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A finite element study on posterior short segment fixation combined with unilateral fixation using pedicle screws for stable thoracolumbar fracture

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Abstract

The objective of this study was to use finite element models to investigate the biomechanics of stable thoracolumbar burst fracture repair using unilateral short-segment fixation and 4 alternate pedicle screw systems.

Four posterior pedicle screw systems were compared for unilateral short-segment fixation using finite element models: intermediate bilateral short pedicle screw fixation, intermediate bilateral long pedicle screw fixation, intermediate unilateral short pedicle screw fixation, and intermediate unilateral long pedicle screw fixation. We compared range of motion (ROM), von Mises stresses on the implants, and stress on the intervertebral discs superior and inferior to the injured vertebra during simulated spinal movements.

There were no significant differences in ROM, von Mises stress, or intervertebral disc stress among the 4 intermediate pedicle screw fixation techniques for all spinal movements evaluated. In addition, there were no consolidated trends depicting beneficial differences between the short and long screw models, or between the unilateral and bilateral screw models.

ROM, von Mises stress, and intervertebral disc stress are the same across the 4, posterior short-segment fixation techniques evaluated using finite element models. The simplest technique—posterior short segment fixation combined with intermediate unilateral short pedicle screw fixation—is a feasible treatment strategy for stable thoracolumbar fracture.

Abbreviations: 3D = 3-dimensional, CT = computed tomography, DICOM = Digital Imaging and Communications in Medicine, L1 = lumbar vertebra 1, ROM = range of motion, T11 = thoracic vertebra 11.

Keywords: biomechanical analysis, finite element analysis, thoracolumbar stable burst fracture, unilateral pedicle screw fixation

1. Introduction

Stable thoracolumbar burst fractures are vertebral fractures caused by compression stress that compromises the anterior and middle columns but not the posterior column of the spine. In more recent years, stable thoracolumbar burst fractures are treated via posterior short-segment fixation combined with intermediate pedicle screws, with good clinical outcomes reported.[1–5] This approach offers many advantages[6–8]: it disperses the stress on the implants to prevent internal fixator breakage; it helps to recover the continuity for all 3 spinal columns; and it provides 3-point fixation by placing screws at the level of the fracture, thereby reducing the cantilever and parallelogram effects. However, compared with conventional methods without the use of intermediate pedicle screws, this technique requires a longer operative time, is frequently associated with higher amounts of intraoperative hemorrhage, and greater interference from the fractured bone fragments. Furthermore, there has been no research investigating the differences in treatment benefits using 4 different intermediate pedicle screw techniques with unilateral short-segment posterior fixation.

To this end, the aim of the present study was to examine various intermediate pedicle screw systems for posterior short-segment fixation using finite element models of the thoracolumbar region spanning thoracic vertebra 11 (T11) to L2 with a fractured lumbar vertebra 1 (L1). Through biomechanical comparisons, we evaluated the application value and feasibility of intermediate unilateral pedicle screw fixation in clinical treatment compared with more complex approaches.

2. Materials and methods

2.1. Creation of the normal finite element model

We selected a healthy, 28-year-old, male volunteer with no history of trauma or fracture to create a normal finite element model, and confirmed an absence of spinal lesions on radiography. The volunteer was recruited at the Hebei Medical University Third Affiliated Hospital in March 2016, and signed the volunteer informed consent. The study was approved by the Ethics Committee of the Hebei Medical University Third

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SY and WX contributed equally to this work.

The authors report no conflicts of interest.

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Table 1

Material properties of the finite element models.

Structure	Elastic modulus/MPa	Poisson ratio	Sectional area/mm^2
Cortical bone	12,000	0.3	
Cancellous bone	100	0.3	
Annular fiber	450	0.3	
Nucleus pulposus	1	0.49	
Anterior longitudinal ligament	7.8	0.3	75.9
Posterior longitudinal ligament	10	0.3	51.8
Ligamentum flavum	15	0.3	78.7
Interspinous ligament	10	0.3	36.3
Supraspinous ligament	8	0.3	75.7
Intertransverse ligament	10	0.3	2
Capsule ligament	8	0.3	102
Pedicle screws and rods	110000	0.3	

Table 2

Comparison between the current intact model and models from previous studies.

	Mean value of ROM (°)		
	Present study	Pflugmachers study[15]	Changqing Li's study[6]
Flexion	5.9	5.3±1.0	4.6±0.6
Extension	4.6	5.7±1.0	4.5±1.1
Left axial rotation	2.6	2.1±0.5	3.2±0.8
Right axial rotation	2.1	2.1±0.5	3.2±0.6
Left lateral bending	4.5	4.3±0.6	4.6±0.7
Right lateral bending	5.3	4.3±0.6	4.8±0.5

ROM = range of motion.

Affiliated Hospital, Hebei, China. We used a 64-slice spiral computed tomography (CT) scanner (Siemens, Erlangen, Germany) to scan the subject's T11 to L2 vertebral levels at a tube voltage of 120 kV, tube current of 200 mA, slice thickness of 1 mm, and interlayer spacing of 1 mm. The image data were exported in Digital Imaging and Communications in Medicine (DICOM) format.

The DICOM images were imported into the interactive medical imaging control system Mimics 14.0 (Materialise, Leuven, Belgium) to create 3-dimensional (3D) vertebral models of the T11 to L2 region. The models were imported into the reverse engineering software Geomagic Studio 12.0 (Geomagic, North Carolina) to produce more elaborate 3D images using handling methods including tailoring, expanding, and Boolean subtraction. The 3D images were then divided into plane-mesh models and endowed with material properties, including elastic modulus and Poisson ratio, by re-importing into the Mimics program (Table 1).[9,10]

The models of the intervertebral discs were built using SolidWorks (Dassault Systemes, S.A, Paris, France). The nucleus pulposus and annular fibers were built separately, as their textures differ. Three intervertebral disc models, T11-T12, T12-L1, and L1-L2, were constructed separately but identically.[11,12] Models of the ligaments (anterior longitudinal ligament, posterior longitudinal ligament, ligamentum flavum, interspinous ligament, supraspinous ligament, intertransverse ligament, and capsule ligament) were built using Workbench (Ansys; Pittsburgh, PA).[13,14] At the end, the various portions of the model were combined to establish a 3D finite element model of a normal T11 to L2 thoracolumbar spine.

2.2. Range of motion of the model

To validate the rationality of the model, 10 N/m of torque and a compressive load of 150 N were applied to the upper surface of the T11 vertebra to simulate flexion, extension, and bending of the vertebra under loading. The mean range of motion (ROM) value was measured during each motion type, and results were compared with previously published results obtained from biomechanical experiments and finite element analyses (Table 2).[6,15]

2.3. Creation of the thoracolumbar stable burst fracture finite element model

The fractured vertebra model was drawn using Geomagic Studio. A V-shaped osteotomy was performed at the middle one third of the anterior border and the upper two thirds of the anteroposterior diameter of the normal L1 vertebra model. The model was then re-imported into the Mimics program, and the plane-mesh models were divided and smoothed.[16,17] Thus, the thoracolumbar stable burst fracture 3D finite element model was established.

2.4. Creation of the pedicle screw-and-rod finite element model

Pedicle screws (6.5 × 45 mm; 6.5 × 30 mm) and rods (6 mm) were drawn using SolidWorks software using sizes based on the size of the 3D finite element models. The insertion points were selected using the herringbone crest vertex technique, and an angle of 5° to 10° was confirmed by the Arbeitsgemeinschaft für Osteosynthesefragen/Association for the Study of Internal Fixation principles of internal fixation. Thus, the 3D finite element model of thoracolumbar stable burst fracture combined with rods and pedicle screws was established.

2.5. Fixation models

The fractured vertebra was fixed at the vertebral pedicles on the left side only. Four fixation models were made, each using a different combination of screws. Pedicle screws inserted into the vertebral bodies of T12 and L2 were 6.5 × 45 mm (1 screw or 2 screws in each vertebra for unilateral or bilateral fixation, respectively). Model A refers to bilateral intermediate fixation with 4 long pedicle screws (in T12 and L2) and 2 short pedicle screws (6.5 × 30 mm; in L1); model B refers to bilateral intermediate fixation with 6 long pedicle screws (2 in each of T12, L1, and L2); model C refers to unilateral intermediate fixation with 4 long (T12, L2) and 1 short pedicle screw (L1); and model D refers to unilateral intermediate fixation with 5 long pedicle screws (2 in each of T12, L2 and 1 in L1; Fig. 1).

2.6. Boundary and loading conditions

Ansys was used to assess boundary and loading conditions and simulations of spinal movement. The L2 vertebral body was assumed to be fixed, and its inferior and posterior structures were set as the boundaries without displacement or rotation in all directions. Spinal motions in the sagittal, coronal, and transverse planes were defined as flexion-extension, lateral bending, and rotation, respectively. According to the bearing capacity of the human body and previously published literature, an axial load of 500 N and a torque load of 15 N/m were applied

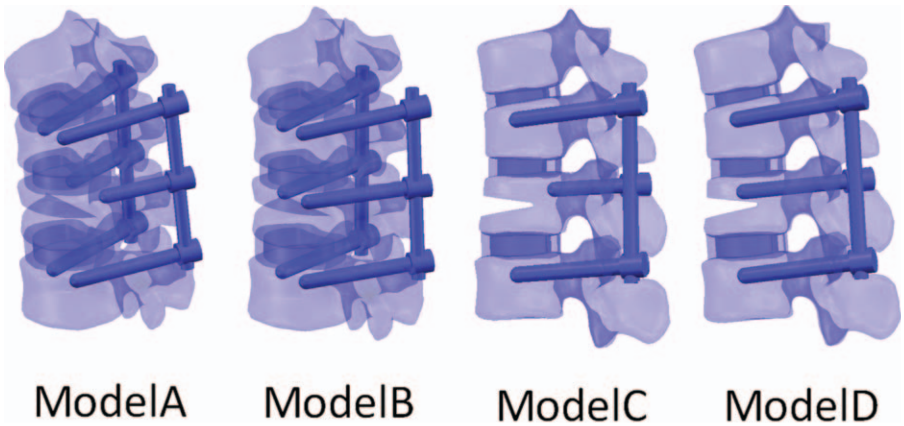

Figure 1. The T11-L2 finite element models.

to simulate flexion-extension, lateral bending, and rotation of the spine.[2,18–20] The axial load was applied to the upper surface of the T11 vertebra, and the torque load was applied to the center of the T11 vertebra.

2.7. Assessment of indices

We analyzed the ROM of the T11-L2 region, the von Mises stress nephograms of the pedicle screws and rods of the 4 fixation finite element models under 6 loading conditions (flexion, extension, left/right lateral bending, and left/right axial rotation), and the stress on the intervertebral discs superior and inferior to the injured vertebra. No statistical analysis was performed in this study, as only 1 subject was modeled.

3. Results

3.1. Range of motion

The maximum ROM values for the 4 fixation models are shown in Figure 2. Among the 4 models, model C showed the largest ROM in lateral bending on the left side and the largest axial rotation on the right side and model D showed the largest ROM in lateral bending on the right side and the largest axial rotation on the left side. The largest ROM in flexion and extension were observed in model A. The model with the maximum ROM under each loading condition had the lowest stability for this type of internal fixation. Although there were differences among the models, the differences were small, with none of the measurements >20% of the average. In addition, there were no consolidated trends between the models, such that we could not determine which model had better stability. The variations in intermediate pedicle screw techniques had no significant influence on the ROM.

3.2. Von Mises stress on the pedicle screws

The maximum values for von Mises stress in the 4 fixation models are shown in Figure 3. Among the 4 models, model C showed the maximum von Mises stress in flexion, extension, and left-side axial rotation; the maximum von Mises stress in right-side axial rotation was observed in model B. Model A showed the maximum von Mises stress in lateral bending.

In all types of motion, the maximum von Mises stress was observed in the juncture of the pedicle screws and the rods, except

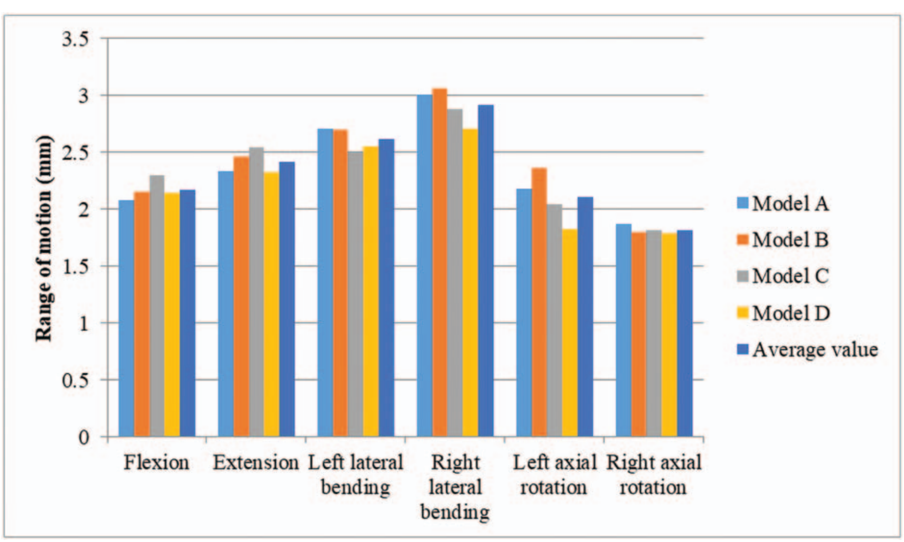

Figure 2. The maximum range of motion.

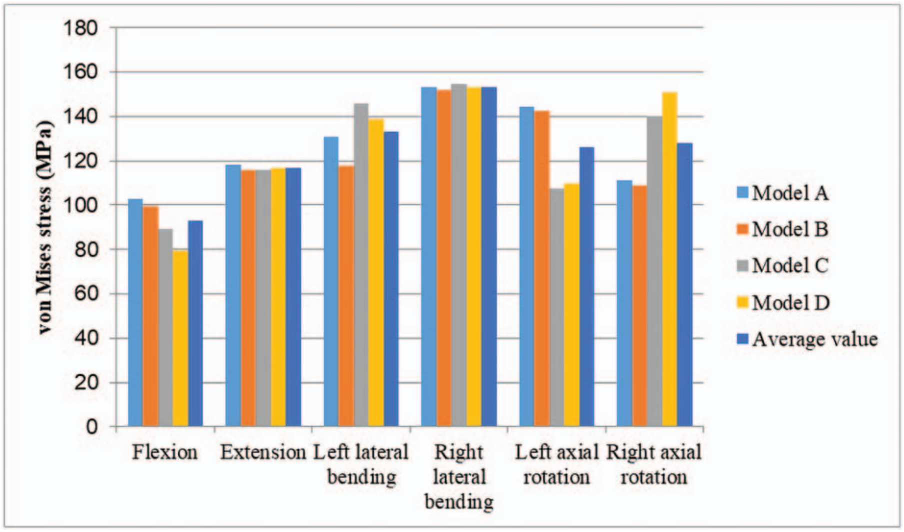

Figure 3. The maximum von Mises stress.

for in extension, for which stress was observed in the middle of the last pedicle screw (Fig. 4). During flexion, maximum von Mises stress occurred at the implant junctures. During left/right lateral bending, the maximum von Mises stress occurred at the lateral implant juncture of the vertebrae cephalad to the fracture level (Fig. 5). During left/right axial rotation, the highest von Mises stress occurred at the axial juncture of the implants in the fractured vertebrae; in model C and model D, during left-side axial rotation, the highest von Mises stress occurred at the left implant juncture of the vertebrae cephalad to the fracture level (Fig. 6). The model with the maximum von Mises stress under each loading condition had the lowest stability in this type of internal fixation.

Overall, although there were differences among the models, the differences were small and within 20% of the average values. Thus, none of the models showed superior stability.

3.3. Stress on the injured vertebral superior and inferior intervertebral discs

The maximum stress sustained to the intervertebral discs superior and inferior to the injured vertebra in each of the 4 fixation models is shown in Figure 7. The maximum intervertebral disc stress during lateral bending on the left side was observed in model C. The maximum intervertebral disc stress during extension and axial rotation on the left side were observed in model D. The maximum intervertebral disc stress during flexion and lateral bending on the right side were observed in model A. The maximum intervertebral disc stress during axial rotation on the right side was observed in model B. For each model, the stress associated with each loading condition may offer insight into how internal fixation can accelerate intervertebral disc degeneration. Again, there were no significant differences or trends among the models,

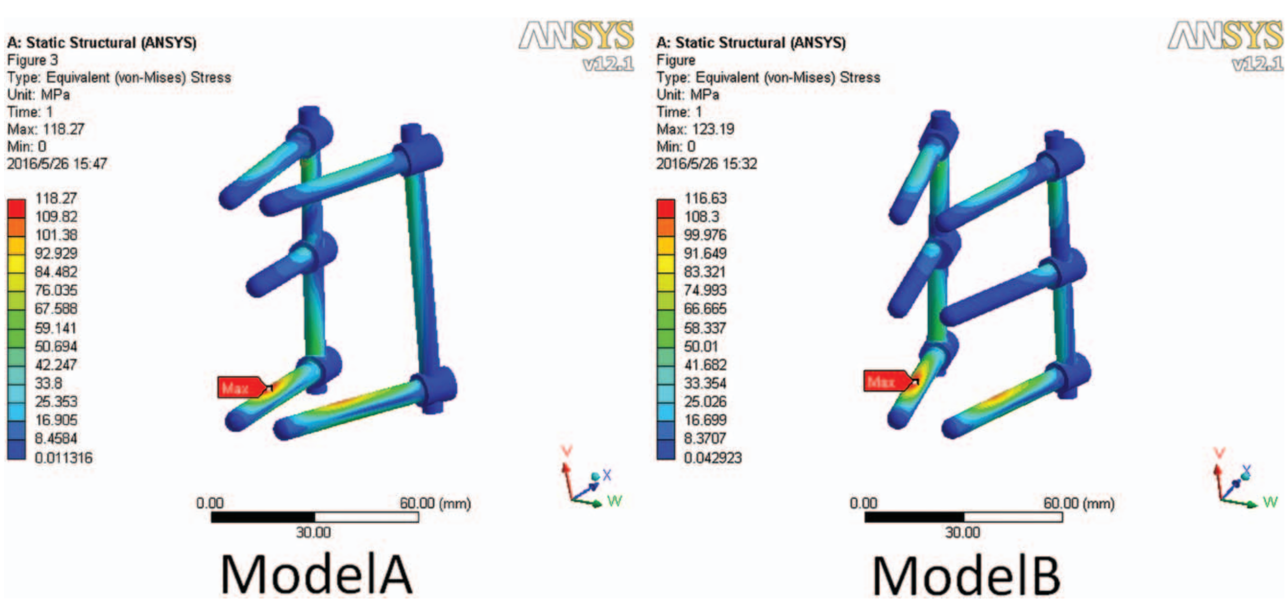

Figure 4. von Mises stress nephogram of model C in spine extension (A) and model B in spine extension (B).

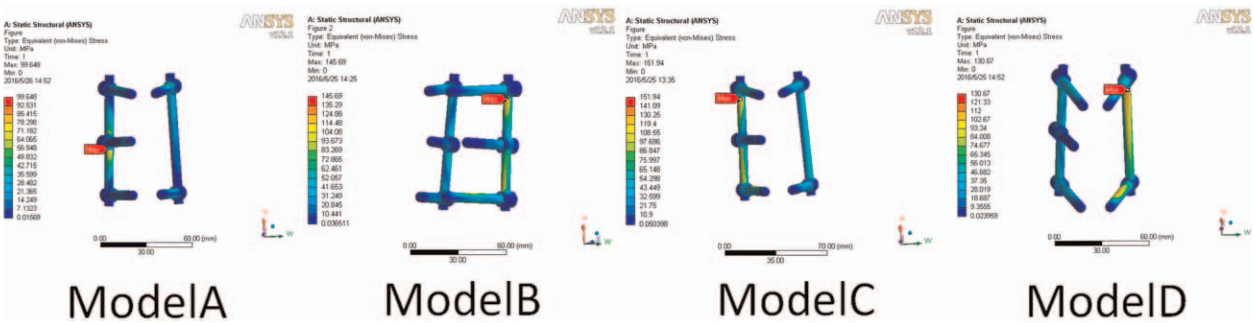

Figure 5. von Mises stress nephogram of model D in spine flexion (A), model A in left lateral bending (B), model D in right lateral bending (C), and model C in left lateral bending (D).

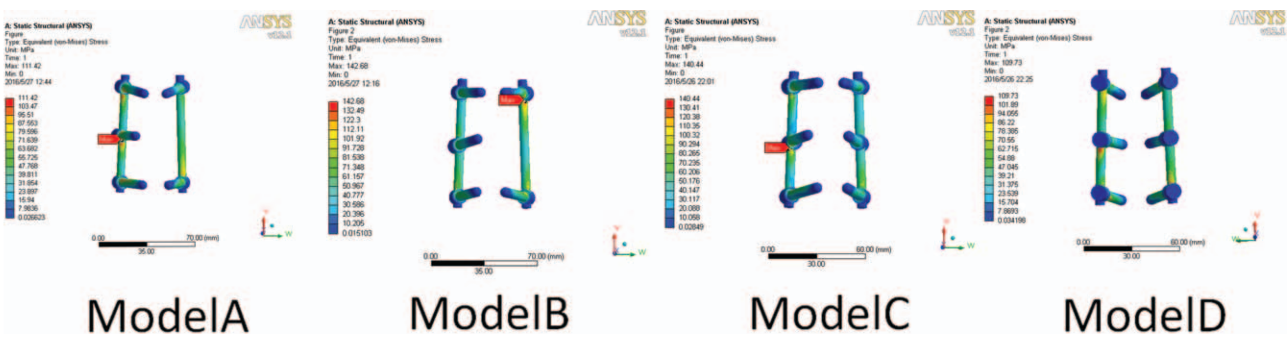

Figure 6. von Mises stress nephogram of model C in right axial rotation (A), model D in left axial rotation (B), model A in right axial rotation (C), and model B in left axial rotation (D).

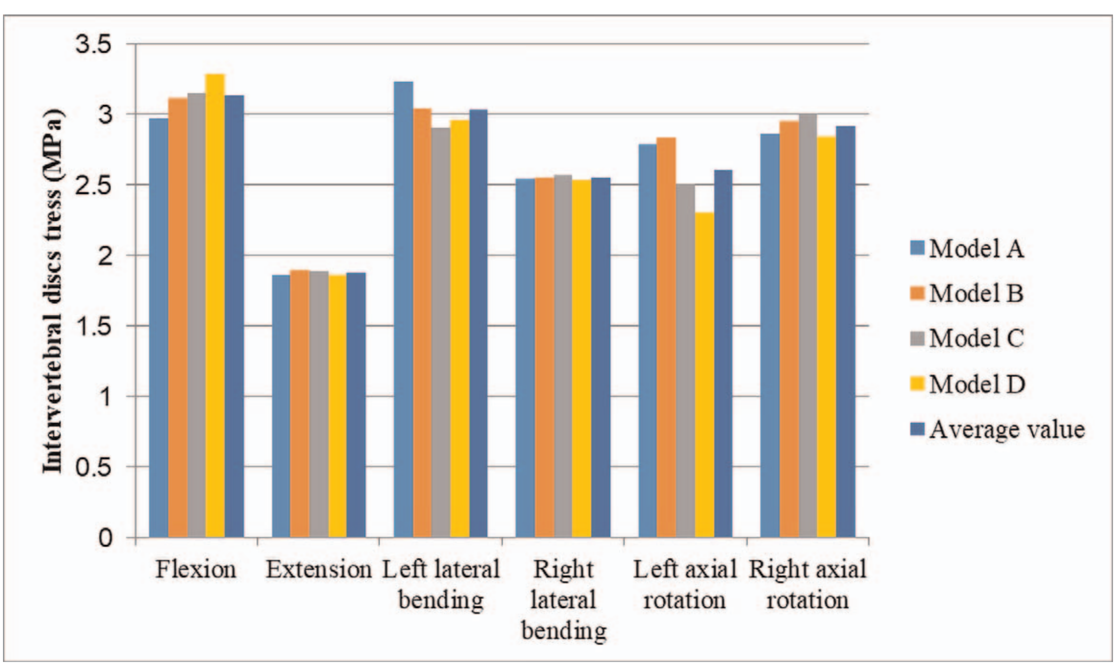

Figure 7. The maximum stress on the intervertebral discs superior and inferior to the injured vertebra in the 4 models.

suggesting that all 4 models had the same effect on the intervertebral discs.

4. Discussion

Thoracolumbar burst fractures can be treated using several posterior surgical techniques, and various biomechanical studies suggest that reinforcement of the fracture with a fracture-level screw combination can help to improve biomechanical stability in the region of the fractured joint.[2,4,7,8] Clinical evidence further suggests that such reinforcement in patients with thoracolumbar burst fracture provides better kyphosis correction, offers immediate spinal stability, more effectively restores fractured vertebral height, and allows for earlier ambulation[3,7]; however, no studies have compared the biomechanical properties among different pedicle screw fixation techniques, especially in posterior short-segment fixation. The purpose of the present study was to compare the biomechanical properties of posterior short-segment fixation with various intermediate pedicle screw techniques (bilateral vs unilateral, short screw vs long screw) using finite element models of human stable thoracolumbar burst fracture.

In the present study, the ROM and von Mises stress data did not differ among the 4 models during each movement evaluated. In addition, there was no consolidated trend among the 4 models. Therefore, we can conclude that intermediate unilateral short pedicle screw fixation (model C) could provide a similar level of stability as that of intermediate bilateral short pedicle screw fixation (model A) or intermediate bilateral or unilateral long pedicle screw fixation (model B and model D, respectively) in terms of withstanding the stress associated with flexion, extension, left/right lateral bending, and left/right axial rotation. In our analysis of the stress nephograms of the pedicle screws and rods, the maximum von Mises stress was observed at the same location in the unilateral screw and bilateral screw models. This stress concentration position is prone to implant breakage, and our results are consistent with clinical practice. The difference in the location of the maximum von Mises stress in the bilateral versus the unilateral pedicle screw models is $<20\%$, so we can conclude that the stress on the side without intermediate screw placement does not increase markedly due to contralateral placement of the pedicle screws. Compared with intermediate bilateral pedicle screw fixation, which is widely used in clinical practice, the use of intermediate unilateral short pedicle screw fixation could reduce operation time, intraoperative hemorrhaging, disturbance to the anterior and central columns, and the economic burden to the patient, while ensuring the stability of implants.

Fracture reduction and the reconstitution of spinal alignment using posterior instrumentation are frequently associated with a loss of correction over time, especially after removal of the implants. Some studies report that this loss of correction and kyphosis occur in the intervertebral disc and intervertebral space rather than due to collapse of the fractured vertebral body.[21–24] The bony loss of correction within the vertebral body is small, but collapse of the disc space eventually leads to a complete loss of segmental reduction and contributes to late kyphotic deformity.[21] Indeed, at follow-up, most patients show a collapsed intervertebral disc and intervertebral space.[25–27] Therefore, protecting the injured intervertebral disc from excessive axial stress is likely to be important for maintaining long-term correction. By analyzing the stress nephograms of the intervertebral discs, we found no significant difference among the 4 implant techniques. We can conclude that unilateral short pedicle screw fixation will not accelerate intervertebral disc degeneration by causing increased or uneven disc stress.

Finite element analysis is based on the construction of models using a single sample, and therefore no statistical analysis can be performed.[19,28] Although there is currently no standard with which to define the differences between models in terms of numerical computation, we considered that a difference of $>20\%$ would reflect "important" or "relevant" differences.[6] Finite element model construction can be based on data collected from CT scans of spinal clinical cases, and, although models constructed in this way will be highly targeted, more direct and involve less intermediate steps, there are insufficiencies, such as limitations in the original data source, a lack of general representative significance, a limited ability to control vertebral compression, and low repetition utilization rate. In the present study, the finite element models were constructed directly from original normal healthy human CT data and the fractured models were modeled based on these data. Using this method, we could exclude interference from factors such as osteoporosis and degeneration to ensure the reliability and universal significance of our findings.

Although the finite element analysis method is an effective method in biomechanical studies, it still cannot completely simulate human treatment comparisons. The experimental results from a finite element analysis represent a new clinical tendency instead of a definite conclusion. Furthermore, the process is limited by the need to use a simplified approach to model ligaments and fractured vertebral bodies. In future studies, we plan to conduct a clinical, randomized, double-blind, controlled study to test the reliability and availability of our findings.

5. Conclusions

In the present study, there were no significant differences among the 4 intermediate pedicle screw techniques in terms of ROM, von Mises stress, or stress to the intervertebral discs superior and inferior to the injured vertebra. The simplest technique using intermediate unilateral short pedicle screw fixation provides reliable stability and will not accelerate intervertebral disc degeneration compared with other intermediate pedicle screw fixation techniques. Therefore, posterior short-segment fixation combined with intermediate unilateral short pedicle screws is a feasible treatment strategy for stable thoracolumbar fracture.

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Author contributions

Conceived and designed the experiments: PCW, YSS, XFW. Performed the experiments: XFW, YSS. Analyzed the data: DR, YJL, SML, YSS, XFW. Contributed reagents/materials/analysis tools: XFW, YSS. Wrote the article: XFW, YSS.

Data curation: Shaoming Liu.

Formal analysis: Yunshan Su, Xiongfei Wang, Shaoming Liu.

Project administration: Dong Ren, Yueju Liu, Pengcheng Wang.

Supervision: Dong Ren, Yueju Liu, Pengcheng Wang.

Validation: Pengcheng Wang.

Writing – original draft: Yunshan Su, Xiongfei Wang.

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