Does the Screw Position in the ACDF Affect the Degeneration of Adjacent Segments? A Three-Dimensional Finite Element Analysis

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Abstract

Background: ACDF is the main treatment of cervical disease. Adjacent Segment Degeneration (ASD) is the main complication of long-term follow-up of ACDF. we conduct a detailed study of ACDF by means of three-dimensional finite element analysis and find the effect of screw placement and location on the occurrence of ASD.

Methods: The cervical computed tomography (CT) data (layer thickness of 0.625 mm) for a 30-year-old healthy male volunteer was collected. All the data were combined to create a C2-7 3D finite element model using Abaqus software. Based on the data and the actual surgical maneuver, a screw positioning model was established, in order to observe the cervical range of motion (ROM) with different positions of screw, as well as the pressure change of the adjacent segment intervertebral disc.

Results: The proposed finite element model of cervical spine was effective, and ROM on all directions of C4-C6 segments changed after ACDF surgery. Under the same torque settings, compared with the control group, C2/3 segment rotational ROM increased; C2/3, C3/4 segments lateral flexion ROM also increased. Regarding the influence of screw positioning, it has limited influence on the ROM and The intervertebral disc pressure (IDP), and compared with different horizontal positions, different vertical positions imposed greater influence on the ROM and IDP.

Conclusions: For ACDF surgery, positioning the screw at the anterior inferior part of the cervical vertebral body could provide more natural cervical ROM and the least IDP, while maintaining high biomechanical stability, and is more in line with human biomechanical requirements.

1 Background

With the rapid development of society and the change of people's lifestyle, the incidence of cervical diseases climbs year by year. Cervical degeneration often leads to spinal cord dysfunction and oppression of spinal cord blood vessels. In north America, degenerative spinal disease affects more than 76% of the population [1]. 50% of the whole population older than 55 years old are diagnosed of cervical spondylosis from various imaging exams, and about 10% are diagnosed of cervical spondylotic myelopathy (CSM), and the figure will continue to increase [2]. In spine department, surgery has become the golden standard for the treatment of CSM, and anterior cervical surgery has come to be a regular operation for CSM [3]. However, the application of anterior cervical titanium plate caused stress change on the adjacent superior and inferior segments. The concentration of stress led to the acceleration of ASD (Adjacent Segment Degeneration), and such postoperative complications have brought us various problems regarding the treatment of spinal diseases and their prognosis. Therefore, the grim facts are compelling us to dig deeper into more advanced cervical surgical technic. In the process, the master of anatomic characteristics of cervical spine and the proper understanding of biomechanics are vital for better treatment of the cervical disease. Recently, with the development of digitalization technology, we are able to combine conventional mechanical analysis with digitalization analysis to conduct linear and nonlinear stress and deformation analysis, granting us to present a more promising solution to the cervical biomechanical research.

Previous studies have conducted studies regarding ASD, but few focused on the biomechanical analysis of the positioning of titanium plate and screw. Herein, in our study, we compared and analyzed the biomechanical characteristics of four different positioning of the titanium plate and screw, in order to provide scientific evidence for the surgical treatment of cervical diseases.

2 Methods

The present study was approved by the institutional review board for involving human subjects. All procedures described in this study were approved by the Ethics Committee of our institution (Project Number:2017093017). The one volunteer provided his written informed consent. The study met the STROCSS criteria as well [4].

2.1 Finite element model of healthy adult male volunteer

One 30-year-old healthy adult male was recruited, with 173 cm of height and 68 kg of body weight. Inclusion criteria are presented as follows: 1. Acquire of the written informed consent from the volunteer; 2. No history cervical disease or basicranial disease; 3. Ruled out deformity, fracture of occipito-cervical region and degenerative cervical disease by X-ray exam; 4. No history of cervical trauma, infection, tumor or surgery. 16-slice spiral CT (Philips) was used and the scan slice thickness was set to 0.625 mm. Cervical C2-C7 segments of the volunteer were scanned to gather raw data, thereafter, in order to 3D-reconstruct the target tissue computed tomography (CT) scan image, and the raw data was imported to Mimics 10.01 software (Materialise, V10.01, Sweden) via Dicom format. The bone 3D geometric data model of C2-C7 segments was meshed using ICEMCFD software (v12.0, ANSYS, USA), and the structure from basis cranii to C1 was set as tetrahedron unit, the structure of the rest C2-C7 segments was set as hexahedron unit.

The constructed finite element model of C2-C7 includes the following parts: vertebral body, facet joint, cervical intervertebral disc; and the ligament model includes cruciform ligament (transverse ligament and cruciate ligament), alar odontoid ligament, apical odontoid ligament, anterior longitudinal ligament (membrana atlantooccipitalis anterior), lamina, posterior longitudinal ligament, ligamentum flavum (membrana atlantooccipitalis posterior), facet joint capsular ligament, interspinous ligament. According to previous literature reports, we have set the thickness of the cortical bone and the cartilaginous end plate in the model to 1.5mm and 0.2mm, respectively. The nucleus pulposus (NP) is encompassed by annulus fibrous (AF), and accounts for 43% of the total area of the disc [5,6]. According to the physiological structure of the target tissue, the contact mode between the superior and the inferior surface of the articular cartilage was set as sliding contact, with the friction coefficient set to 0.1, and the articular cartilage space of the facet joint as 0.5 mm [7]. The contact mode between cartilaginous end plate and the vertebral body was set as conode contact and the contact mode between NP and AF was set as Tie contact [6,8]. Since the transverse ligament is a relatively low elasticity tissue and it is quite firm, we selected membrane element to simulate it. Apart from the transverse ligament, for other ligament, according to previous studies, we applied two node T3D2-element to simulate [8]. The setting of the enthuses of all the ligaments were acquired from previous studies [9]. The value assignment of each simulated tissue parts are shown in the Table 1.

Table 1. Settings and parameters of the model parts

2.2 Test of the C2-C7 cervical spine finite element model and its loading condition in experiments

The normal model data was imported to Abaqus finite element software (version 6.11; Dassault, USA) finite element analysis software in IPN format. In the simulation, the C7 cartilaginous end plate was fixed, and a 50N loading was applied on each vertebral body along the curvature of vertebral body vertically from top to bottom to simulate the weight of head. Torques in 6 different directions (anterior flexion, posterior extension, right/left rotation, and right/left lateral flexion) were applied on C2 odontoid process. The range of motion (ROM) between each two vertebral bodies and the results were compared with previous literatures. In addition, under identical settings, if the change of the angular displacements and the von-Mises stress nephogram of the model in our study are in accordance with previous models in the studies of Panjabi [10] and Zhang [11], the establishment of our model is considered as effective as well.

2.3 Finite element simulation of cervical C2-C7 (C4-C6 ACDF, Figure1)

The cervical data model was modified: in the simulation, screws were inserted into C4-C6 vertebral bodies, and the models were divided into 4 groups based on the position of the distal-end of the screw. The front 2/3 part of the vertebral body was defined as “anterior” and the rear 1/3 part as “posterior”. With the fusion gap as the center, the upper end plate of the superior vertebral body is above and the lower end plate is below (I: Anterosuperior of the vertebral body, II: anteroinferior of the vertebral body, III: posterosuperior of the vertebral body and IV: posteroinferior of the vertebral body, Figure1). A plane-coordinate system with 4 quadrants were drawn using the center of vertebral body as the origin point, I was located on the superior lateral quadrant, II on inferior lateral quadrant, III on the superior interior quadrant and IV on the inferior interior quadrant. Afterwards, the model was mesh mapped. Since bone graft fusion was applied on the intervertebral disc in the operated segments (C4/5, C5/6), the material parameter for the intervertebral disc in such segments was set to cortical bone. Besides, the friction coefficient between the screw and the bone was set to 0.42. Thus a postoperative cervical finite element model with 4 different positions of screw was established (**Figure 1).**

3 Results

The cervical 3D hexahedron mesh C2-C7 model contains vertebral body, intervertebral disc, facet joint cartilage and ligament, etc. The appearance of our model was in accordance with normal anatomical structure. After calculation and comparison, we found that the ROM of each segment of the FE/Intact model was consistent with the test result acquired by Panjabi etc. [9] with their model sample. Moreover, the ROM results on C2/3, C3/4 and C6/7 segments of our model were in accordance with the results collected by Brolin etc. [7] and Zhang etc. [11]. In addition, under all operating condition, the stress distribution tendency and stress concentration tendency reflected by the von Mises stress nephogram yielded identical results with previous studies conducted by Brolin etc. [8]. Our FE/Intact model was hence considered to be appropriated designed and efficient.

Our data model showed that, the ROM in all direction on C4-C6 segment altered after ACDF surgery. Under the same torque settings, compared with the control group, C2/3 segment rotational ROM increased; C2/3, C3/4 segments lateral flexion ROM increased as well. The intervertebral disc pressure (IDP) on C3/4 segment postoperative decreased on anterior flexion, while it increased on rotation and lateral flexion; the IDP of C6/7 segment increased on anterior flexion, while decreased on lateral flexion **(Figures 2 and 3)**. Different positions od screw impose limited influence, relatively speaking, between group I and group III, as well as between group II and group IV, presented similar pattern regarding the change of ROM and IDP, which is, the vertical screw positioning had more influence on ROM and IDP than horizontal screw positioning. In addition, stress nephogram, we could notice more influence of horizontal screw positioning on the stress condition of surgical screw and plate **(Figure 4)**.

We could find out that, the internal fixation bears more stress when positioned in the posterior part of the vertebral body, compared to the anterior part. When comparing group I and group II, the stress in group II (screw close to the superior end plate of cephalad adjacent level vertebral body) was less than that in group I (screw closer to the superior end plate). Thus, based on the results yielded from the stress nephogram, group II had the optimal screw positioning, in which, the screws were inserted close to the superior end plate of cephalad adjacent level vertebral body.

4 Discussion

With the fast development of computer technology and frequent updates of various finite element analysis software, finite element analysis has become a major method for biomechanical studies [11]. The purpose of our study was to create a series of cervical C2-C7 segments 3D model for finite element analysis, in order to further probe into the screw positioning during ACDF surgery and the stress change in the segments adjacent to the fused segments.

ACDF is considered to be the most classical surgical method for treating cervical spondylosis, long term follow-up period for clinical studies after surgery showed that, ACDF could relieve the symptoms of neck-shoulder pain, and the relatively satisfactory fusion effect could attenuate the risk of second operation on the responsible levels as well. However, ASD caused by fusion surgery cannot be ignored [13]. Hilibrand etc. [14] reported a 2.9% incidence of ASD one year after surgery, and the incidence rises to 25.6% 10 years after surgery, in addition, more than half of the patients with ASD presented neurologic symptoms. Studies conducted by Zhang et al. showed that, it is not necessary for ASD patients without positive symptoms to receive treatment, and only one third of the ASD patients presenting symptoms required a second surgery [15]. Maldonado et al. [16] followed up 105 patients who underwent ACDF and reported an incidence of 10.5% for ASD in the patients who received their surgery three or more years ago. In addition, after a long term follow up study, Angelo et al. [17] concluded that the major cause for ASD after ACDF surgery was the increase in the activity in such segment. However, the exact mechanism of ASD after ACDF surgery remains unclear. Currently, scholars mainly concur to the theory that, the biomechanical characteristic alter ACDF or the natural degeneration of adjacent levels are responsible for ASD, which requires us to delve deeper into the actual mechanism [18]. In theory, the responsible segments lose their ROM after ACDF surgery, and the stress transfers away, causing the concentration of stress on the adjacent segments, accelerating their process of degenerating. The model analysis indicated that the ROM of adjacent segments increased to compensate the loss of ROM on the responsible segments, moreover, the stress change of each segments are different because varied levels. The ROM of the cephalad adjacent segment to the operative levels increased significantly after single level ACDF surgery, while the ROM of the whole cervical spine decreased linearly. Similarly, during the IDP monitoring, the mean IDP of the adjacent segments to the fused segments was higher than that of normal people, and the most significant IDP increase was observed on the superior adjacent segment [19].

Our study specifically focused on the ASD due to change of internal fixation screw positioning, and we discovered that different screw positioning during fusion of the C4-C6 caused different change of IDP on the adjacent segments. As shown in Figure4, the IDP in C2/3 are not significantly affected by the 4 different screw positioning, and the anteroinferior screw positioning in group II as well as the posteroinferior positioning in group IV brought the least IDP, hence we could know that the IDP could be closer to natural pressure when the screws are inserted in the superior part of the vertebral body. From the IDP change in C3/4, we found that except the IDP was the lowest under the rotation setting in group IV, all other settings brought similar IDP change. While on the C6/7 level, it is obvious that the posteroinferior screw positioning under posterior extension, rotation and lateral flexion settings yielded the minimum IDP value, and when under the anterior flexion setting, it returned identical value as the anteroinferior screw positioning. Therefore, from the stress test, we found that screw positioning has limited influence on the IDP change, however, the inferior screw positioning in group II and group IV could bring the most natural IDP.

As shown in Figure 3,under anterior flexion and posterior extension settings, each segments in group II and IV achieved higher ROM, and the ROM of the segments in group I and III were closer to natural state. Under left and right rotation settings, ROM of segments were higher in group II and IV than in group I and III, and group I and III still achieved more natural state on ROM; under left and right rotation setting, the ROM of C3/4 decreased because of the fusion of C4/5, and ROM of C2/3 increased to compensate the ROM loss of C3/4, hence, the ROM were closer to normal state when the screws were inserted in the anterior part of the middle column. Under left and right lateral flexion settings, ROM in group IV were smaller than those in the other three groups, and closer to angels in normal activity. The analysis result above proved that, on the cephalad end of the model, the pressure stress on C2/3 segment significantly increased when the vertebral body underwent lateral/anterior flexion and posterior extension. When an axial rotation changes in the vertebral body, relatively prominent with respect to the cephalic segment changes, and may directly affect the fusion of the distal segment. The IDP in the adjacent segments to the operative levels underwent significant change after surgery due to the change of stress, besides, the increase of the adjacent segments ROM, the concentration of stress and the IDP increase in adjacent segments would all contribute to the degeneration of ASD, which is in good accordance of previous studies results concluded by Watanabe S etc [20].

The stress on nephogram (Figure 4) of the model with different simulated anterior flexion and posterior extension activities presented us that, after ACDF surgery, the pressure stress was shifted upward 2 levels to C2/3 level, and cause IDP in the disc, which was supposed to bear much less load physiologically, to rise significantly, and further expedites the degeneration of segments in cephalad end. In addition, from the stress nephogram of the model with different Flexion and straight rotation. It also can be concluded that, the pressure stresses exerted on the screw and titanium plate in group III and group IV were the maximum, which indicated that such fused segments possess the strongest.

5 Conclusions

In conclusion, the screw positioning during ACDF surgery does have influence on the stability of cervical spine. The screw positioning induced less influence on the adjacent level IDP if the screws were placed in the antero/postero inferior part of the vertebral body (group II and IV) than placed in the antero/postero superior part of the vertebral body (group I and III). Regarding to the ROM of vertebral body, placing the screws to the anterior could achieve more natural ROM as normal cervical vertebral body than placing them in the posterior. In addition, placing the screw in the anteroinferior part of the vertebral body would yield optimal biomechanical efficacy, however, such result further requires verify from long term clinical follow-up studies and biomechanical experiments.

6 Abbreviations

ACDF
Anterior Cervical Discectomy and Fusion surgery
AF
annulus fibrous
ASD
Adjacent Segment Degeneration
CSM
cervical spondylotic myelopathy
CT
computed tomography
IDP
intervertebral disc pressure
NP
nucleus pulposus
ROM

range of motion

Declarations

Ethical approval and consent to participate

The present study was approved by the Institutional Review Board. All the procedures described in this study were approved by the Ethics Committee of our institution. patient provided written informed consent as well.

Consent for publication

Informed consent for the publication of details, images, or videos relating to the individual participant was obtained from the participant.

Availability of data and materials

Please contact the author for data requests.

Competing interests

The authors declare that they have no competing interests.

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Author contribution

HL and KG made substantial contributions to the study design, data analysis and manuscript writing; JWL and ZQZ contributed to the concept of the study and the interpretation of data; BDS, TDW and XML performed the operations. YFH and ZYB involved in the critically revising of the manuscript and offered valuable intellectual advises; DSW gave final approve of the version to be published. Each author participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Tables

Table 1 Settings and parameters of the model parts

Model parts	Unit	Young modulus(MPa)	Poisson’s ratio
Cancellous bone	C3D4	450	0.25
Cortical bone	S3	10000	0.3
Cartilaginous end plate	S3	1000	0.3
Anterior longitudinal ligament	Truss	30	0.3
Posterior longitudinal ligament	Truss	20	0.3
Ligament flavum	Truss	10	0.3
Interspinous ligament	Truss	8	0.3
Joint capsule ligament	Truss	30	0.3
Titanium alloy	C3D4	110000	0.33
Annulus fibrosus	C3D6	3.4	0.3
Nucleus pulposus	Fluid cavity	-	-

Figures

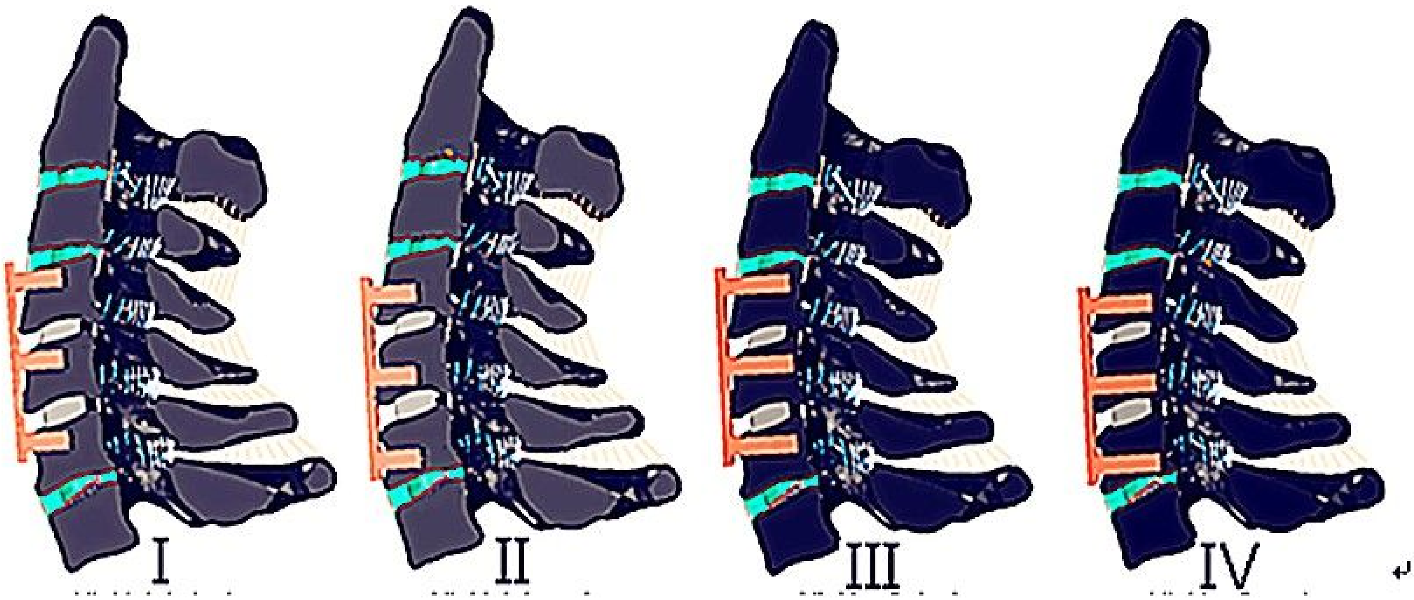


Figure 1

Postoperative cervical finite element model with 4 different screw positioning With the fusion gap as the center, the upper end plate of the superior vertebral body is above and the lower end plate is below (I: Anterosuperior of the vertebral body, II: anteroinferior of the vertebral body, III: posterosuperior of the vertebral body and IV: posteroinferior of the vertebral body).

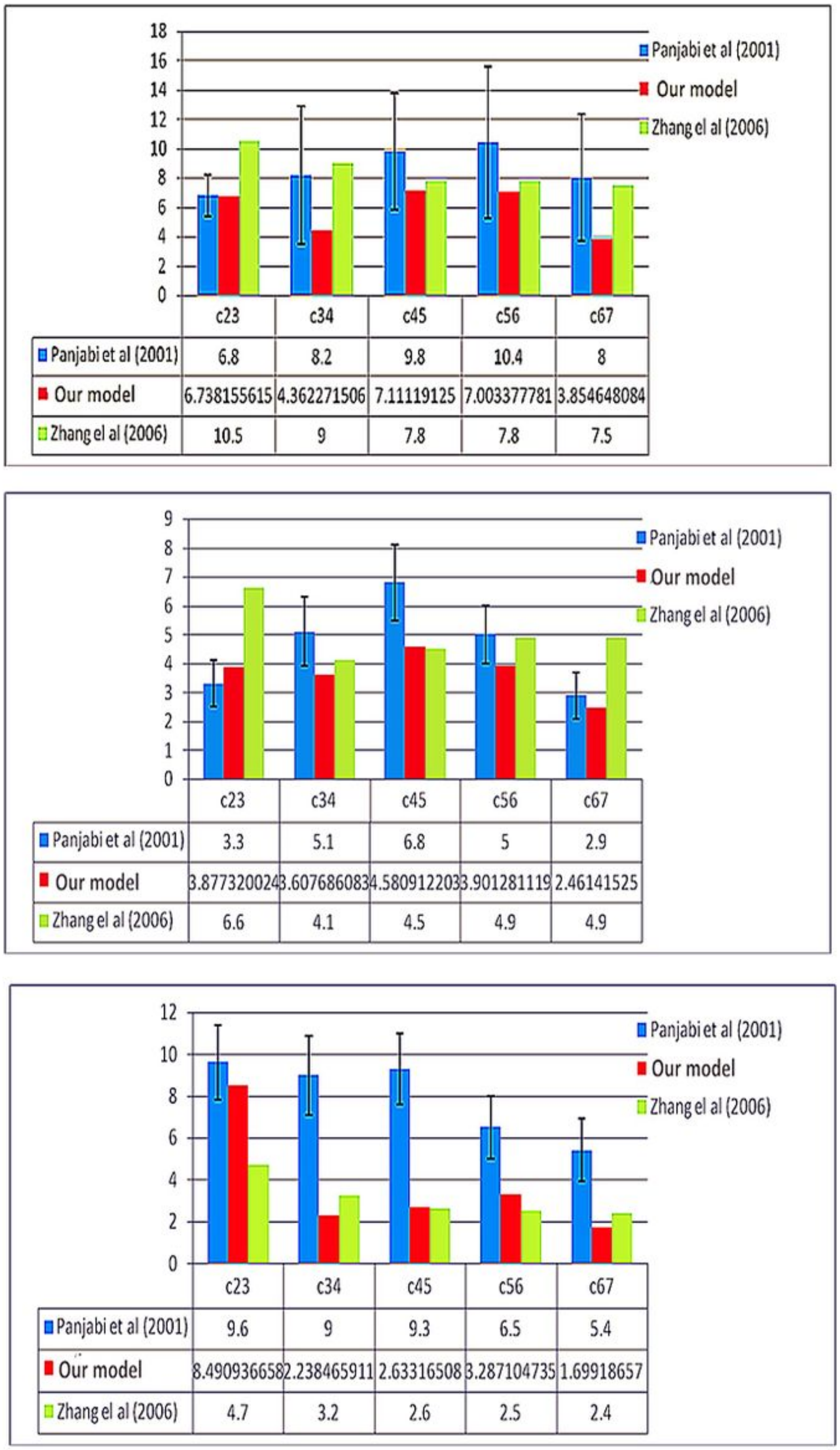
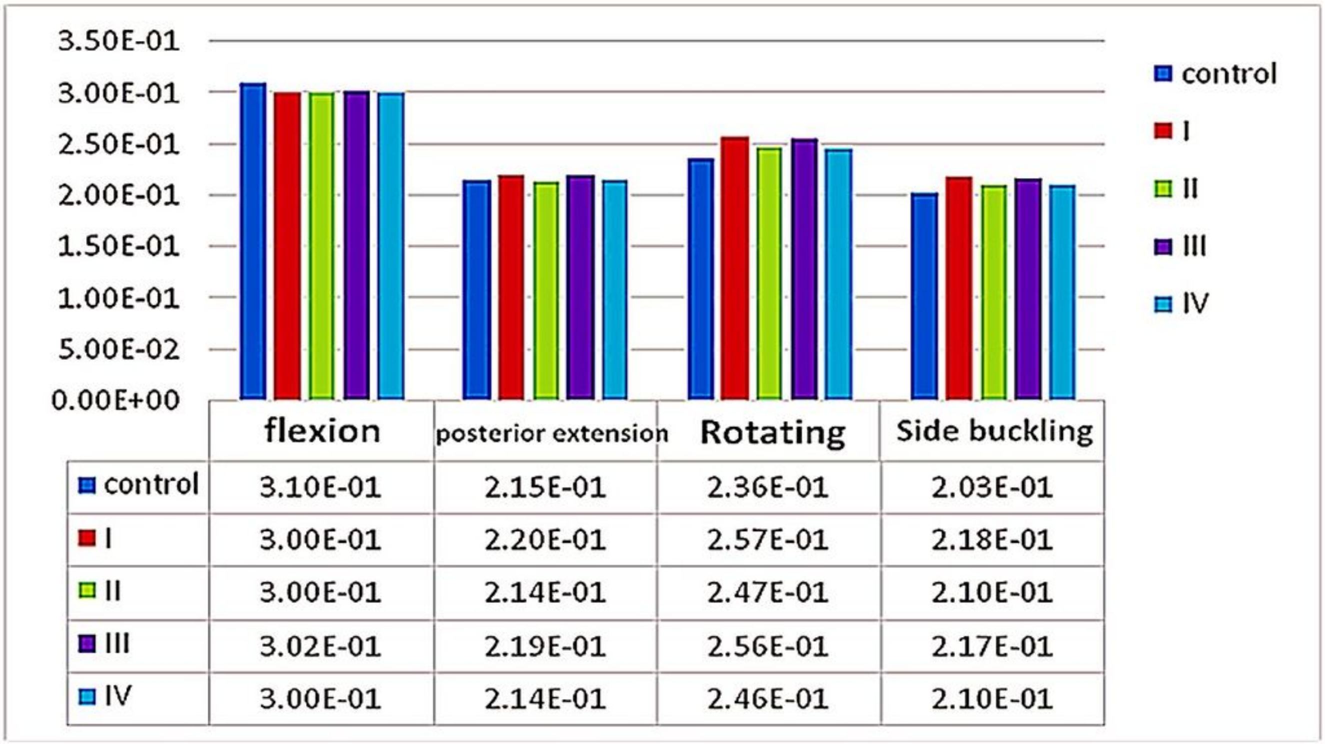


Figure 2

flexion+ posterior extension The ROM on anterior flexion+ posterior extension of the 4 postoperative cervical model in comparison with normal cervical model (unit: °) left rotation+ right rotation The ROM on left rotation+ right rotation of the 4 postoperative cervical model in comparison with normal cervical model (unit: °) left lateral flexion+ right lateral flexion The ROM on left lateral flexion+ right lateral flexion of the 4 postoperative cervical model in comparison with normal cervical model (unit: °)



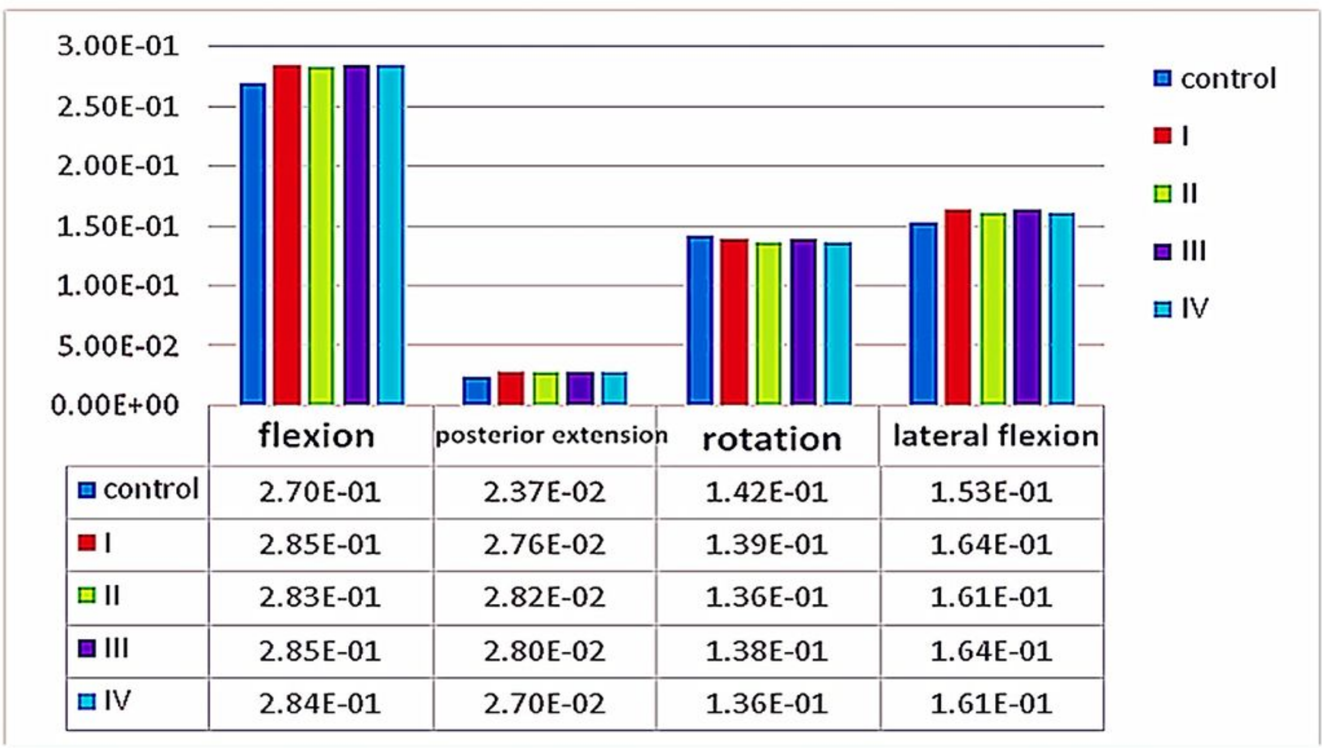


Figure 3

The maximum limit of motion on each direction (1Nm)+ intervertebral disc pressure of C3/4 segment (MPa) of the 4 postoperative cervical model in comparison with normal cervical model The maximum limit of motion on each direction (1Nm)+ intervertebral disc pressure of C6/7 segment (MPa) of the 4 postoperative cervical model in comparison with normal cervical model

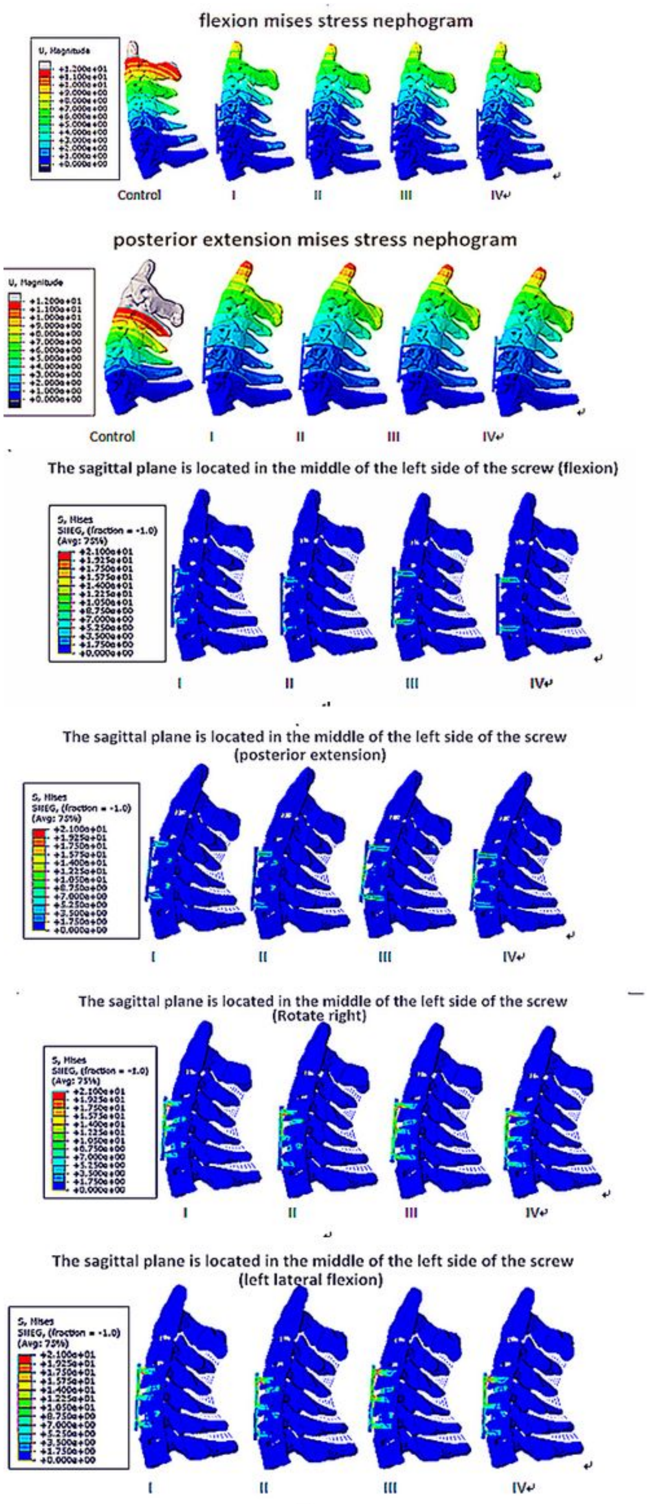


Figure 4

Flexion mises stress nephogram Compared with the control group, C2-C3 activity has changed. The torque is moved up. After ACDF surgery, the pressure stress was shifted upward 2 levels to C2/3 level, and cause IDP in the disc, which was supposed to bear much less load physiologically, to rise significantly, and further expedites the degeneration of segments in cephalad end. Posterior extension mises stress nephogram Compared with the control group, C2-C3 activity has changed. The torque is moved up. After

ACDF surgery, the pressure stress was shifted upward 2 levels to C2/3 level, and cause IDP in the disc, which was supposed to bear much less load physiologically, to rise significantly, and further expedites the degeneration of segments in cephalad end. The sagittal plane is located in the middle of the left side of the screw(flexion) Groups I and III, II and IV showed similar patterns in mobility and intervertebral disc pressure. The upper and lower positions of the screw have a greater influence on the vertebral body mobility and the pressure in the intervertebral disc than the anteroposterior position. The position of the front and rear of the screw affects the force of the screw and the steel plate. When the screw is fixed in the front position, the fixed stress in each direction is small, and the stress in the rear position screw is obviously increased. The sagittal plane is located in the middle of the left side of the screw(posterior extension) Groups I and III, II and IV showed similar patterns in mobility and intervertebral disc pressure. The upper and lower positions of the screw have a greater influence on the vertebral body mobility and the pressure in the intervertebral disc than the anteroposterior position. The position of the front and rear of the screw affects the force of the screw and the steel plate. When the screw is fixed in the front position, the fixed stress in each direction is small, and the stress in the rear position screw is obviously increased. The sagittal plane is located in the middle of the left side of the screw(rotate right) Groups I and III, II and IV showed similar patterns in mobility and intervertebral disc pressure. The upper and lower positions of the screw have a greater influence on the vertebral body mobility and the pressure in the intervertebral disc than the anteroposterior position. The position of the front and rear of the screw affects the force of the screw and the steel plate. When the screw is fixed in the front position, the fixed stress in each direction is small, and the stress in the rear position screw is obviously increased. The sagittal plane is located in the middle of the left side of the screw(left lateral flexion) Groups I and III, II and IV showed similar patterns in mobility and intervertebral disc pressure. The upper and lower positions of the screw have a greater influence on the vertebral body mobility and the pressure in the intervertebral disc than the anteroposterior position. The position of the front and rear of the screw affects the force of the screw and the steel plate. When the screw is fixed in the front position, the fixed stress in each direction is small, and the stress in the rear position screw is obviously increased.