Biomechanical Evaluation of Subaxial Lateral Mass Prothesis: A Finite Element Analysis Study

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Research

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Abstract

Background: Pathologies of a lateral masses due to trauma, tumors, and surgery, could lead to bone destruction and biomechanical changes of the cervical spine. Their treatment includes lesion resection and internal fixation. However, the resulting bone defect of a lateral mass is often neglected, resulting in difficulty in bone fusion. Therefore, we designed a subaxial lateral mass prosthesis to achieve lateral mass joint fusion by implanting the prosthesis along with granular bone.

Objective: To evaluate the role of a new subaxial lateral mass prosthesis in load sharing using finite element analysis.

Methods: Cervical computed tomography was performed on a healthy volunteer. Five finite element models (intact, lateral mass resection, screw-rod fixation, prosthesis implantation, and prosthesis fusion groups) were compared in terms of the range of motion (ROM), prosthesis von Mises stress, and screw-rod von Mises stress during flexion, extension, lateral bending, and rotation.

Results: After lateral mass resection, the ROM of the model increased significantly. The ROM was significantly reduced after fixation with screws and rods. Screw-rod fixation combined with prosthesis implantation further reduced the ROM, especially during left and right bending. After bone fusion in the prosthesis, the ROM can also be reduced slightly. The von Mises stress of the bilateral screws and rods was significantly decreased after prosthesis implantation. The von Mises stress of the prosthesis was further decreased during the right bending after bone fusion was achieved.

Conclusion: Subaxial lateral mass prosthesis can help to restore the stability of the cervical spine after lateral mass resection and can reduce the stress on the bilateral screws and rods. Reconstruction of a lateral mass is more consistent with the mechanical transmission of the three-column spine and contributes to interbody fusion of the lateral mass joint.

Introduction

In the subaxial cervical spine, each level is composed of three columns. The bilateral facet joints and lateral masses along with the anterior vertebral body and intervertebral discs form the intervertebral joints and the three-column framework of the cervical spine. In the three-column spine framework, both lateral masses are important in maintaining the stability of the cervical spine, as they carry 64% of the load.[1–4] The lateral masses also play an important role in limiting excessive flexion, extension, and rotation of the cervical spine.[1–6]

Pathologies of a lateral masses due to trauma, tumors, and surgery, could lead to bone destruction and biomechanical changes of the cervical spine. Their treatment includes lesion resection and internal fixation. However, the resulting bone defect of a lateral mass is often neglected, resulting in difficulty in bone fusion.

Therefore, we designed a subaxial lateral mass prosthesis to achieve lateral mass joint fusion by implanting the prosthesis along with granular bone. Finite element analysis and computer modeling and simulation were used to reveal biomechanical changes in different motion states in the model. In this study, finite element analysis was performed to analyze the stability of the C3–C7 cervical spine after a subaxial lateral mass prosthesis implantation.

Materials And Methods

Materials and software

One healthy volunteer was selected. The inclusion criteria were as follows: aged 20–30 years; height. 165–175 cm; and weight. 55–70 kg. This study was approved by the institutional ethics committee, and the volunteer signed an informed consent form.

Cervical magnetic resonance imaging and radiography were performed to exclude any prior surgical history and cervical diseases, such as cervical disc herniation, spinal stenosis, cervical deformity, fracture, tumor, infection, and tuberculosis, and there was no history of cervical trauma or surgery. Cervical computed tomography examination was performed with a scanning range of C0-T1 and scanning-layer spacing of 0.625 mm. Digital Imaging and Communication in Medicine data were obtained. Mimics (Version 13.1, Materialise HQ Technologielaan, Leuven, Belgium; Geomagic Studio 12.0; Geomagic Inc., North Carolina, USA; Hypermesh 2017; Altair Engineering Corp, Michigan, USA) and Ansys software, version 14.0 (Ansys Inc., 14.0, Canonsburg, Pennsylvania, USA) were used in the study.

Study group

The study group was divided into the following five groups: the intact C3–C7 group, lateral mass resection group (removal of the right C5 lateral mass), screw-rod fixation group (removal of the right C5 lateral mass and fixation with lateral mass screws), prosthesis implantation group (removal of the right C5 lateral mass, fixation with prosthesis and lateral mass screws and rods, as well as prosthesis implantation with granular bone), and prosthesis fused group (removal of the right C5 lateral mass, fixation with prosthesis and lateral mass screws, and bone fusion with the prosthesis).

3D model reconstruction

Mimics was used to reconstruct 3D models of the C3–C7 cervical spine from DICOM data, and the data were exported in the Standard Template Library (STL) format. Then, the STL file was imported into Geomagic Studio for trimming, repair, noise reduction, and surface generation. Ligament, disc, endplate, facet joint, and other models were further added.

The right C5 mass was excised based on the intact C3–C7 cervical model, and the geometric model construction and assembly of the lateral mass prosthesis, screw, and rod were performed.

The subaxial lateral mass prosthesis was divided into two parts: the first part was the anterior bone graft column that was used to fill the autogenous bone and to support the defect between the lateral mass, and the second part was the rear fixing plate, which was attached to the adjacent lateral mass for screw implantation. The device is composed of titanium alloy (Ti6Al4V). The anterior bone graft column has 13, 15, and 17 mm tall for different sizes of patients. Its articular surfaces are 41 degrees to the posterior fixation plate (Fig. 1A-C).

Finite element meshing

The geometric model was imported into Hypermesh for mesh construction (Fig. 2A-C, 3A-D). Then, it was imported into Ansys 14.0 to set the finite element mesh attributes, material properties, load application, and boundary conditions, and for computational analysis.

For the meshing of the five groups of cervical models, the vertebral body, endplate, intervertebral disc, and intervertebral joint adopted solid units of tetrahedral TetMesh Tet4 Element. The disc structure was divided into hexahedral mesh elements (IsoMesh Hex8 Element). A two-node nonlinear Spring unit (1D Spring) was adopted for each ligament. The prosthesis and articular surface were set as a contact in the implant model and as a commonnode fusion in the fusion model. The number of elements and the number of nodes in each group are shown in Table 1.

Table 1
The number of elements and nodes in each group

Parameters	Intact group	Lateral mass resction group	Screw-rod-fixation group	Prothesis implantation group	Prothesis fusion group
Nodes	87968	111018	122790	131709	130515
Elements	275989	398199	446047	483512	483512

Material properties

Based on published data,[8, 22–25] we set the values of the properties of the materials as shown in Table 2 and Table 3.

Table 2
Material parameters of each structure of cervical spine

Item	Elastic modulus (MPa)	Poisson's ratio
Cortical bone	12000	0.29
Cancellous bone	450	0.29
End plate	500	0.40
Posterior element	3500	0.29
Annulus	3.4	0.40
Nucleus	1.0	0.499
Facet cartilage	10	0.30
Bone in the implant	450	0.29
Prothesis and screw as well as rod(Ti6Al4V)	110000	0.34

Table 3
Parameter table of nonlinear spring stiffness of cervical ligaments

Item	S:F(mm:N)	Range(mm:N)
anterior longitudinal ligament	9:210	(5–13):(100–300)
posterior longitudinal ligament	10:80	(0–20):(0-160)
ligamentum flavum	6:90	(5–7):(20–150)
capsular ligament	10:300	(5–14):(170–460)
intertransverse ligament	25:400	(10–40):(360–500)
interspinous ligaments, supraspinous ligament	7:35	(5–9):(35–39)

Boundary and loading conditions

(1) The lower surface of the C7 vertebral body was fixed and constrained. The models were limited in 6 degrees of freedom.

(2) The cortical bone, cancellous bone, upper and lower endplates, facet joints, and intervertebral discs were assumed to be isotropic, uniform, and continuous linear elastic materials.

(3) Ligaments were assumed to be nonlinear spring elements with only tension.

This study focused on the biomechanical properties of the study groups under six different motion states: flexion, extension, right and left lateral bending, and right and left rotation. According to the published literature, the weight of the head is 50 N, and the motion torque was 1.0 N.m.[8] The model predictive control function was used to couple the upper surface of the C3 vertebral body to a reference point, and the head weight and torque values were applied to simulate the structural stress under the conditions of flexion, extension, lateral bending, and rotation.

Model correctness verification

According to published parameters,[7–10] the upper surface of the C3 vertebral body in the intact group was subjected to the same load and constraints, and six types of motion (flexion and extension, right and left lateral bending, and right and left rotation) were simulated. The ROM values under various motion states were obtained and compared with the data of Panjabi et al. and Zhang et al.[7–10]

Results

Model correctness verification

The trend and value of the ROM of the models obtained in this study were consistent with the results of previous studies (Table 4, Fig. 4); [7–10] hence, the cervical models were considered to be correct.

Table 4
Table 4 ROM Comparison (°)

Level	Present study			Panjabi et al			Zhang et al		
	Flexion and extension	Lateral bending	Axial Rotation	Flexion and extension	Lateral bending	Axial Rotation	Flexion and extension	Lateral bending	Axial Rotation
C3-C4	7.31	3.59	5.08	8.2 ± 5.1	4.9 ± 3.4	6.5 ± 1.8	9.11	3.16	4.10
C4-C5	6.55	3.17	5.16	9.7 ± 4.9	4.6 ± 2.9	6.8 ± 2.8	7.98	2.77	4.30
C5-C6	6.73	2.99	5.33	10.3 ± 6.0	4.5 ± 2.7	6.9 ± 2.5	7.92	2.56	4.89
C6-C7	6.12	2.83	5.50	8.0 ± 4.9	4.2 ± 3.4	5.4 ± 2.0	7.41	2.35	4.89

ROM

After the resection of the right C5 lateral mass, the ROM increased to varying degrees in each motion state. ROM increased significantly for right lateral bending and left and right rotation by 57.4%, 75.9%, and 101.4%, respectively, compared with those of the intact group. Especially, the increase of ROM in the right bend state increased by approximately one time.

The ROM of the screw-rod fixation group was significantly reduced in each motion state compared to that of the intact group, with a decrease of -49.0–26.1%.

After removing the lateral mass, and performing fixation with screws and rods, and prosthesis implantation, the ROM decreased significantly under each motion state compared to those of the intact group, and ranged from − 56.3% to -31.9%.

The difference between the prosthesis implantation group and screw-rod fixation group in the state of flexion, extension, and left and right rotation was not significant, with a difference of < 5%. However, in the left and right bending states, compared to the screw-rod fixation group, the ROM in the prosthesis implantation group continued to decrease to a value of − 8.3% and − 25.6%, respectively. No significant difference was observed in the ROM before and after prosthesis fusion (Fig. 5A-B).

Prosthesis von mise stress

After the lateral mass prosthesis was implanted, the peak stress of the prosthesis was 7.75–34.06 MPa, especially under conditions of flexion, right lateral bending, and left and right axial rotation.

When the prosthesis reached fusion, the stress of the lateral mass decreased slightly compared to that before fusion, especially in the right bending state, which decreased by approximately 19.4% (Fig. 6A-B).

Screw-rod von mises stress

The peak stress of the left screw and rod in the screw-rod fixation group ranged from 16.68 to 70.79 MPa and that of the right screw and rod ranged from 17.70 to 92.97 MPa.

In the prosthesis implantation group, the peak stress of the left screw and rod ranged from 9.77 to 59.06 MPa and that of the right screw and rod ranged from 8.73 to 32.13 MPa.

In the fusion group, the peak stress of the left screw and rod ranged from 9.85 to 59.14 MPa and that of the right screw and rod ranged from 8.89 to 32.67 MPa.

Compared to the screw-rod fixation group, the stress of the screw and rod was reduced in multiple motions after implantation (except for the left screw and rod under extension). The stress increment of the left and right screws and rods was − 65.1–4.0% and − 82.7–43.8%, respectively. The stress reduction of the right screw-rod system was more obvious than that of the left, especially during right lateral bending, and in left and right rotations.

Before and after the fusion of the prosthesis, the stress on the screw and rod changed minimally (Fig. 7A-D).

Discussion

The lateral mass is an important component of a vertebra that maintain stability. The morphology of a subaxial lateral mass is different from that of the lumbar spine: larger articular processes and isthmus, together with the gradual facet surface, constitute the unique columnar lateral mass structure of the cervical spine[11–13]; thus, it bears more longitudinal load.[14]

The cervical nerve roots originate from the cervical cord and exit the spinal canal through the intervertebral foramina in front of the lateral masses. Therefore, to expose a dumbbell tumor originating from the nerve root during surgery, it is necessary to resect the whole or part of the lateral mass.[15] In addition, primary spinal tumors often directly involve the lateral mass, and their treatment even requires total en bloc spondylectomy (including the vertebral body, lateral mass, lamina, transverse process, and other structures). In addition, infection and trauma may lead to bone destruction of lateral masses. After lateral mass destruction of > 50%, cervical stability decreases significantly.[1, 5, 6]

The main internal fixation method used to maintain posterior cervical stability is the fixation of screws, such as lateral mass screw and pedicle screw. Although screw and rod fixation can stabilize the cervical spine and reduce the ROM promptly, stress was not low in the screw-rod fixation group compared to those in other groups, indicating that the screw and rod play an important role in maintaining stability, but are likely to be subjected to high stress-induced instrument failure insidiously. Although pedicle screw implantation with the strongest biomechanical properties can and bear more load and have four times the pull force of the lateral mass screw [16, 17], it cannot reduce the stress of the instrument and carries a high risk of damaging surrounding artery and nerve tissue. In addition, although screw and rod fixation can provide prompt cervical stability, it does not compensate for the bone defect and it is difficult to attain the aim of lateral joint fusion; thus, the risk of long-term instrument failure due to fatigue is insidious. Even if supplemented with common posterolateral bone grafting, it is difficult to achieve bone fusion in time due to the lack of stress stimulation that caused bone graft resorption.

Therefore, our strategy uses a safer lateral mass screw fixation technique combined with lateral mass reconstruction and interfacet bone grafting. Considering the importance and safety of the lateral mass reconstruction, we designed the subaxial lateral mass prosthesis for interbody bone grafting, and its biomechanical superiority was verified using finite element analysis. First, after the lateral mass prosthesis implantation, the ROM was significantly reduced and the model was stable. Second, the weight above the prosthesis can be transmitted along the prosthesis, which is more consistent with the normal three-column transmission of the subaxial cervical spine, thus promoting bone fusion in the prosthesis. Third, it can significantly reduce the stress of the screw and rod.

Minimum ROM, optimal stability

Zdeblick et al., Raynor et al., and Cusick et al., examined the graded resection of facet joints and found that when more than 50% of a facet joint is removed, the displacement during flexion, extension, and rotation significantly increases, and torsional stiffness, shear strength, and the capacity to withstand compression-flexion loads is significantly reduced.[1, 3, 5] Similar results were found in our study, although we did not perform graded excision. The ROM significantly increased after lateral mass resection, especially in the right bending and rotation states, indicating that the lateral mass plays a significant role in limiting excessive movement in these directions.

Ji et al. conducted biomechanical experiments on seven cervical spine specimens and found that, based on unilateral pedicle screw and contralateral lamina screw fixation, the application of a bone graft to reconstruct the lateral mass can effectively reduce the ROM in all directions and could increase stability. However, the reconstruction type used was less stable than bilateral pedicle fixation without lateral mass reconstruction during lateral bending and axial rotation.[18] What was different in our study was the addition of a prosthesis based on bilateral fixation. Compared with the screw-rod fixation group, the ROM after prosthesis implantation was reduced in all movements, especially − 8.3% and − 25.6% during the left and right bending movements, respectively. This may be due to the improvement in the overall structural stiffness of the adjacent segments through the support of the bone graft column and the fixation of the posterior fixation plate.

Hence, the use of lateral mass prostheses can achieve optimal cervical stability based on screw fixation. Simultaneously, this early spinal stability provides a good mechanical environment for subsequent bone fusion.[19]

Prosthetic load sharing promotes interbody fusion

In various movement states, the lateral mass prosthesis shared the weight above the prosthesis, especially in flexion, right bending, and rotation. This further indicates that the lateral mass structure can limit excessive movement and maintain stability in these movements. Similar to interbody fusion during discectomy, we implanted autologous granular bone into the prosthesis. The body's weight applied to the prosthesis fully stimulates the bone graft in the prosthesis[20] and promotes intervertebral fusion of the interfacet space, which has a higher fusion rate than that of a posterolateral bone graft.[21]

After fusion was achieved, the stress of the prosthesis decreased in the right bending state compared to that before fusion. This may have occurred because the fused bone was tightly attached to the adjacent facet, and the weight over the prosthesis was shared by the fused bone in the prosthesis during right bending. This suggests that the reduced stress of the prosthesis after bone fusion helped to reduce the risk of subsidence.

Reduce the stress of the screw and rod

Compared to the fixation group, the stress on both screws and rods was reduced after prosthesis implantation. This is mainly due to the load-sharing effect of the prosthesis, which transferred the weight from above the prosthesis to along the prosthesis, resulting in stress reduction on the bilateral screw and rod in various motion states (except the left screw and rod during extension).

The stress reduction on the right screw and rod was significantly greater than that on the left screw and rod, especially during the right bending and left rotation, which indirectly indicated that the prostheses could significantly limit these movements and reduce the load on the right screw and rod.

Before and after the fusion of the lateral mass prosthesis, no significant difference was found in the force of the screw and rod mainly because the sliding trend of the prosthesis was limited by the relatively stable and reliable connection between the screw and rod set by the finite element model.

Traditional specimen experiments have only compared the ROM, which cannot reflect the advantages of load sharing and stress reduction of the screw and rod system. Our finite element analysis study properly reflects the above advantages and is a practical analysis of the reconstruction of the lateral mass structure. However, it cannot reflect the fatigue and maximum failure values; thus, the investigation of the overall stability of the model is not comprehensive and can only be used as a supplement to the in vivo experiment.

Conclusion

This study theoretically demonstrates the role of subaxial lateral mass prostheses in load sharing and reduction of stress on the screws and rods. In these five models, the lateral mass prosthesis combined with screw and rod fixation is the most reliable method for cervical stability after bone fusion.

Abbreviations

range of motion (ROM)

Standard Template Library (STL)

Declarations

Ethics approval and consent to participate: This study was approved by the ethics committee of Xuanwu Hospital, Capital Medical University. Written informed consent was obtained from the participant.

Consent for publication: Not applicable

Availability of data and material: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: Qiang Jian wrote the manuscript. Zhenlei Liu and Wanru Duan contributed significantly to the revision. Fengzeng Jian and Zan Chen contributed to the conception of the study. Xuefeng Bo contributed to interpretation of data and software used in the work.

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Figures

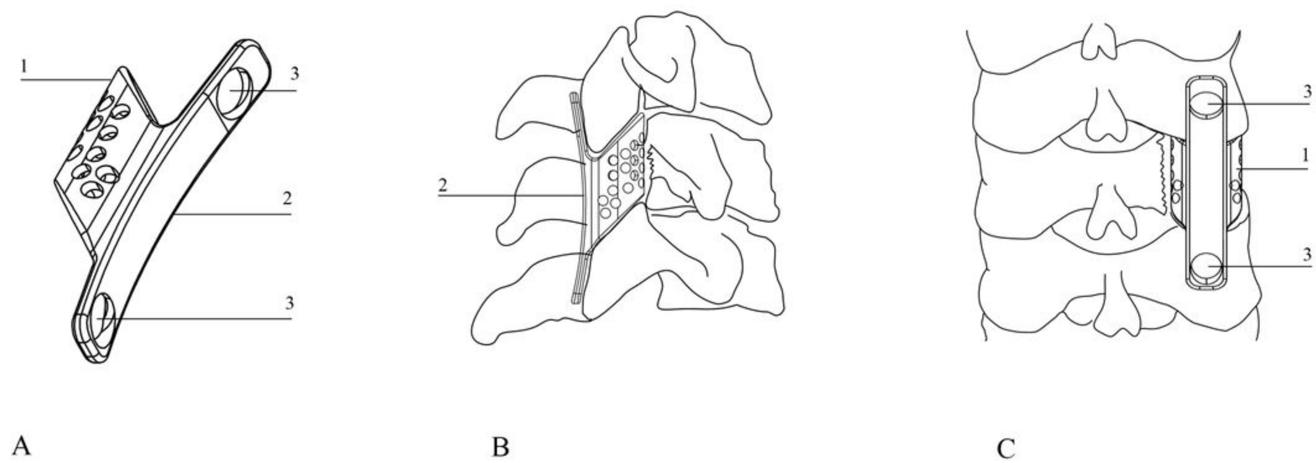

Figure 1

Schematic diagram of the subaxial lateral mass prosthesis (A) Oblique view of the prosthesis. (B) Lateral view of the prosthesis after implantation. (C) Posterior view of the prosthesis after implantation.

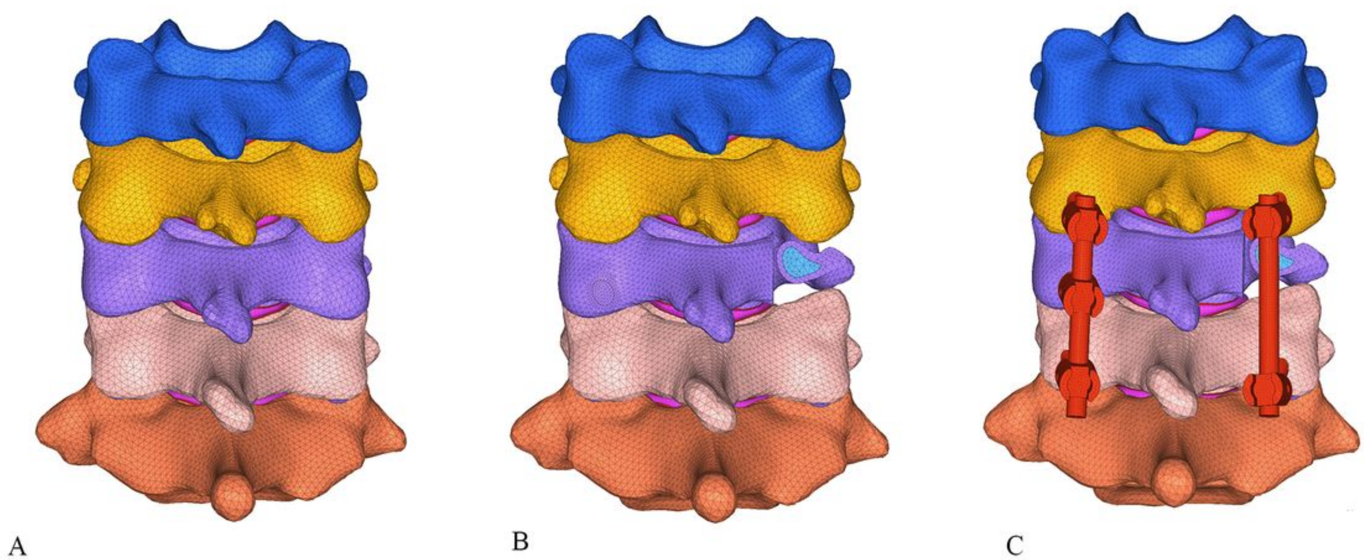

Figure 2

Posterior view of the finite element model of the intact group, lateral mass resection group, and screw-rod fixation group

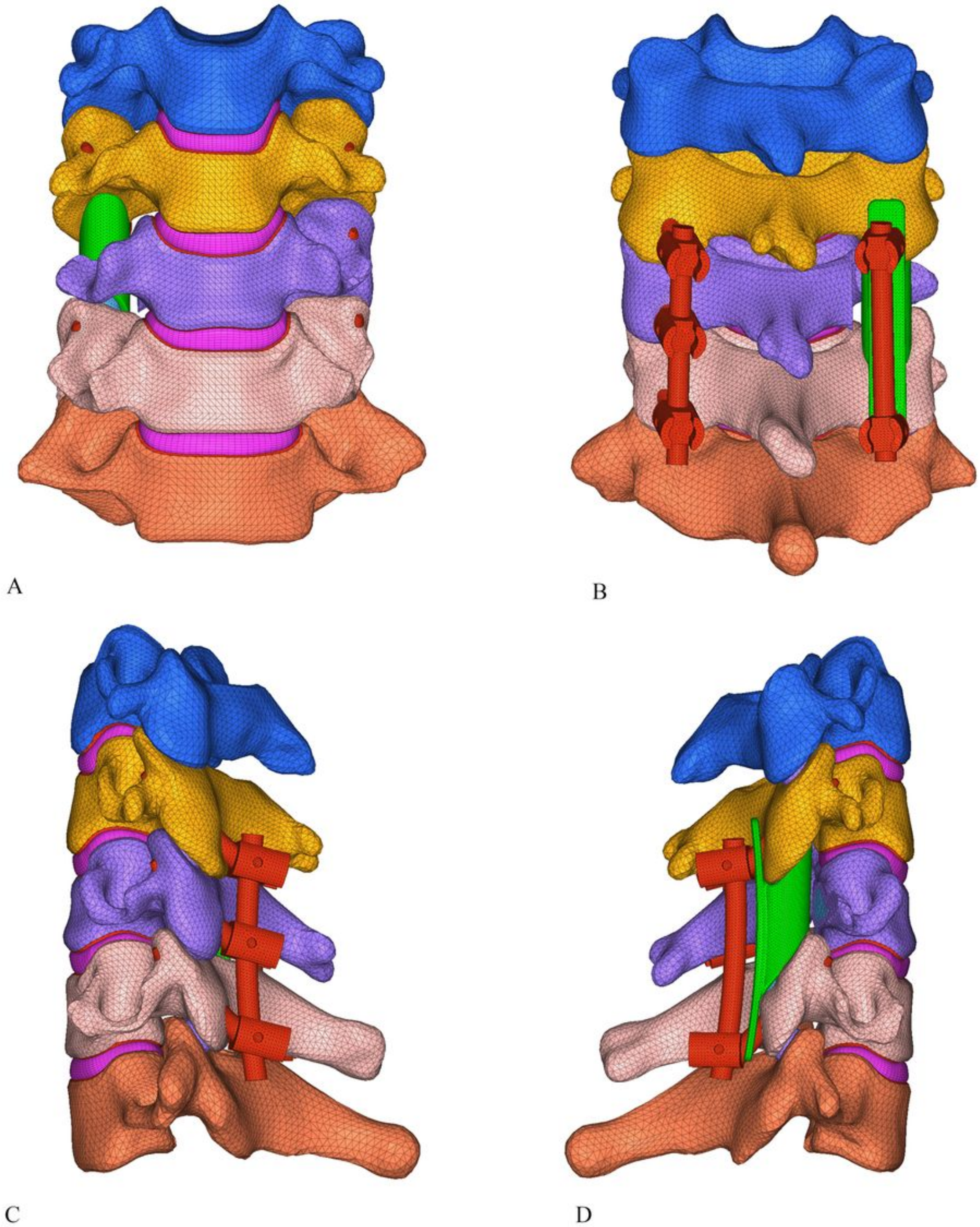

Figure 3

Finite element model of the prosthesis implant group and fusion group (A) Elevation view. (B) Rear view. (C) Left view. (D) Right view

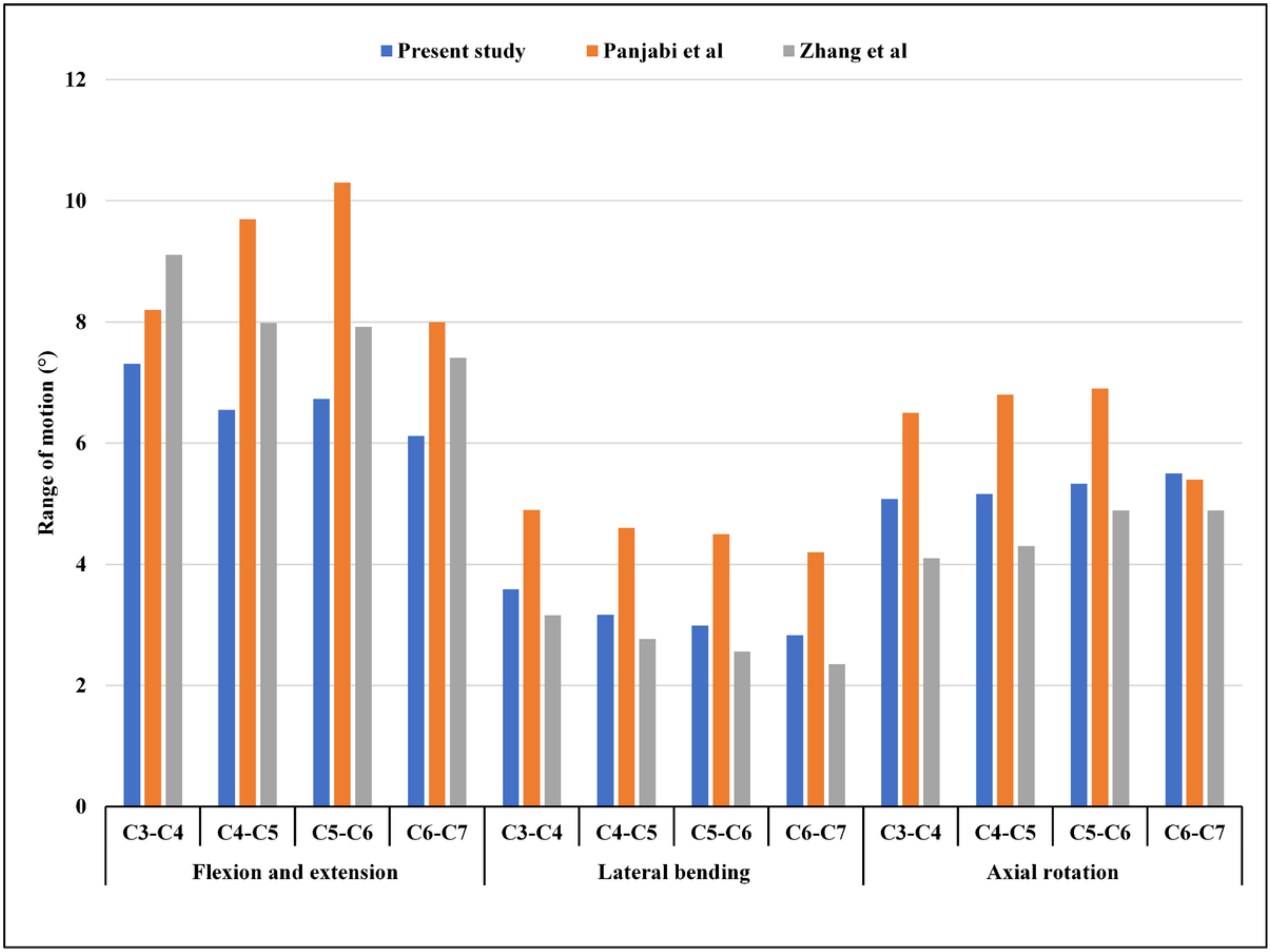

Figure 4

Comparison and verification of the intact model in this study and data from previous studies

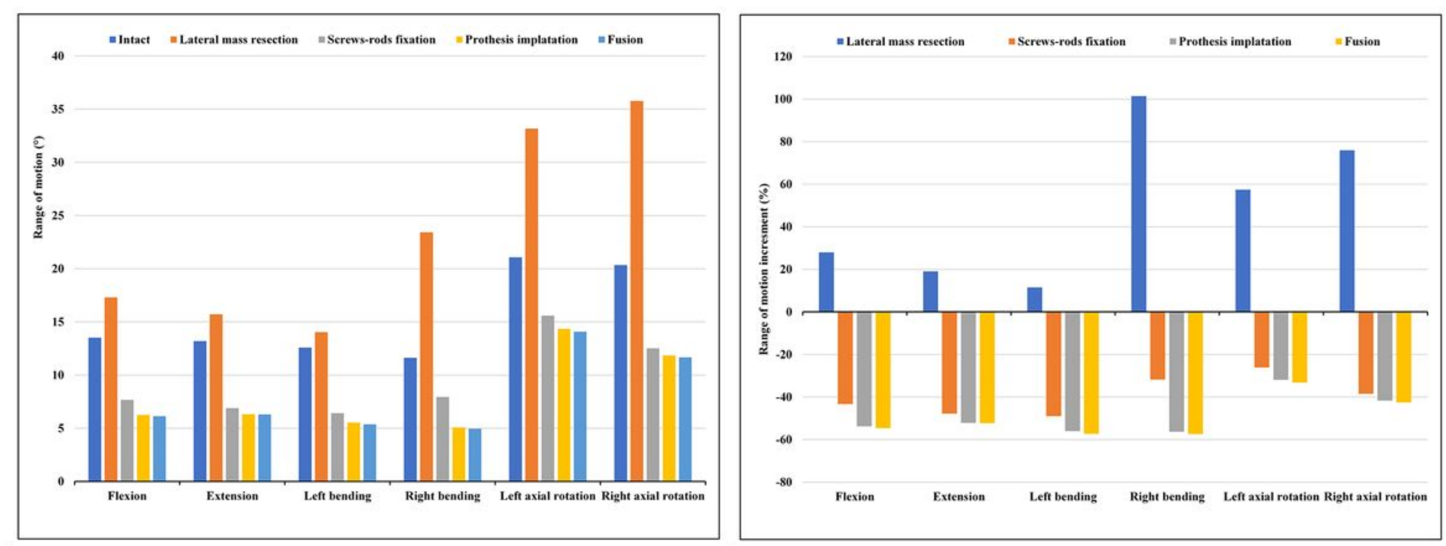

Figure 5

Range of motion of each group (A) Comparison of the range of motion of each group. (B) Comparison of the incremental changes in the screw-rod fixation group, prosthesis implantation group, and fusion group, relative to the intact group.

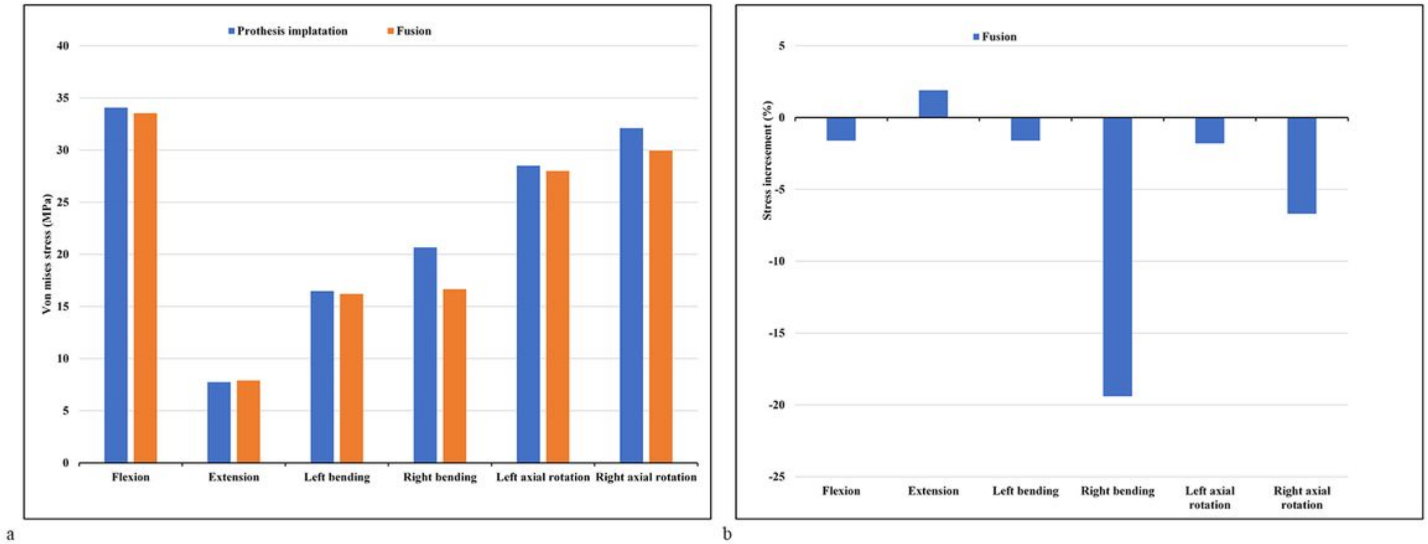

Figure 6

Lateral mass prosthesis stress (A) Comparison of the prosthesis stress before and after prosthesis fusion. (B) Prosthesis stress increment in the fusion group in comparison to the prosthesis implantation group.

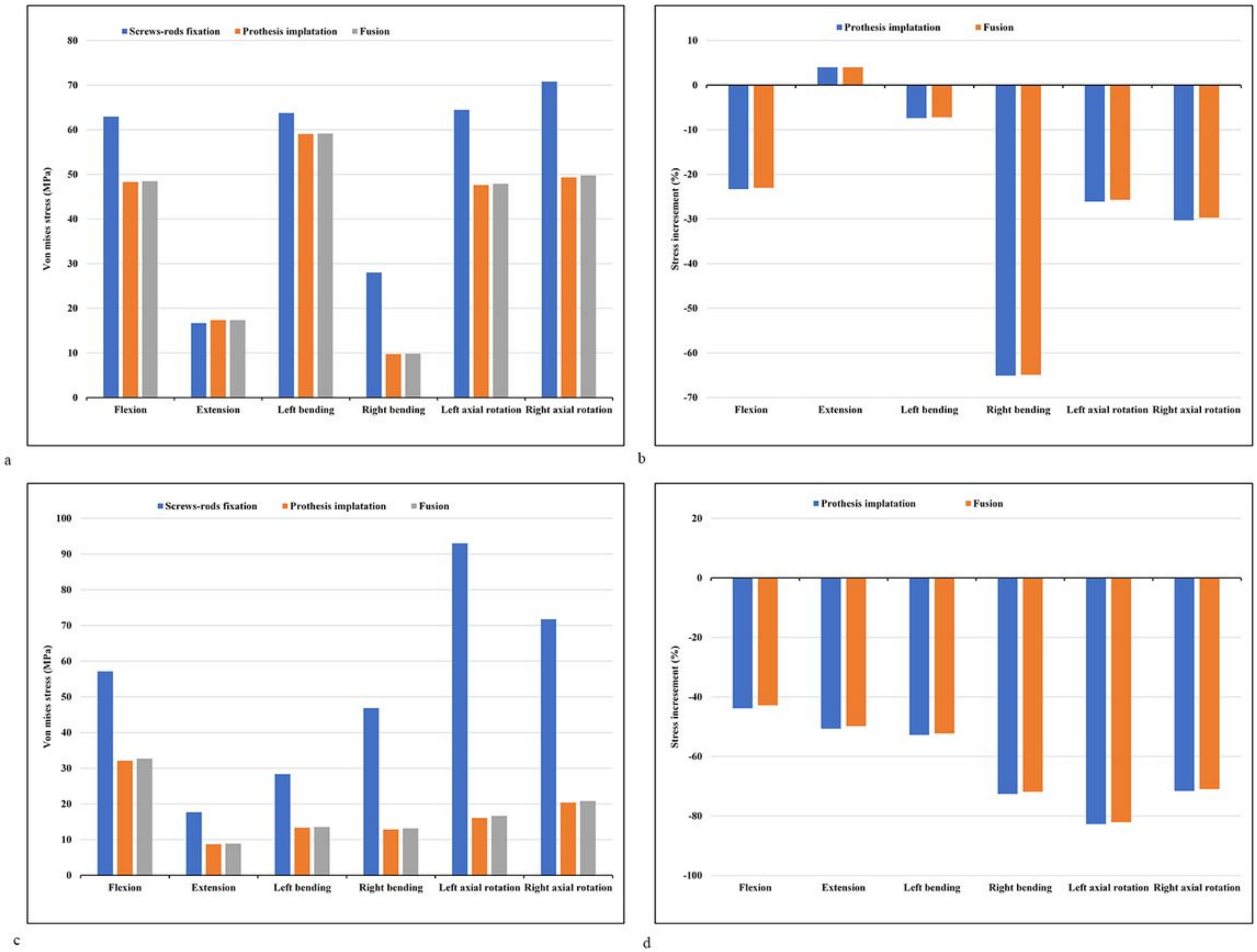

Figure 7

Screw-rod stress (A) Left screw-rod stress. (B) Left screw-rod stress increment of the prosthesis implantation and fusion group compared with that of the screw-rod fixation group. (C) Right screw-rod stress. (D) Right screw-rod stress increment of implantation and fusion group compared with that of the screw-rod fixation group.