accompanying images.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1
The material properties of the spinal soft tissues and hard tissues used in the finite element model.

Description	Element Type	Young’s Modulus (MPa)	Poisson’s Ratio
Cortical bone	C3D4	12,000	0.3
Cancellous bone	C3D4	100	0.2
Posterior elements	C3D4	3500	0.25
Facet cartilage	C3D4	10.4	0.4
End plate	C3D4	600	0.3
Nucleus pulposus	C3D4	1	0.49
Annulus ground substance	C3D4	3.4	0.4
Annulus fibers	T3D2	450	0.45
Titanium plate	C3D4	120,000	0.3
Titanium screw	C3D4	120,000	0.3

Table 2
The material properties of the ligaments

ALL		PLL		LF		ISL		CL	
Displacement (mm)	Force (N)	Displacement (mm)	Force (N)	Displacement (mm)	Force (N)	Displacement (mm)	Force (N)	Displacement (mm)	Force (N)
0	0	0	0	0	0	0	0	0	0
1	35.5	0.9	1.33	1.7	2.2	1.2	0.75	1.7	2.452
2	64.9	2	29.0	3.74	45.9	2.7	16.9	3.9	53.6
4	89.7	3	51.4	5.61	82.9	4.0	24.4	5.8	87.9
5	108.6	4	71.38	7.48	119.6	5.4	29.5	7.7	109.4
6	119.6	5	85.8	9.35	133.7	6.7	32.9	9.7	125.8
		6	94.7	11.3	147.2	8.1	34.9	11.5	134.8

Abbreviations: ALL, anterior longitudinal ligament; PLL, posterior longitudinal ligament; CL, capsular ligament; LF, ligamentum flavum; ISL, interspinous ligament; SL, supraspinous ligaments

Table 3
The von Mises stress of the structures in different lengths of titanium plates

von Mises stress (MPa)		PDD = 0 mm	PDD = 5 mm	PDD = 10 mm
C4/C5 Intervertebral disc	Flexion	1.417 ± 0.297	1.411 ± 0.257	1.422 ± 0.271
	Extension	1.337 ± 0.027	1.333 ± 0.019	1.346 ± 0.032
	Bending	1.382 ± 0.038	1.426 ± 0.119	1.388 ± 0.041
	Rotation	1.384 ± 0.047	1.378 ± 0.036	1.387 ± 0.038
C6/C7 Intervertebral disc	Flexion	1.483 ± 0.036	1.476 ± 0.045	1.455 ± 0.030
	Extension	1.425 ± 0.027	1.419 ± 0.016	1.413 ± 0.018
	Bending	1.402 ± 0.030	1.415 ± 0.032	1.398 ± 0.020
	Rotation	1.351 ± 0.170	1.292 ± 0.170	1.224 ± 0.080
Bone graft	Flexion	0.255 ± 0.040 b c	0.307 ± 0.025 a c	0.400 ± 0.031 a b
	Extension	1.527 ± 0.051 b c	1.668 ± 0.042 a c	1.812 ± 0.053 a b
	Bending	1.522 ± 0.084 b c	1.868 ± 0.057 a c	2.308 ± 0.055 a b
	Rotation	1.620 ± 0.026 b c	1.714 ± 0.053 a c	1.945 ± 0.140 a b
Titanium plate	Flexion	57.886 ± 3.374 b c	48.363 ± 4.237 a c	36.822 ± 1.049 a b
	Extension	58.069 ± 6.173 b c	41.552 ± 3.822 a c	24.791 ± 1.740 a b
	Bending	94.691 ± 1.859 b c	83.956 ± 2.769 a c	73.790 ± 1.708 a b
	Rotation	68.463 ± 2.529 b c	62.311 ± 2.526 a c	57.824 ± 0.929 a b
Screw	Flexion	32.983 ± 1.238 b c	42.075 ± 3.569 a c	58.018 ± 3.083 a b
	Extension	34.820 ± 1.386 b c	58.166 ± 3.206 a c	95.603 ± 22.040 ab
	Bending	55.388 ± 1.090 b c	60.705 ± 1.258 a c	66.406 ± 0.647 a b
	Rotation	56.617 ± 1.467 b c	64.038 ± 1.663 a c	75.025 ± 2.727 a b

Abbreviations: *a* $P<0.05$: Compared with titanium plates of 0 mm PDD, *b* $P<0.05$: Compared with titanium plates of 5 mm PDD, *c* $P<0.05$: Compared with titanium plates of 10 mm PDD

Figures

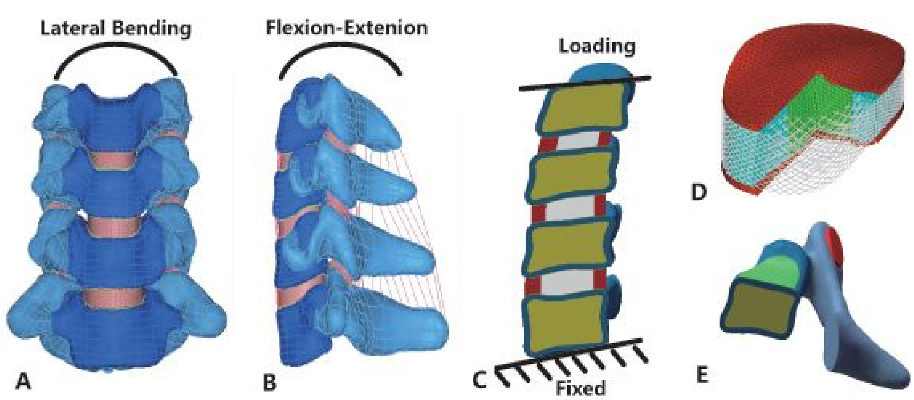

Figure 1

Finite element models of preoperative and postoperative C4–C7 cervical spine and other structures and details. (A) Frontal view of preoperative model; (B) Lateral view of preoperative model; (C) Loading and boundary condition; (D) Intervertebral disc details; (E) Vertebral body details;

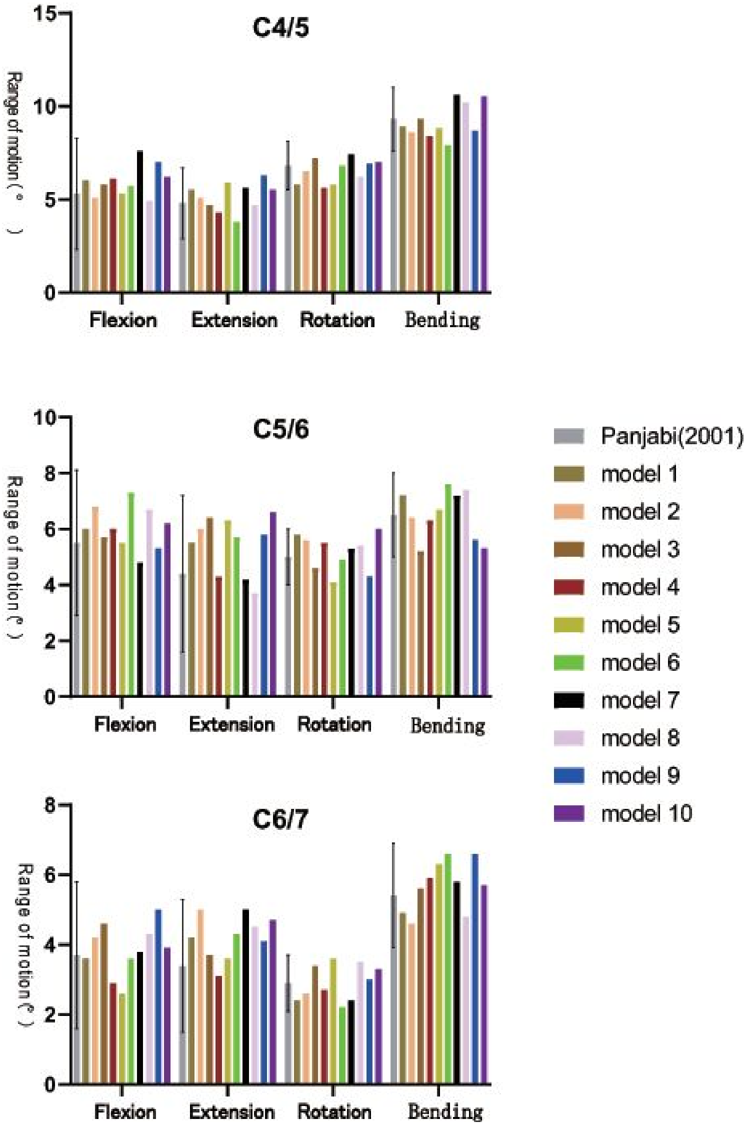

Figure 2

The predicted ranges of motion (ROM) of the preoperative model are validated by previous published study

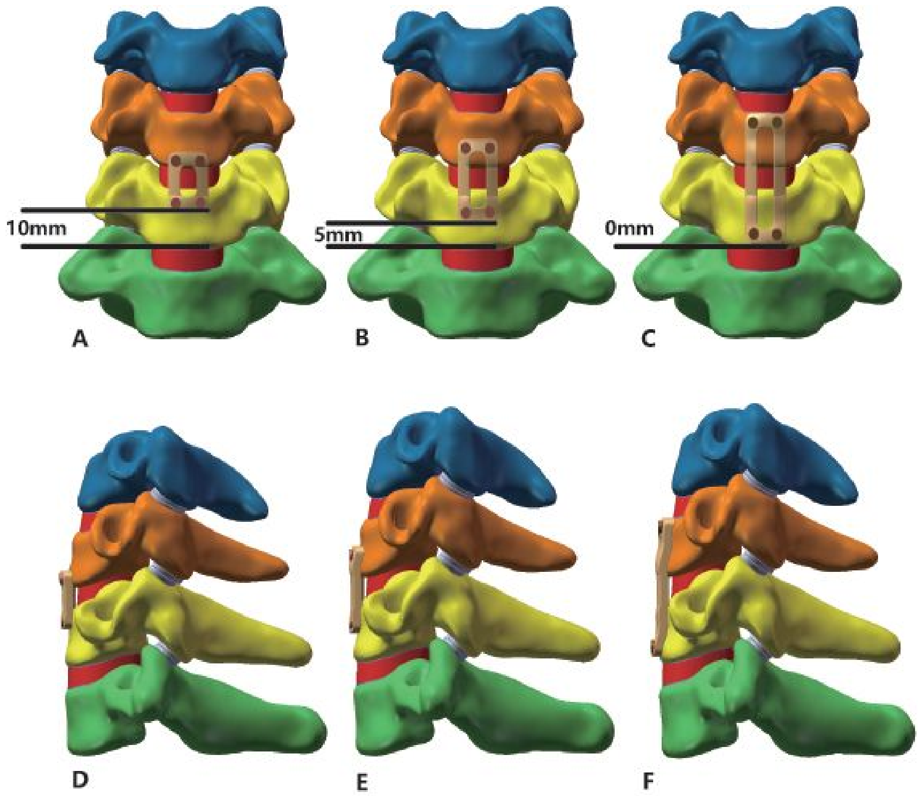

Figure 3

(A and D) Frontal and lateral view of postoperative model with long PDD titanium plate; (B and E) Frontal and lateral view of postoperative model with middle PDD titanium plate; (C and F) Frontal and lateral view of postoperative model with short PDD titanium plate

Image not available with this version

Figure 4

The Mises stress distribution diagram of adjacent intervertebral discs with different PDD titanium plates in different loading conditions (A: C4/C5; B: C6/C7)

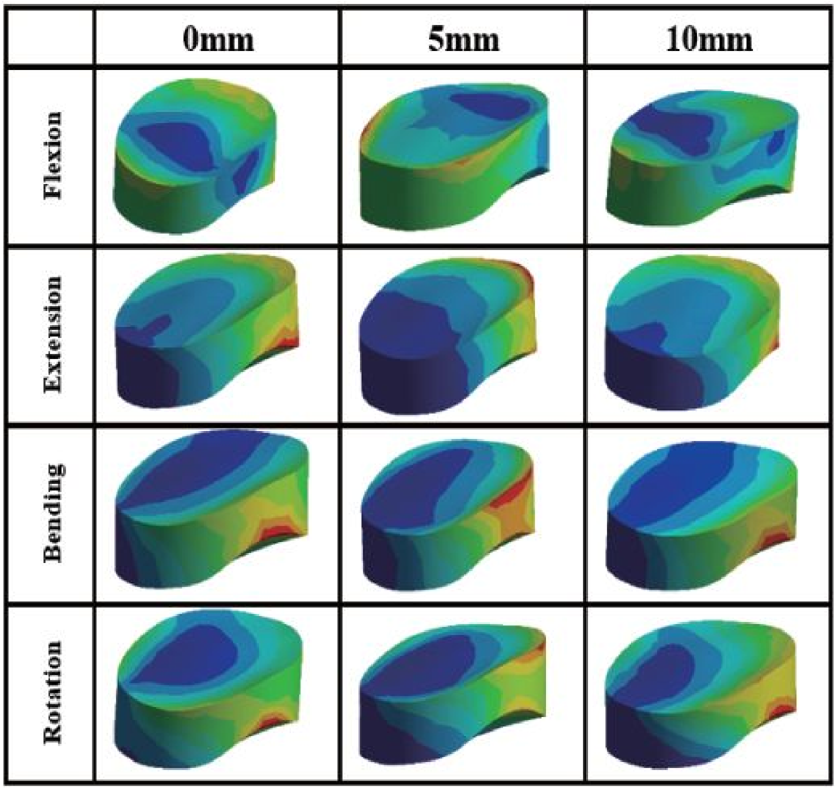

Figure 5

The Mises stress distribution diagram of bone graft with different PDD titanium plates in different loading conditions

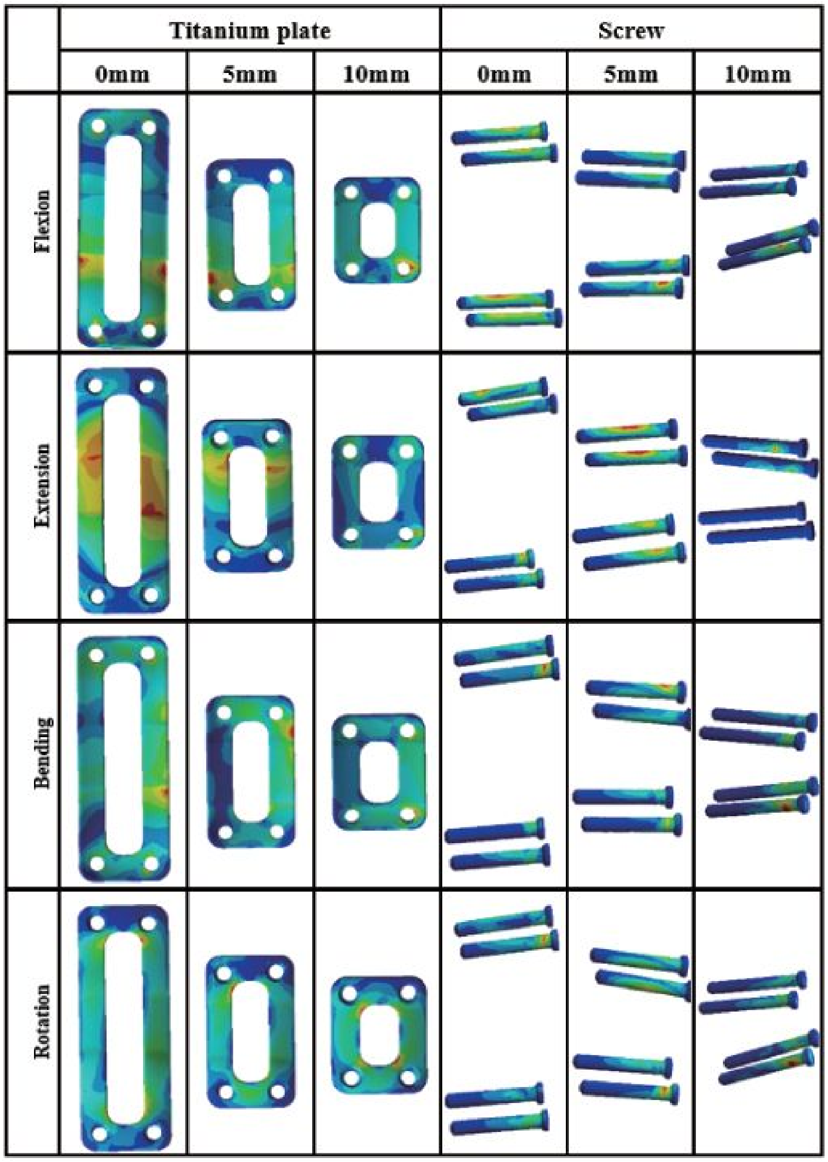

Figure 6

The Mises stress distribution diagram of titanium plate and screw with different PDD titanium plates in different loading conditions