Finite Element Analysis of Stability of Internal Fixation Reconstruction Methods for Lumbar Total Vertebral Resection

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Abstract

Objective To compare the effect of different fixation methods on spinal stability after total en bloc spondylectomy(TES) of lumbar spine.

Method The finite element models were established based on the CT scan of a healthy volunteer. After the validity of the models was confirmed, the models with different posterior fixation methods of the lumbar spine were established with and without the artificial vertebral body, respectively. The motions of flexion, extension, lateral bending and rotation under supine and standing conditions were simulated. The angular displacement of T11-L3 and stress of internal fixations were compared and analyzed.

Results The finite element models of spinal reconstruction after TES were obtained. When the anterior support existed, the movement of the spine after TES was not affected by the gravity of the upper body. The movements in the opposite direction on the same plane were similar. All three methods provided enough stability to the spine. The improved short-segment fixation shared stress of the artificial vertebral body with no obvious negative effect. The long-segment fixation had stronger fixation effect with the huge loss of the range of motion of lumbar spine. When the anterior support failed, obvious rotation showed in lateral bending in all models. The short-segment fixation and the long-segment fixation failed to maintain the spinal stability with fixations breakage or functional loss. The improved short-segment fixations showed strong ability in maintaining the spinal stability. The vertebral body screws can prevent the failure of anterior fixation by sharing great stress of the whole internal fixation system. The improved short-segment had huge advantages over the others.

Conclusion After TES, the improved short-segment fixation can provide more stability to the spine. The vertebral body screws can prevent the failure of the internal fixation by reducing the stress of the anterior support. This fixation method should be promoted in clinical practice while the effect requires more observation.

Introduction

The spine is the most frequent site of malignant tumour bony metastases [1]. The primary tumour is also insensitive to radiotherapy and chemotherapy[2]. Previously, surgery was often only used as a palliative treatment for spinal tumours. In 1997, Tomita and other scholars proposed total en bloc spondylectomy (TES),[3] which achieves the most thorough resection of spinal tumours. TES effectively relieves pain, controls nerve function damage, and significantly reduces the local recurrence rate.[3–7]

In single-segment TES, posterior bilateral pedicle screw fixation, with two or three segments above and below the anterior titanium mesh or artificial vertebral body, is used to reconstruct the stability of the spine[8]. The yield strength of the vertebral body is much smaller than that of the internal fixation device[9]. Some patients also have osteoporosis, and there have been reports of adverse events in these patients, including the subsidence of the anterior support and endplate fracture. With long-term follow-up

after TES[10, 11], the rate of internal fixation failure caused by the failure of the front support is about 40%, predominantly caused by the concentration of back stress owing to front support failure and internal fixation failure. With multi-segment TES, anterior support subsidence can be observed 1 month after surgery[12]. Therefore, it is essential to maintain the stability of the front pillar after TES. In this study, we used a finite element analysis to determine which fixation method maximizes the stability of the anterior column and prevents internal fixation failure. We also provide guidance for its clinical application.

Materials And Methods

Finite element model of a normal human spine

The model was a 45-year-old male volunteer, with a height of 177 cm, body mass index of 24, and no history of spinal disease. The study was approved by the Ethics Committee of Zhongshan Hospital, Fudan University and informed consent was achieved. We removed the effect of the thoracic region (including the floating ribs) on the stability of the spine, and selected L1 as the surgical segment. A computed tomography (CT) scan of the whole spine was performed in the volunteers to obtain CT images of T10–L4 segments, with a layer thickness of 0.5 mm. *Mimics 20.0 (Materialise, Leuven, Belgium)* and *Geomagic 12.0(3D Systems, North Carolina, Usa)* were used to construct the models, which were combined to obtain the T10–L4 segment model without L1. We selected the appropriate material parameters according to literature[13–15] (Table 1), and the material dimensions were consistent with the clinical situation (Table 2).

Table 1
Material parameters of the materials used in the finite element model

	Young's modulus (MPa)	Poisson's ratio
Cortical bone	12,000	0.3
Cancellous bone	100	0.2
Posterior bony unit	3500	0.25
Cartilage endplate	4000	0.3
Fibre ring	4.2	0.45
Nucleus pulposus	1.0	0.4999
Titanium alloy	108,000	0.3

Table 2
Material dimensions in the finite element model

	Size (mm)
Cortical bone thickness	1
End plate thickness	0.5
Connecting rod diameter	5.5
Artificial vertebral diameter	16
Artificial vertebral body outer diameter	20
Pedicle screw	6.5 × 45
Vertebral nail	6.5 × 40

Internal fixation model with artificial vertebral bodies

After the finite element model was confirmed, finite element models of the different reconstruction methods used after TES, including an artificial vertebral body, were established according to the clinical situation (Fig. 1). Posterior bilateral pedicle screw fixation of T11, T12, L2, and L3 was defined as short segment fixation (group A); posterior bilateral pedicle screw fixation of T11, T12, L2, and L3 combined with lateral unilateral vertebral body nails on T12 and L2 was defined as modified short segment fixation (group B); and posterior bilateral pedicle screw fixation of T10, T11, T12, L2, L3, and L4 was defined as long segment fixation (group C). The models were built and assembled in *Unigraphics 10.0*, and pre-processed in *HyperMesh 6.14*, analysed in *Abaques 6.14* with additional material parameters and conditions. The lower endplate of L4 was completely fixed, and there's no movement between the screw and bone.

Internal fixation models without artificial vertebral bodies

To consider the clinical failure of the anterior support, finite element models of the different reconstruction methods were established without the artificial vertebral body, based on the definitions and conditions described above (Fig. 1). These were designated groups A', B', and C' and simulated the changes in the spine when the anterior support was completely lost.

*Pre-loading and observational indicator*s

The design was without pre-loading to simulate the horizontal position, and an axial load of 500 N was pre-applied to simulate the vertical position. The model was flexed forward, backward, to the left, to the right, rotated to the left, and rotated to the right with a torque of 7.5 N m. The model was calculated and solved, and the angular displacement of T11–L3 and the stress distribution on the internal fixation system were calculated when the different models moved differently in different postures.

Results

Establishment and verification of T10–L4 spinal segmental model

The spinal T10–L4 segment model without L1 contained a total of 404,665 units and 117,489 nodes. The degrees of motion in the L2–3 and L3–4 segments were measured, and the angular displacement during descending flexion, extension, side bend, and rotation with a torque of 10 N m was measured. Our results were compared with those in the literature[16–18] (Fig. 2). The relative relationships and trends in the segmental activities of the models were similar to those in the literature. Thus, the data were successfully modelled.

Variation in angular displacement with internal fixation method

(1) Variation in angular displacement with artificial vertebral body model

The differences in angular displacement in the three fixed models under different motion conditions are shown in Fig. 3. During each action, the angular displacement in group B was slightly smaller than that in group A. The angular displacement in group C was about 1/3 of those in the other two groups during flexion and extension, and was about 1/4 of those in the other two groups during lateral bending. During each action, the angular displacement of group C was 11.00–77.44% less than that in group A, and 9.44–77.06% less than that in group B. Postural change had little effect on the outcomes.

(2) Angular displacement changes in models without the artificial vertebral body

The angular displacement changes in the three fixed models during different types of motion are shown in Fig. 4. During flexion, extension, and rotation, the angular displacement was smallest in group B'. The angular displacement in group B' was 5.06–83.10% less than that in group A', and 26.12–72.79% less than that in group C'.

During the side-bending action, the three models showed twists in the different postures (Fig. 5), and the directions of the twist differed. When changing from the supine position to the upright position, the group A' twist angle increased by 62.56% and 77.31%, the group B' twist angle increased by 0.11% and 7.10%, and the group C' twist angle increased by 28.37% and 29.99%. Among the three groups, the degree of torsion in group B' was smallest, and was 42.93–65.11% less than that in group A', and 32.34–4.24% less than that in group C'.

Stress analysis of different internal fixation methods

(1) Peak stress position in the internal fixation systems

In the supine position, in the models with an artificial vertebral body, the peak stress was concentrated at the vertebral body level at both ends of the model. In the models without an artificial vertebral body, more than half the peak stress was at the T12 and L2 levels. In the models containing an artificial vertebral body, more than half the peak stress was at the T12 and L2 levels. In the models without an artificial vertebral body, the peak stress was all at the T12 level.

(2) Peak stress with an artificial vertebral body

In the supine position, the peak stress on the three-group internal fixation system ranged from 45.07 to 143.10 MPa. In the upright position, the peak stress range was 93.84–214.90 MPa. The stress changes on the artificial vertebral body are shown in Fig. 6. The artificial vertebral body in group A was most stressed under the same conditions. The peak value of the artificial vertebral body in group B was 0.86% and 0.22% higher than that of group A during flexion and extension in the upright position, respectively, but 3.28–20.64% lower than that of group A during the other movements. In the supine position, the peak values for the artificial vertebral body during all movements were 2.73–16.9% less in B group than in group C; and in the upright position, the peak stress on the artificial vertebral body during left bending and rotation was 2.77–12.7% less in group B than in group C.

Peak stress without artificial vertebral body

In the supine position, the peak stress in the three internal fixation systems ranged from 77.47 to 294.00 MPa, and the peak stress in group B' was somewhat lower than that in the other two groups (Fig. 7a).

In the upright position (Fig. 7b), the peak stress was much smaller in group B' than in the other two groups during all actions, ranging from 174.40 to 379.20 MPa. Except during post-extension, the peak stress in group A' was greater than 1000 MPa (1013.00–1279.00 MPa), and the peak stress in group C' was greater than 850 MPa (858.80–1190 MPa). The peak stress in group B' was 68.73–87.11% and 65.31–79.69% lower than that in groups A' and C', respectively.

When the position was changed from supine to upright, the peak stress in group A' increased by 94.96–1048.86%, the peak in group B' increased by 44.99–531.68%, and the peak stress in increased by 288.32–1058.95%. The peak stress was 0.63% lower in group B' than in group A' during all movements, except left bending. The front flexion and extension movements were 85.60% and 85.53% lower in group B' than in group A', respectively. The peak stress in group B' was lower during flexion, extension, and rotation comparing to group C'. And the reductions during flexion and extension were 83.31% and 83.30%.

Discussion

TES surgery is difficult, the learning period is long, and great skill is required of the surgeon[19–21]. Zaidi et al.[19] reported that surgical and fixation methods using a posterior–lateral approach are safer and more effective than simple posterior fixation. Kawahara et al.[8] believed that the posterior fixation of the two

segments above and below the affected segment can meet the stability requirements, but that internal fixation failure may occur in patients with longer survival and no fusion of the bone graft.

In this study, a finite element model of the artificial vertebral body was established. The angular displacements during flexion and extension, left and right bending, and left and right rotation were almost equal in the same position. The angular displacement of the reverse motion performed was almost identical. In group B, the presence of the vertebral body nails did not significantly reduce the angular displacement because the addition of the artificial vertebral body greatly improved the stability of the spine. The angular displacement in group B was smaller than in group A during the same movement in a same position. This indicates that compared with short segment fixation, the modified method (group B) has certain advantages in controlling angular displacement and thus maintaining spinal stability, whereas the presence of vertebral body nails has no such effect and can adversely affect the immediate stability of the spine. The angular displacement in group C was significantly smaller during all movements than in groups A or B, indicating that when there is effective anterior support, long-segment fixation can achieve a strong fixation effect, but the mobility of the lumbar vertebrae is greatly reduced. The peak stress in the three internal fixation systems was much smaller than that observed with TC4 titanium alloy (850–900 MPa).[22] The yield strength indicated that in the three groups, the internal fixation was not easily broken, and all three models effectively maintained the stability of the spine. Therefore, we believe that anterior support plays a crucial role in the immediate stability of the spine after TES. Because long segment fixation sacrifices the normal mobility of the lumbar spine while offering no further gains in stability, it may not be the optimal choice. The peak stress on the artificial vertebra was lower in group B than in the other two groups, suggesting that the presence of vertebral nails partly absorbed the stress on the artificial vertebral body when the anterior support was effective.

In the finite element model without an artificial vertebral body, the same kind of fixation method showed large differences in angular displacement during flexion, extension, and bending motions, and the direction of displacement had no obvious regularity. At the same time, the model appeared to be twisted. This may be because the L1-vertebral body was fully cut. The front pillar support was lost and the centre of gravity had moved to the rear pillar. This also shows that the failure of the anterior support will lead to a significant reduction in the stability of the spine, especially during lateral bending, when the spine will be twisted, further increasing the risk of the posterior instrument failure. When the supine position was changed to the upright position, the torsion angles in the groups increased. Group A' had the largest increase, followed by group C', and group B' had the smallest increase. In the same position, group B's torsion angle was smallest, suggesting that the change in body position and the shift in the centre of gravity had relatively small effects on the modified short segment model, even given its poor overall stability. The angular displacement during all the actions was lower in group B' than in group A'; the angular displacement was lower in group B' than in group C' during flexion, extension, and rotation, and when these were combined with torsion. Therefore, we believe that when the anterior support fails, the stability of the improved short segment was much better in group B' than in groups A' or C'.

When the model was changed from the supine position to the upright position, the peak stress in all three groups increased, but group B' showed the smallest increase. The peak stress was significantly lower in group B' than in the other two groups, suggesting that the modified short segment provides better stability to the spine when the anterior support fails. In the upright position, the peak stress in group B' was in the safe range, whereas those groups A' and C' reached the yield strength, even the limit strength(960–970).[22] When the ultimate strength in all directions (except during extension) was measured, the peak stresses in group A' all reached the ultimate strength, whereas most peak stresses in group C' reached the yield strength and some reached the ultimate strength. Therefore, groups A' and C' failed or even broke when there was no action in the upright position, indicating that these two sets of fixation methods are insufficient to maintain the stability required for spinal reconstruction. However, the improved short segment fixation method can still be guaranteed without front column support. The safety of movements in all directions suggests that the presence of the vertebral body nails allowed a large part of the stress to be absorbed by the posterior nail system, and that the nail system does not fail or break, even in the event of anterior failure.

We found that at the peak stress position of the internal fixation system, the stress in the three groups was concentrated on the nail system at T12 and L2, which are both segments adjacent to L1. This indicates that the segments adjacent to the resected segment were internally fixed. Where the system is relatively weak, reinforcement will help to reduce the burden on the inner and front support. The vertebral body nails in the modified short segment fixation are implanted in the two vertebral bodies, so that the stress on the internal fixation system is effectively shared, and failure of the internal fixation is prevented.

In summary, when there is effective anterior support, the improved short segment fixation method has no obvious negative effects, and can effectively share the stress of the artificial vertebral body. However, the fixed segment with increased fixation of the long segment does not confer further benefits on the patient. Once the anterior support is ineffective, the improved short segment fixation maintains better spine stability through the reinforcement afforded by the vertebral body nails, and is therefore a safe and effective fixation method. The presence of the vertebral body nails effectively prevents the failure of the anterior support, thereby reducing the occurrence of internal fixation failure. Moreover, the improved short segment fixation method does not require extra surgical incisions, reduces the stripping range, and shortens the operation time, which reduces the trauma, the risk of complications, such as bleeding and infection, and the cost of the device.

Some conditions were simplified in the construction of the model to facilitate modelling and calculation. Because this was a biomechanical study, the practical application of our research model must be tested clinically. In the future, our research team will continue to design and establish TES models for pathological conditions, such as osteoporosis, spinal degeneration, and spinal stenosis with soft tissue conditions, and further explore the effects of this fixation method.

Abbreviations

TES
Total en bloc spondylectomy
ROM
Range of motion
BMI
Body Mass Index
CT
Computed tomography
Fl
flexion
Ex
extension
LB
left bending
RB
right bending
LR
left rotation
RR
right rotation

Declarations

Ethics approval and consent to participate

The study was approved by the Ethical Committee of Zhongshan Hospital Fudan

Consent for publication

Not applicable

Availability of data and materials

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

Conflicts of Interest Statement

The author(s) have no conflicts of interest relevant to this article

Competing interests

The authors have no conflicts of interest relevant to this article

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Not applicable

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Figures

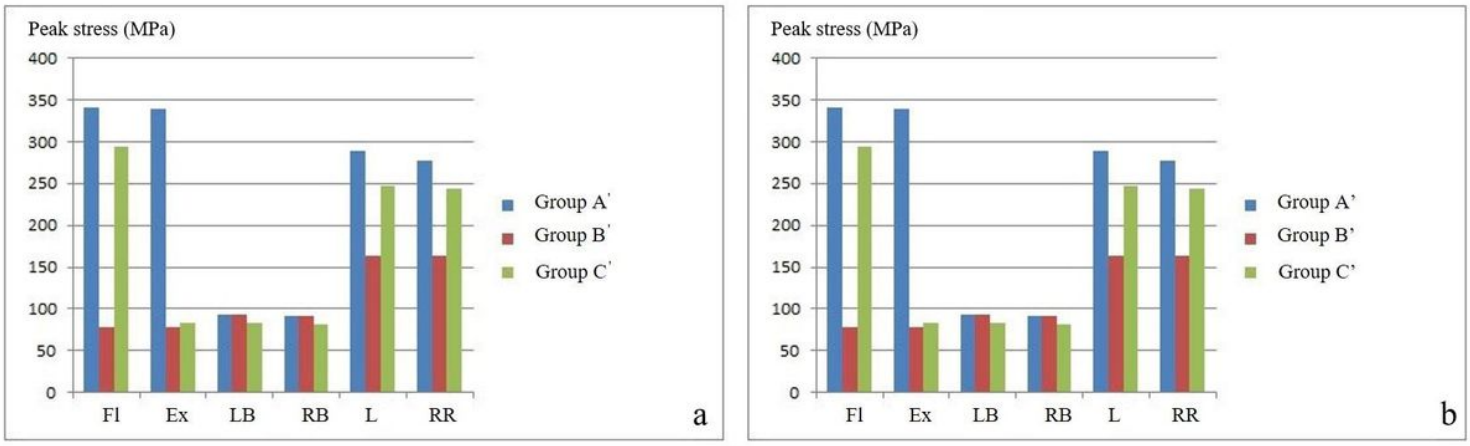

Figure 1

a. Changes in peak stress in the supine position without an artificial vertebral body for groups A', B', and C'. 7.b is that in the upright position (Fl: flexion; Ex: extension; LB: left bending; RB: right bending; LR: left rotation; RR: right rotation.)

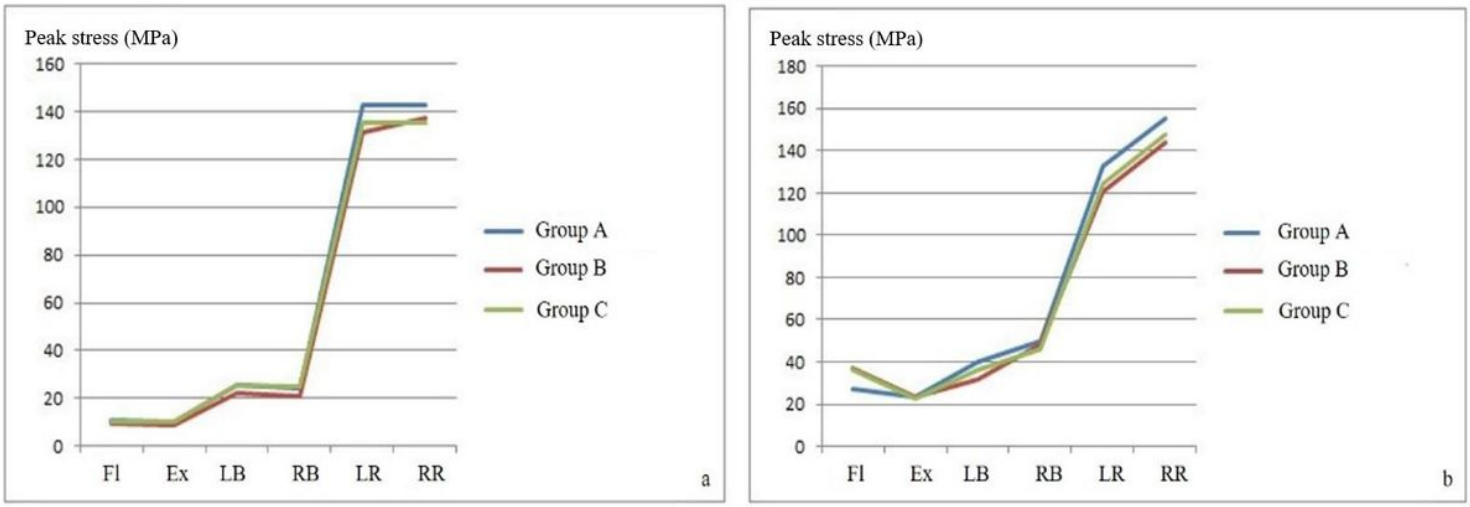

Figure 2

Variation in peak stress on the artificial vertebral body for groups A, B, and C. (a. Supine position; b. upright position.; Fl: flexion; Ex: extension; LB: left bending; RB: right bending; LR: left rotation; RR: right rotation.)

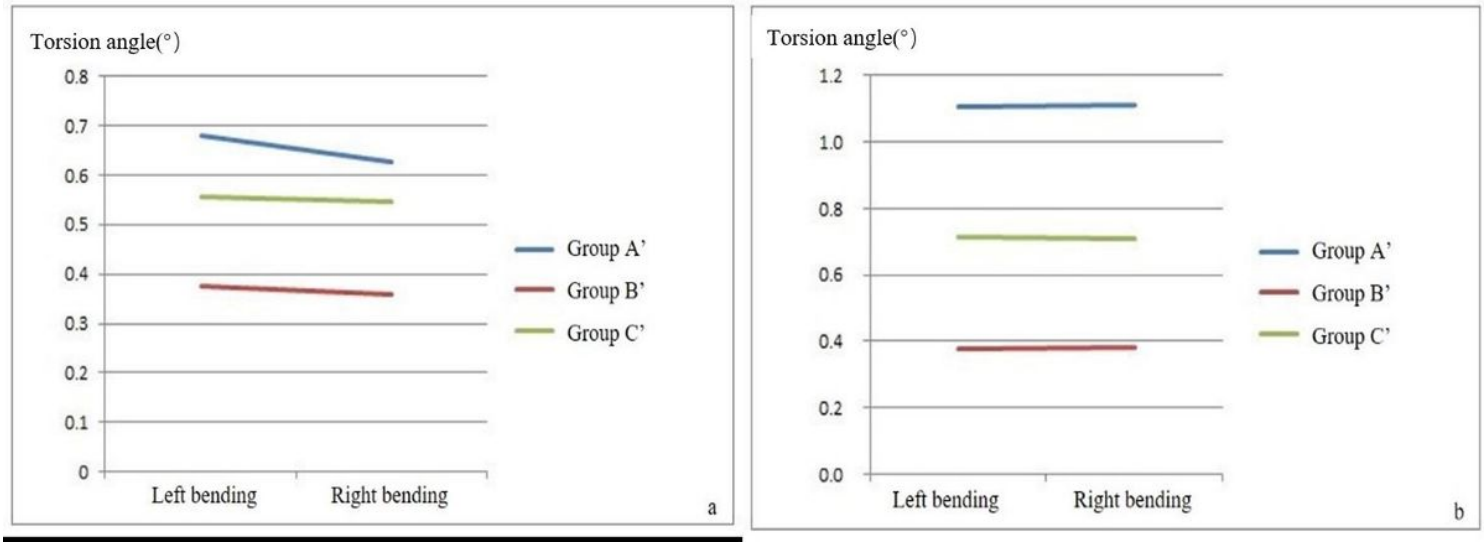

Figure 3

Torsion angles during different sideways bending motions without an artificial vertebral body for groups A', B', and C'. (a. Supine position; b. upright position.)

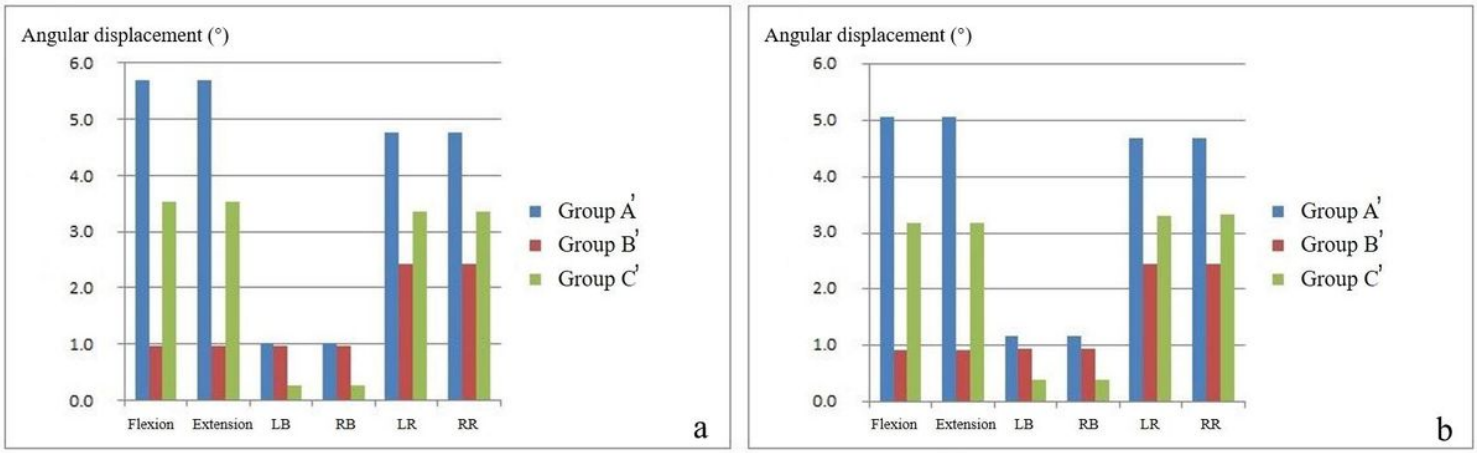

Figure 4

Variation in angular displacement in the supine position without the artificial vertebral body for groups A', B', and C'. And 4b is the upright position (LB: left bending; RB: right bending; LR: left rotation; RR: right rotation.)

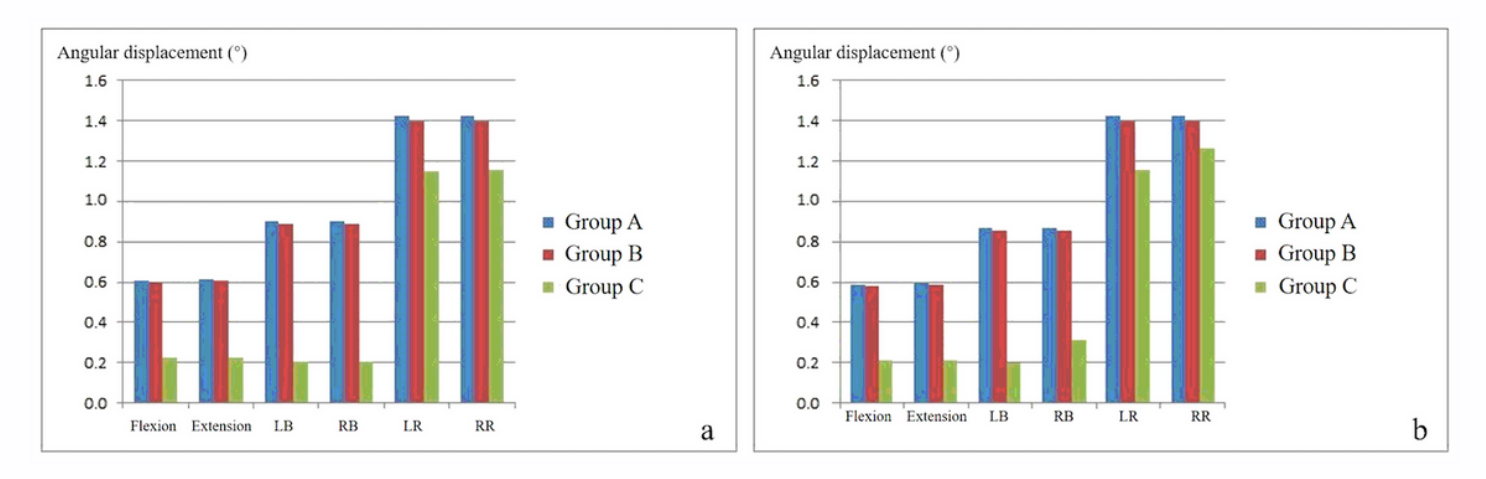

Figure 5

a shows the differences in angular displacement with the artificial vertebral body in the supine position for groups A, B, and C. While 3.b is in the upright position. (LB: left bending; RB: right bending; LR: left rotation; RR: right rotation.)

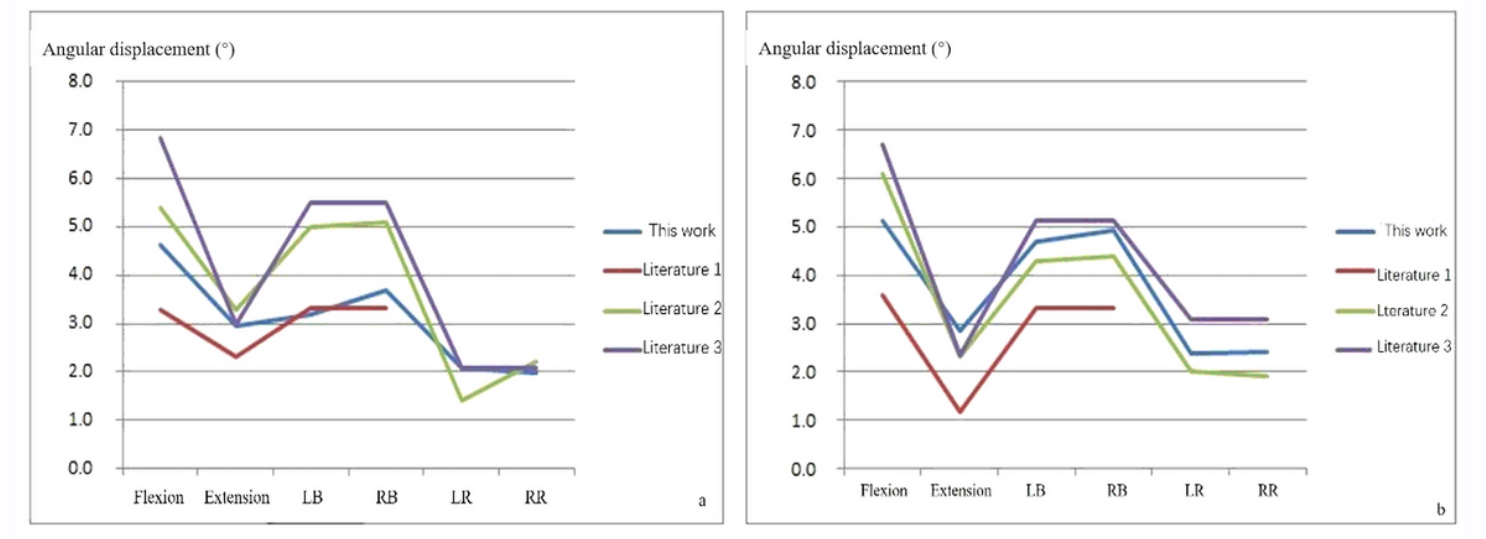

Figure 6

Comparison of activities in the study model with those in Refs. [16], [17], and [18]. a. L2–3; b. L3–4. LB: left bending; RB: right bending; LR: left rotation; RR: right rotation.

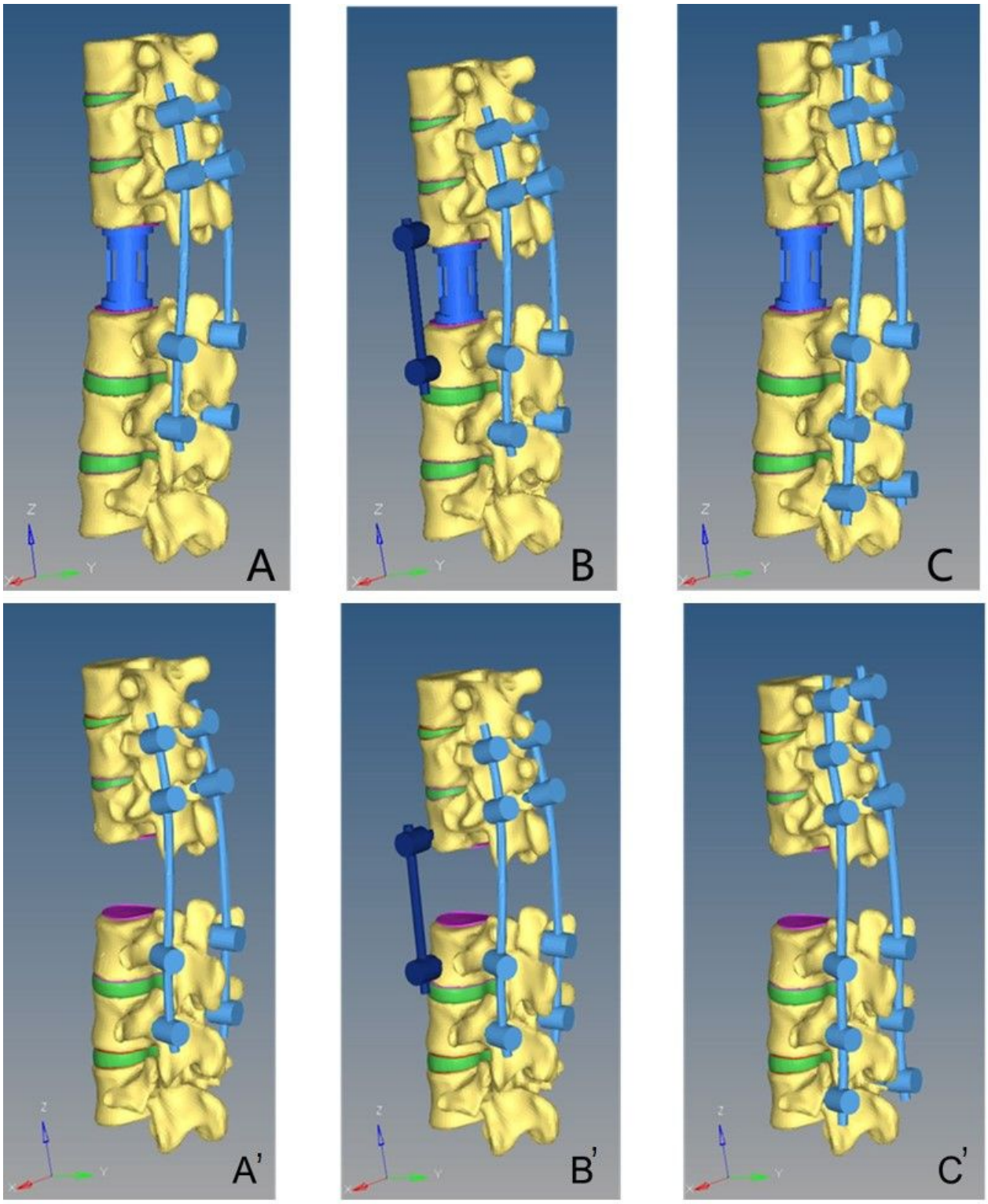

Figure 7

Finite element models of reconstruction methods with artificial vertebral bodies after TES for groups A, B, C. And methods without the artificial vertebral body after TES for groups A', B', C'.