Finite Element Analysis and Comparative Study of 4 Kinds of Internal Fixation Systems for Anterior Cervical Discectomy and Fusion in Children

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Abstract

Background: Spinal injury in children usually occurs in the cervical spine region. Anterior fixation of lower cervical spine has been applied in the treatment of pediatric cervical spine injury and disease due to its stable and firm mechanical properties. This study performed finite element analysis and comparison of 4 different anterior cervical internal fixation systems for children, and explored more stable methods of anterior cervical internal fixation in children.

Methods: A finite element model of 6-year-old children with lower cervical spine C4/5 discectomy was established, and the self-designed lower cervical spine anterior locking internal fixation system ACBLP and the children's anterior cervical internal fixation system ACOP, ACVLP, ACSLP plate screws were fixed and loaded on the model. 27.42N•m torque load was applied to each internal fixation model under 6 working conditions of anteflexion, backward flexion, left flexion, right flexion, left rotation and right rotation, to simulate the movement of the cervical spine. The activity and stress distribution cloud diagram of each finite element model was obtained.

Results: In the four internal fixation models of ACOP, ACVLP, ACSLP, and ACBLP, the mobility of C4/5 segment basically showed a decreasing relationship, and the mobility of adjacent segments increased significantly. In the Mises stress cloud diagram of the cervical spine of the four models, the vertebral body and accessories of the ACBLP model born the least stress, followed by ACSLP; The steel plate and screws in the ACVLP internal fixation model were the most stressed; The stress of the internal fixation system (plate/screw) in all models increased in the order of ACBLP, ACSLP, ACVLP, and ACOP.

Conclusions: ACBLP internal fixation system had obvious advantages in anterior internal fixation of lower cervical spine in children, C4/5 had the smallest degree of movement, relative displacement was minimal, the stress on the pedicle was the least while the stress on the plate screw was relatively the smallest.

1 Introduction

Bühler et al.[1] first used cervical plate and screw internal fixation system for anterior cervical interbody fixation in 1964 to improve the mechanical stability of cervical lesions after surgery. Anterior plate construct is considered to be one of the devices for maintaining cervical spine stability, promoting intervertebral fusion and reducing intervertebral dislocation after anterior cervical discectomy and fusion in subsequent clinical treatment. Some scholars had conducted experimental research on the relevant mechanics of the anterior cervical plate screw internal fixation system[2–4], Yachao Zhao et al.[5] believed that the locking independent fusion cage was more effective than the anterior plate internal fixator in the anterior cervical discectomy and fusion. Cai Feng et al.[6] compared the mechanical properties of the cross nails and parallel nails in the anterior cervical plate screw system. It was found that there was no significant difference in the maximum pull-out force and fatigue strength of the two steel plates. However, the cross nails were more conductive to the operation, with the internal fixation effect not weaken.These studies all suggest that cross nails and locking fusion are more suitable for anterior cervical treatment. In

addition, most of the current studies are based on adult cervical spine models, but children's cervical spine is flatter and weaker than adults, and the vertebral arch The root is narrower and thinner, and it is difficult to insert 2 pedicle screws at the same time, and the patient's postoperative recovery is poor. In order to solve the problem of the stability of the child's nail placement, this study designed an anterior cervical bicortical pedicle locking plate, and Establish an unstable three-dimensional finite element model of children's cervical C4/5 discectomy, perform finite element analysis on this internal fixation method and other three different internal fixation methods, compare the mobility and stress strain of the four internal fixation methods, and explore Better clinical internal fixation treatment for neck injuries in children.

2 Methods

2.1 Experimental data

In 2019, in the Digital Medicine Center of Inner Mongolia Medical University, the finite element analysis of 4 different methods of internal fixation of the child's anterior cervical approach was completed. The experimental specimen came from the corpse of a 6-year-old girl from the Anatomy Laboratory of Inner Mongolia Medical University. Height 115cm, weight 41kg. X-ray of cervical spine was taken to exclude cervical vertebra deformity, trauma, tumor, etc. The CT(United States, GE, Lightspeed dual-source 64-slice spiral CT) scan range was a spiral axial scan of the whole cervical spine from top to bottom. Scanning parameters: tube voltage 120KV, tube current 125mA, layer thickness 0.625mm, no interval scanning. Complete cervical spine CT image data was obtained and saved in DICOM format. The experiment was approved by the Ethics Committee of Inner Mongolia Medical University.

2.2 Experimental method

2.2.1 Establish a finite element model for the removal of the C4/5 disc of the lower cervical spine in children

CT data was constructed into a normal child C3-C7 three-dimensional finite element model by Mimics 21.0, Pro/E 5.0, Geomagic studio 2015, HyperMesh 14.0, Abaqus 6.14. Multiple unit types were used to build the model, 361012 units and 509161 nodes were contained. The C4/5 disc removal of the model was modified into an unstable finite element model. The boundary conditions and loading conditions were the same as the full model loading conditions. In the experiment, the ligament was hidden for view convenience, but the finite element analysis results were not affected.

2.2.2 Establish 4 kinds of internal fixed finite element models

According to the child's cervical instability model, a three-dimensional model of the internal fixation steel plate and fixed locking screw was constructed. Four kinds of internal fixation plate screws were used to construct geometric solid models to build four personalized anterior cervical internal fixation models:

(1) Anterior cervical Orion plate internal fixation (ACOP) for children's anterior cervical locking internal fixation system, which consisted of 4 ordinary vertebral screws with connected and fixed steel plates, and the screws were directly driven into the vertebral body.

(2) Anterior cervical vertebral locking plate (ACVLP) included 4 vertebral screws with threaded heads and corresponding locking plates, which inserted into the vertebral body in the same way as ACOP.

(3) Anterior cervical single cortical pedicle locking plate (ACSLP), included 2 vertebral screws and 2 pedicle screws. Vertebral screws and pedicle screws were ross-locked of in the vertebral body.

(4) This study designed an anterior cervical bicortical pedicle locking plate (ACBLP) combined with the commonly used anterior cervical ORION internal fixation system. It composed of 2 full-thread vertebral screws and 2 full-thread bicortical pedicle screw penetrating side block through pedicle. The vertebral screws and full-thread bicortical pedicle screw were cross-locked in the vertebral body. At the same time, the two screw caps were double fused and locked with the steel plate.

The elastic modulus, Poisson's ratio, element type and characteristic value of the implant material were inputted into the model [7] (implant titanium alloy E = 110000MPa, μ = 0.3, tetrahedral element). The three-dimensional finite element models of the four internal fixation systems after cervical C4/5 discectomy were established, as shown in Figure 1.

2.2.3 Loading calculation of 3D finite element model

The cervical vertebra screw and the vertebral screw were defined as close contact without sliding and compression deformation. Constraint boundary: The degrees of freedom of all nodes on the lower edge of the C7 cone were restricted in all directions, C3 was not subject to any restrictions, and the center of the upper edge of the vertebral body received a load that simulated the weight of the head. Assumptions: The material properties of the biological materials involved in this experiment were assumed to be continuous, homogeneous and isotropic; there was no mutual sliding between the sections of the model under force; there was enough stability between the units; the stress and deformation of each part of the material during the loading process were excluded. Loading conditions: A 27.42N simulated head weight preload is applied to C3, and the additional pure moment of movement is 1.8Nm[8]. ABAQUS finite element software was used for finite element analysis. According to the experimental methods of cervical spine movement characteristics and specimens, simulated cervical spine movement was divided into six types of movement: anteflexion, backward flexion left flexion, right flexion, left rotation and right rotation.

2.2.4 Setting and operation of different working conditions

The stress value of the model was set. A 27.42N•m torque load was applied to simulate cervical spine movement to ACOP, ACVLP, ACSLP, and ACBLP after cervical C4/5 discectomy internal fixation model respectively under 6 working conditions. Five points were randomly selected from C4, C5's superior articular process, contralateral superior articular process, bilateral pedicle and vertebral body, the corresponding values were obtained to compare and analyze the biomechanical activity and stress changes of the four internal fixation models. At the same time, the stress distribution and strain of the steel plate and screw unit of the four kinds of internal fixation systems of the lower cervical spine in children were observed.

2.2.5 Statistical analysis

The data were inputted into SPSS 22.0 for analysis. The data is expressed by $\bar{x} \pm s$. The same measurement parameter was compared in different internal fixation models by one-way analysis of variance (One-way ANOVA) with multi-sample means comparison, and $P<0.05$ was considered as significant difference.

3 Results

3.1 Comparison of activities of 4 internal fixation models under 6 working conditions

After C4/5 segment fixation, the immediate stability of the segments of all internal fixation models was improved. In the research, smaller activity indicated higher stability. The internal fixation method had an obvious effect on reducing mobility. The ACBLP internal fixation model had the advantages of good immediate stability and relatively small impact on adjacent segments. For the overall lower cervical spine range of motion of the four internal fixation models, ACOP>ACVLP>ACSLP>ACBLP, ACOP had significant differences with ACVLP, ACSLP, ACBLP ($P<0.0001$); ACBLP is the smallest, and the difference was significant compared with ACOP and ACVLP ($P<0.0001$), see Table 1.

Table 1
The motion range of the four internal fixation systems in different motion states ($\bar{x}$±s,mm)

Motion	ACOP	ACVLP	ACSLP	ACBLP
Anteflexion	1.98±1.20	1.42±0.88[a]	1.01±0.61[ab]	0.74±0.43[ab]
Backward Flexion	5.53±3.34	3.86±2.39[a]	2.70±1.61[ab]	1.98±1.17[ab]
Left Flexion	7.58±4.38	5.45±3.16[a]	3.19±2.24[ab]	2.85±1.59[ab]
Right Flexion	7.90±4.68	5.46±3.20[a]	3.80±2.09[ab]	2.83±1.57[ab]
Left Rotation	5.85±3.68	4.26±2.75[a]	3.03±1.89[ab]	2.22±1.33[ab]
Right Rotation	5.78±3.50	4.28±2.51[a]	3.03±1.74[ab]	2.21±1.27[ab]

Note: Compared with ACOP group, [a] $P<0.05$, compared with ACVLP group, [b] $P<0.05$, compared with ACSLP group, [c] $P<0.05$

3.2 Cervical spine Mises stress comparison of the 4 internal fixation models under the 6 working conditions

As shown in the figure, different stress values corresponded to different colors (or) gray levels, at the same time, the calibration reference value was attached to the left side of the model. The range of the stress value could be judged by comparing the fit between this value and the color. There were obvious differences in the cervical spine Mises stress distribution characteristics in the ACOP, ACVLP, ACSLP, and ACBLP internal fixation models, as shown in Figure 2.

For the overall lower cervical spine stress values of the four internal fixation models, ACOP>ACVLP>ACSLP>ACBLP, ACOP was significantly different from ACVLP, ACSLP, ACBLP (P<0.0001); ACBLP was the smallest, compared with ACVLP and ACSLP, the difference was significant (P<0.0001), see Table 2.

Table 2
The stress strain range of 4 internal fixation systems in different motion states($\bar{x}\pm s$,Mpa)

Motion	ACOP	ACVLP	ACSLP	ACBLP
Anteflexion	2.48±2.23	1.83±1.69[a]	1.29±1.16[a]	0.96±0.84[ab]
Backward Flexion	3.69±1.39	2.66±1.12[a]	1.91±0.71[ab]	1.42±0.53[abc]
Left Flexion	4.28±2.78	3.15±2.08[a]	2.26±1.47[ab]	1.66±1.06[ab]
Right Flexion	4.17±2.59	3.09±2.04[a]	2.24±1.45[ab]	1.70±1.11[ab]
Left Rotation	4.28±1.64	3.07±1.21[a]	2.21±0.89[ab]	1.61±0.63[abc]
Right Rotation	4.24±1.77	2.95±1.12[a]	2.09±0.81[ab]	1.59±0.64[abc]

Note: Compared with ACOP group, [a] $P<0.05$, compared with ACVLP group, [b] $P<0.05$, compared with ACSLP group, [c] $P<0.05$

3.3 Steel plate screws stress comparison of 4 internal fixation models under 6 working conditions

After removal of the C4/5 disc, the Mises stress cloud diagram of the steel plate screw under the six loading conditions of anteflexion, backward flexion, left flexion, right flexion, left rotation and right rotation of different internal fixation models were shown in Figure 3. The stress of the steel plate screws of the internal fixation system in the model increased in the order of ACBLP, ACSLP, ACVLP, and ACOP. It showed that the stress of the ACOP internal fixation system was relatively concentrated, the stress of ACBLP was dispersed, and the stress concentration was not obvious, in line with biomechanical fixation.

4 Discussion

The study established a 6-year-old child's unstable working condition model after C4/5 disc removal was, and the model was used to compare and analyze stability and stress characteristics of 3 kinds of children's anterior cervical locking internal fixation systems ACOP, ACVLP, ACSLP with the self-designed internal fixation system ACBLP. According to the analysis of the applied mechanical results, the conclusion was that under various working conditions, the ACBLP had the smallest mobility and was the most stable, while the ACOP had the worst stability; The increase in mobility of adjacent segments in the ACBLP internal fixation model was relatively small, while the increase in the mobility of adjacent segments in the ACOP internal fixation model was relatively large. The change in mobility was because the conjunction of vertebral screw and pedicle screw when fixing the unstable model. At the same time,

the pedicle screw penetrated the double cortex, enhanced control and stability, and the cross-locking further enhanced the firmness.

In the Mises stress cloud diagram of the cervical spine under 6 loading working conditions, under anteflexion and backward flexion conditions, although the stress of the cervical spine in the four internal fixation models was mostly concentrated in the C6 and 7 vertebral bodies and pedicles, it was obvious that the stress on the cervical spine in the ACBLP internal fixation model was relatively small and ACVLP was relatively large. The study believed that it was because the stress concentration point was lower during anteflexion and backward flexion, the impact on the internal fixation model is relatively small, which was consistent with the previous research results of Wangjiajia et al.[9]. In the left and right flexion conditions, the stress of the cervical spine in the four internal fixation models was mostly concentrated around the C4 and 5 vertebral screw holes. For the left flexion, the ACBLP had the least stress in C4 and 5. For the right flexion, the stress on the C4 and 5 vertebral bodies of ACVLP was larger than other models. In the left and right flexion conditions, the force of the vertebral screw was greater than the pedicle screw, which would lead to loosen of vertebral screws after surgery. In the left and right rotation conditions, the stress of the cervical spine was distributed to each vertebral body in all the 4 models, the vertebral bodies of the lower cervical spine were relatively uniformly stressed. The influence on each vertebral body was not great, comparing with the previous 4 working conditions. The ACOP model had a higher vertebral body stress, and the ACBLP model had less vertebral body stress.

In the Mises stress cloud diagram at the steel plate and screw,under anteflexion and backward flexion conditions, C4 left screw of ACVLP, ACSLP, ACBLP suffered greater stress. The stress was concentrated at the junction of the screw head and the nail shaft,In the ACOP model, the screw stress was concentrated on the C5 vertebral screw during backward flexion.The stress change provided a possible reference for the loosening or breaking point of the screw[10, 11]. In the left and right flexion conditions, ACBLP, ACSLP, ACVLP, ACOP steel plates were subject to increasing stress. The steel plate in the ACBLP was the least stressed. In the ACOP, the stress was relatively concentrated at the middle of the steel plate, as in other models, the stress relatively concentrated at the left side of the steel plate. In the four models, the C5 vertebral screw was relatively large. ACBLP screw stress was concentrated on the front third of the nail shaft. The reason might be that there was a slight movement between the screw and the steel plate in the ACOP model. In the left and right rotation conditions, the stress on the steel plate and screws in the four internal fixation models was relatively uniform. For the left rotation, the stress of upper right corner and lower left corner of the steel plate were slightly higher and the stress of the internal fixation screw was basically concentrated on the upper right corner and the lower left corner screw. The stress on the steel plate in all models was greater than the stress on the screw, showing the stress concentration of the steel plate. However, the maximum stress value of all internal fixation was 35.591 Mpa (the C5 right screw right flexion condition), still much smaller than the yield strength of titanium alloy 894-3790Mpa. Therefore, it was not easy to cause fatigue fracture of the screw, clinical fatigue fracture was relatively rare correlated with it[12–15].

In summary, unlike adult anterior cervical discectomy and fusion with plate screw internal fixation, children’s cervical spine is not yet mature, the vertebral body is relatively flat, the pedicle is small, it is very difficult to place pedicle screws in both pedicles in the vertebral body. The advantages of the ACBLP internal fixation system independently designed by this study are: Placing 1 vertebral screws and 1 double cortical pedicle screw in each vertebral body to improve the stability by cross nails and reduce the damage and destruction of the children's cervical vertebral body .Adding threads matching the steel plate to all screw caps, fusion locking the thread and steel plate, preventing the occurrence of withdrawal or loosening of screws after surgery. For the pedicle screw, a full-threaded bicortical pedicle screw with the pedicle penetrating the lateral mass was used, Compared to a single cortical pedicle screw, further increasing the holding force of the screw in the vertebral body, reducing screw slippage caused by too weak cervical spine in children. Therefore, stability and force distribution of ACBLP and ACSLP internal fixation systems are relatively good. The ACBLP internal fixation system provides good support for the three columns of the lower cervical spine in children. The corresponding displacement of the stress on the three columns is obviously smaller than other internal fixation models, embodying the good mechanical properties of locking pedicle screws. The ACBLP internal fixation model enjoys the advantages of good immediate stability and relatively small impact on adjacent segments. The result provides detailed quantitative reference information for preoperative planning and prediction of postoperative mid- and long-term efficacy. The results of the study can be used for clinical reference.

Abbreviations

ACOP Anterior cervical orion plateACVLP: Anterior cervical vertebral locking plate; ACSLP :Anterior cervical single cortical pedicle locking plateACBLP Anterior cervical bicortical pedicle locking plate.

Declarations

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Authors' Contributions

Shaojie Zhang, Ziyu Li and Jianqiang Zhou conceived and designed this study. Xiaoyan Ren, Kun Li and Xing Wang conducted experiments and analysed data. Shang Gao and Xiaohe Li performed anatomic and morphological analysis. Shaojie Zhang, Ziyu Li and Zhijun Li wrote the manuscript.

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Availability of data and materials

Corresponding author Zhijun Li can be contacted to request the raw data.

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

Declaration of Competing Interes

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

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Figures

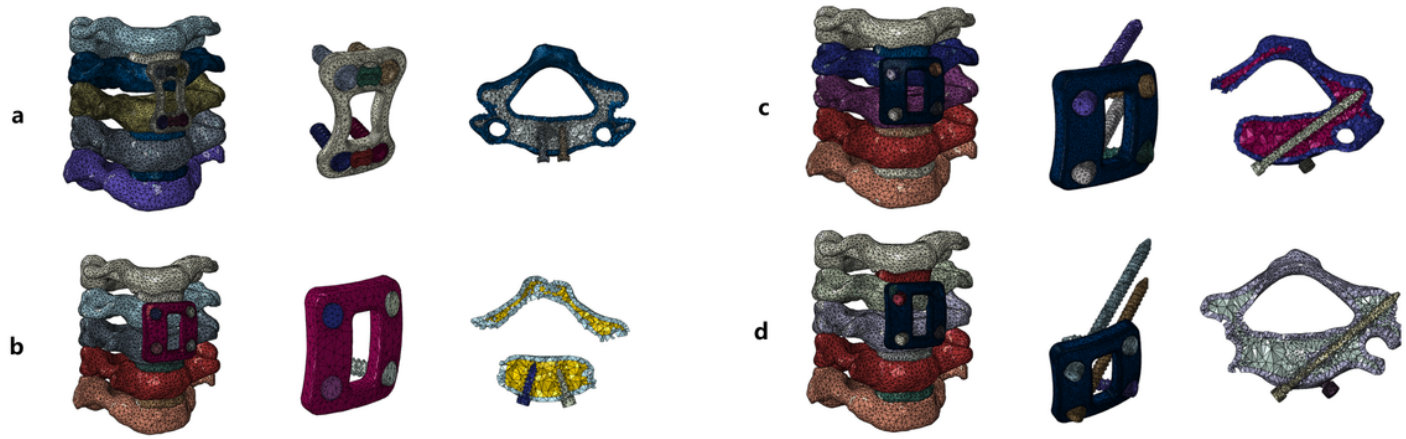

Figure 1

Three-dimensional finite element model of four internal fixation methods after removal of the C4/5 cervical disc in children a: ACOP b: ACVLP c: ACSLP d: ACBLP

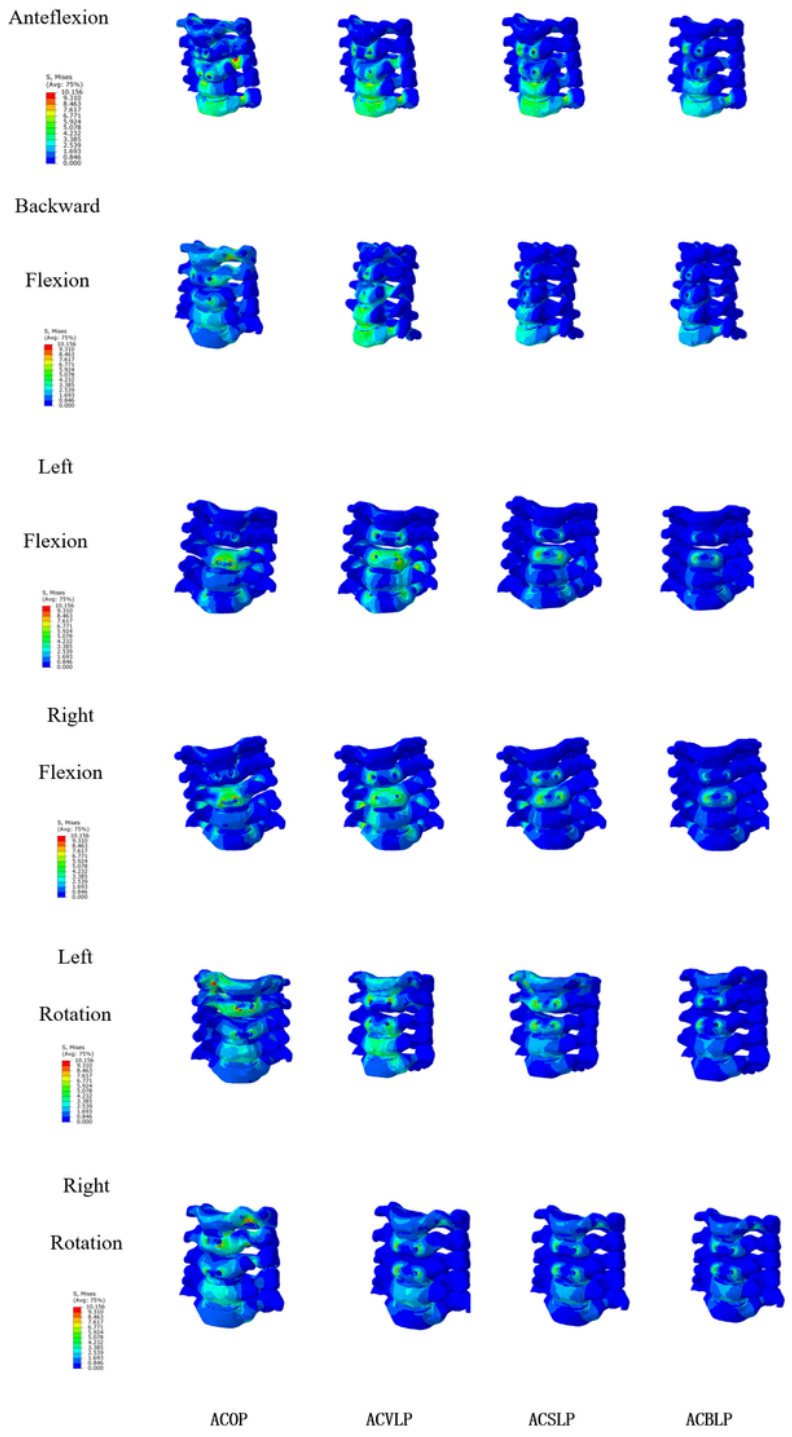

Figure 2

Cervical spine Mises stress cloud diagram of the four internal fixation models

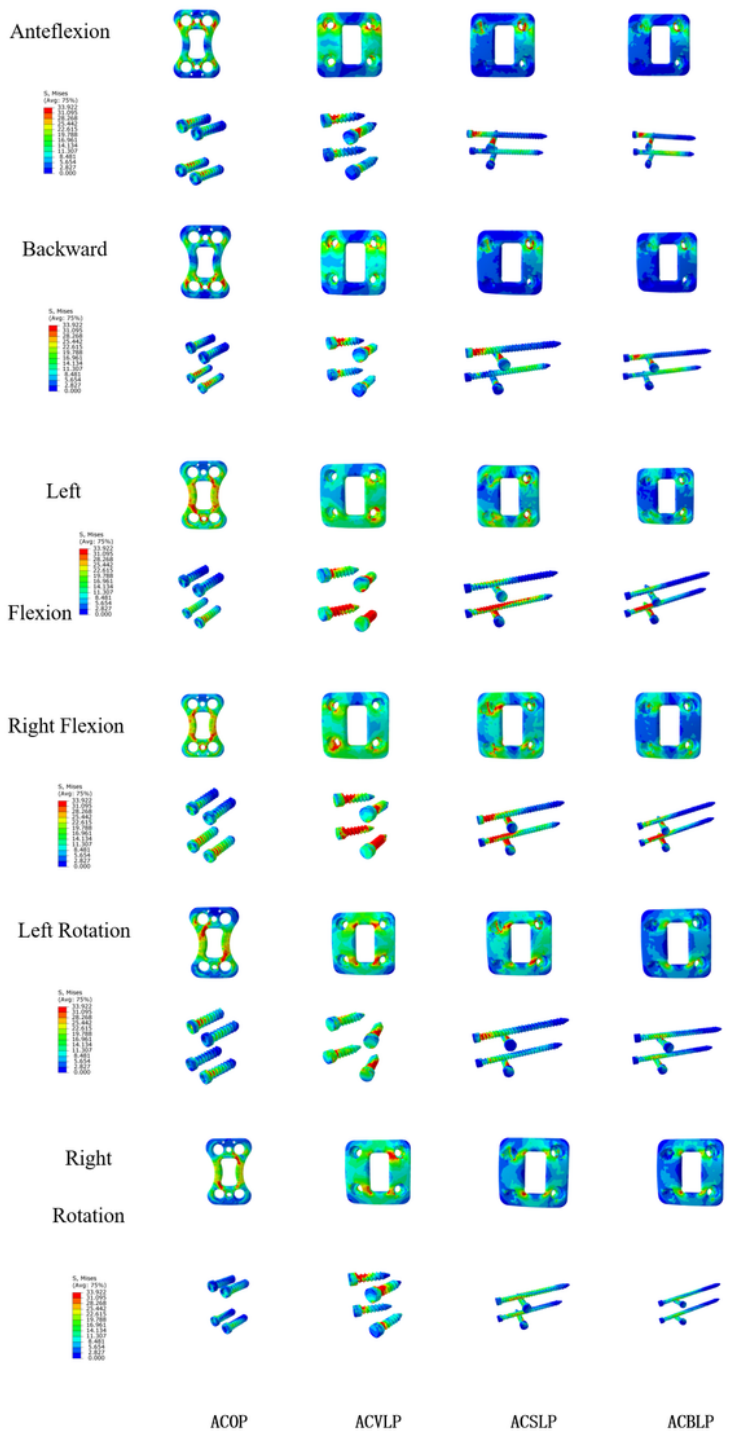

Figure 3

Mises stress cloud diagrams of steel plates and screws of four internal fixation systems