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Original article

Biomechanical comparison of instrumentation techniques in treatment of thoracolumbar burst fractures: a finite element analysis

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Abstract
Background. There are several surgical techniques currently employed to treat thoracolumbar burst fractures, including anterior fixation, posterior fixation, or combined anterior-posterior fixation. Biomechanical analysis of the various types of surgical techniques is therefore critical to enable selection of the appropriate surgical method for successful spinal fusion. However, the effects of the various spinal fusion techniques on spinal stiffness have not been clearly defined, and the strengths and weaknesses of each fusion technique are still controversial.
Methods. The biomechanical effects of increasing the number of anterior rods and removing the mid-column in anterior fixation, posterior fixation, and combined anterior-posterior fixation on spinal stiffness in thoracolumbar burst fractures was investigated. Finite element analysis was used to investigate the effects of the three fusion methods on spine biomechanics because of its ability to control for variables related to the material and experimental environment.
Results. The stiffness of the fused spinal junction highly correlates with the selection of an additional posterior fixation. The mid-column decompression showed a significant change in stiffness, although the effect of decompression was much less than that with the application of posterior fixation and the anterior rod number. In addition, two-rod anterior fixation without additional posterior fixation is able to provide enough spinal stability; and one-rod anterior fixation with posterior fixation yields better results in regard to preventing excessive motion and ensuring spinal stability.
Conclusions. The present study shows that careful consideration is necessary when choosing the anterior rod number and applying posterior fixation and mid-column decompression during surgical treatment of thoracolumbar burst fractures.

Introduction

Approximately 90% of spinal fractures are found in the thoracolumbar junction, and burst fractures comprise 10%–20% of such injuries.[1,2] Although conservative treatment is commonly indicated for a relatively stable fracture, surgical treatment is effective when there are serious transformations and neurological deficits. Spinal fusion is one of the most common surgical techniques for treating spinal fractures to decrease the possibility of nonunion of the fracture. There are several surgical spinal fusion techniques for treating burst fractures, including anterior fixation, posterior fixation, and combined anterior-posterior fixation.[2] Although there are many important factors to take into consideration to minimize the damage of pulmonary, visceral, and vascular structures as well as soft tissue damage (e.g., a high degree of surgical skill, the operating time, the choice of surgical site), stiffness of the fused spinal junction is one of the most essential factors when choosing an appropriate surgical technique for a patient. The stiffness of the fused spinal junction, which means the stiffness of the instrumentation, can be defined by dividing the applied moment to the spinal junction by the rotated angle of the junction. Low stiffness of the fused junction may produce nonunion of the fracture or instrument failure, while excessively high stiffness may result in excessive motion of adjacent spinal junctions, which can lead to adjacent segment disease.[2,3] Therefore, biomechanical analysis of stiffness resulting from the various spinal fusion methods is indispensable when planning spinal fusion to treat a fracture.

Biomechanical analyses of the stiffness of fused spinal junctions have commonly been performed by experimental studies evaluating individual surgical technique. However, these experimental studies have significant drawbacks: Large numbers of subjects or cadavers are required, and the results of the experiment are dependent on the material and experimental environment.[4,5]

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For example, only one fusion method can be applied to each subject. Therefore, finite element analysis, which has been used in the spine biomechanics field for the last three decades,[6] was utilized in this study to investigate the effects of various fusion methods on spine biomechanics because finite element analysis can easily control for variables related to the material and experimental environment.

In this study, we investigated the biomechanical effect of the increase in number of anterior rods, combined posterior fixation, and removal of the mid-column for decompression on spinal stiffness in thoracolumbar burst fractures in anterior fixation, posterior fixation, and combined anterior-posterior fixation using finite element analysis. We developed a finite element model of the intact thoracolumbar junction from T12 to L2, and various spinal fusion models were developed using the intact model. Spinal stiffness of each model, which is the stiffness of the fused spinal junction, was then calculated and analyzed.

Table 1. Material properties used in the finite element model of the lumbar spine

Spinal site	Young's modulus (MPa)	Poisson's ratio	Cross-sectional area (mm^2)
Vertebra			
Cortical bone	12000	0.3	
Cancellous bone	100	0.2	
Endplate	1000	0.4	
Cartilage	10	0.4	
Intervertebral disc			
Nucleus pulposus	0.2	0.4999	
Annulus ground	4.2	0.45	
Annulus fibrosus	450	0.3	0.15
Ligament			
Anterior	20.0	0.3	63.7
Posterior	20.0	0.3	20
Flavum	19.5	0.3	40
Intertransverse	58.7	0.3	3.6
Interspinal	11.6	0.3	40
Supraspinal	15.0	0.3	30
Capsular	32.9	0.3	60

Materials and methods

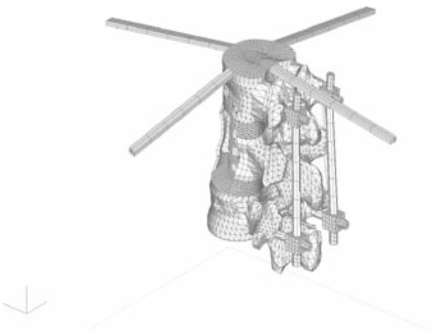
Finite element model of an intact thoracolumbar junction (T12–L2)

Computed tomography (CT) scanning of a 1-mm slice from T12 to L2 was performed on a 21-year-old healthy man with a height of 175 cm. A solid model of the lumbar spine (T12-L2) was reconstructed using 3D-Doctor software (Able Software, Lexington, MA, USA) to detect the boundary edge of each slice and Rapidform software (Inus Technology, Seoul, Korea) to stake the slices and to convert the images into an IGES-type model. The finite element model was then developed from the solid model using FEMAP ver. 8.2 software (UGS, Plano TX, USA) (Fig. 1). Each vertebra model consisted of a cortical and cancellous bone and two endplates. The cortical bone was modeled with a thickness of approximately 1.5 mm, and both the upper and the lower end-plates were assumed to be 0.5 mm thick.[3,7] The vertebrae were aligned to have a 0.8° angle between T12 and L1 and a 2.5° angle between L1 and L2 in the sagittal plane.[8] About 5 mm of cartilage layers were built on the surface of the facet joints, which were in contact with an initial gap of 0.5 mm and a friction coefficient of 0.1 between the superior and inferior cartilages.[9,10]

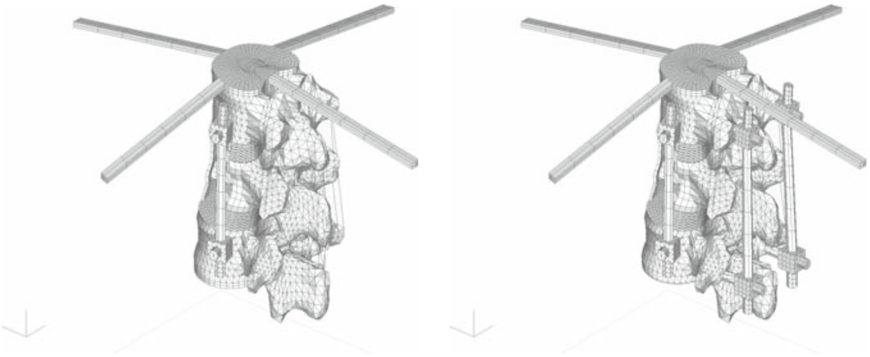
The intervertebral disc consisted of a nucleus pulposus, annulus ground substances, and annulus fibrosus. The nucleus pulposus was created as an incompressible fluid-filled cavity inside the annulus fibrosus, and its area was assumed to be 43% of the intervertebral disc area.[9] The annulus fibrosus was constructed in five layers in the radial direction with an approximate angle of 30° to the adjacent end-plates where the cross-sectional area of the annulus fibrosus was assumed as the total volume of annulus fibers was 19% of the total annulus volume.[5–7] All seven spinal ligaments, including the anterior longitudinal ligament, posterior longitudinal ligament, intertransverse ligament, ligamentum flavum, interspinal ligament, supraspinal ligament, and capsular ligament, were also included in the finite element model of the intact thoracolumbar junction. The material and anatomical properties were based on previous literature (Table 1).[5,9–11] The developed finite element model of an intact thoracolumbar junction from T12 to L2 had 25 018 nodes and 36 306 elements. The developed intact model of T12-L2 was initially validated by comparing its stiffness to the stiffness reported in previous studies when using one or two motion segments from L1 to L2 and from T12 to L2 in flexion, extension, lateral bending, and torsion loading, respectively.

Finite elements models of spinal fusion thoracolumbar spine

Three-dimensional computer-aided design (CAD) models of implants such as pedicle screws, rods, and a cage (Medtronic, Minneapolis, MN, USA) for anterior and posterior fixation, were constructed using SolidWorks software (SolidWorks, Concord, MA, USA) based on the drawing information from the manufacturer. The finite element models of the implants were

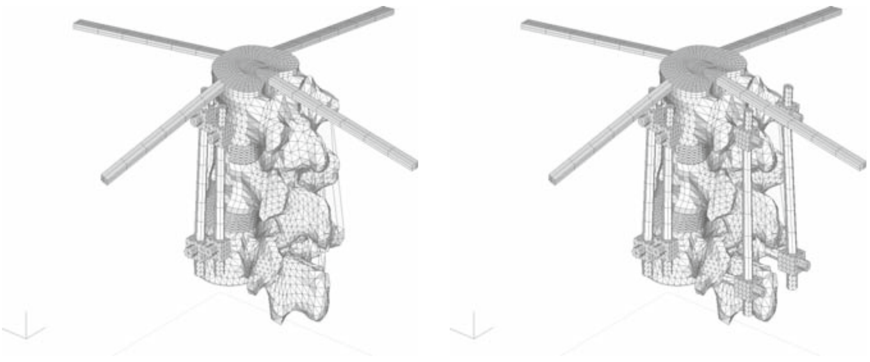


(a) 0R-ND-P



(b) 1R-ND-NP

(c) 1R-ND-P



(d) 2R-ND-NP

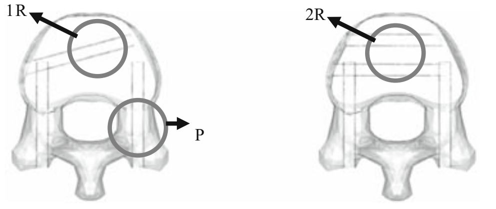
(e) 2R-ND-P

Fig. 1. Five fusion models of no mid-column decompression (ND). **a** Posterior fixation (0R-ND-P). **b** One-rod anterior fixation (1R-ND-NP). **c** One-rod anterior fixation with posterior fixation (1R-ND-P). **d** Two-rod anterior fixation (2R-ND-NP). **e** Two-rod anterior fixation with posterior fixation (2R-ND-P). Five fusion models with mid-column decompression were also developed. *0R*, *1R*, and *2R* indicate the number of rods used for anterior fixation. *D* and *ND* indicate decompression or no decompression of the mid-column, respectively. *P* and *NP* indicate that posterior fixation or no posterior fixation was performed, respectively

then developed from these CAD models and were assumed to have the material property of titanium with an elastic modulus of 77 GPa and a Poisson's ratio of 0.3.[9] Ten spinal fusion models were developed with a surgeon's consultation using the developed finite element models of the intact thoracolumbar junction and the implants according to the change of anterior rod number from 0 to 2, with or without posterior fixation, with decompression or no decompression of the mid-column: 0R-ND-P, 0R-D-P, 1R-ND-NP, 1R-D-NP, 1R-ND-P, 1R-D-P, 2R-ND-NP, 2R-D-NP, 2R-ND-P, and 2R-D-P (Fig. 1). 0R, 1R, and 2R indicate the number of rods used for anterior fixation; D and ND indicate decompression and no decompression of the mid-column, respectively; and P and NP indicate if posterior fixation was performed or not performed, respectively.

Different corpectomies were performed in the L1 vertebra for the no mid-column decompression and the mid-column decompression (Fig. 2a,b). For no mid-column decompression (ND), the left lateral part of the vertebral body in L1 was removed, as shown in Fig. 2a. For mid-column decompression (D), the whole posterior part of vertebral body in L1 was additionally removed, as shown in Fig. 2b. The cage was then inserted in the center of the L1 vertebra for no mid-column decompression (ND) or moved approximately 5 mm in

(a) No mid-column decompression model (b) Mid-column decompression model



(c) Positions of screws for anterolateral and posterior fixation

Fig. 2. Surgical options for developing the finite element models. **a** No mid-column decompression model. **b** Mid-column decompression model. **c** Positions of screws for anterolateral and posterior fixation

the posterior direction from the center for mid-column decompression (D). A high friction coefficient of 0.8 was assigned between the superior plate of the cage and the inferior plate of T12, and the inferior plate of the cage and the superior plate of L2, owing to teeth on the surface of the cage that prevent the implant from slipping.[9] The friction coefficient between the flank surface of the cage and the L1 vertebra was set to 0.1. For posterior fixation, three ligaments — supraspinal ligament, interspinal ligament, ligamentum flavum — were removed, and two pedicle screws were inserted in the same position regardless of the models (Fig. 2c). For anterior fixation, the screws were positioned anterolaterally according to the number of rods (Fig. 2c).

Loading and boundary conditions

The bottom of the L2 vertebra was fixed and 5 Nm of pure moment was applied on the top of the T12 vertebra for flexion, extension, lateral bending (left/right), and torsion (left/right) using two 100-mm rigid bars (Fig. 3). The spinal stiffness for each loading of the intact thoracolumbar junction and 10 spinal fusion models were obtained by dividing the rotation angle by the applied moment. For finite element analysis, Abaqus/Standard 6.5 (Abaqus/Simulia, Providence, RI, USA) was used.

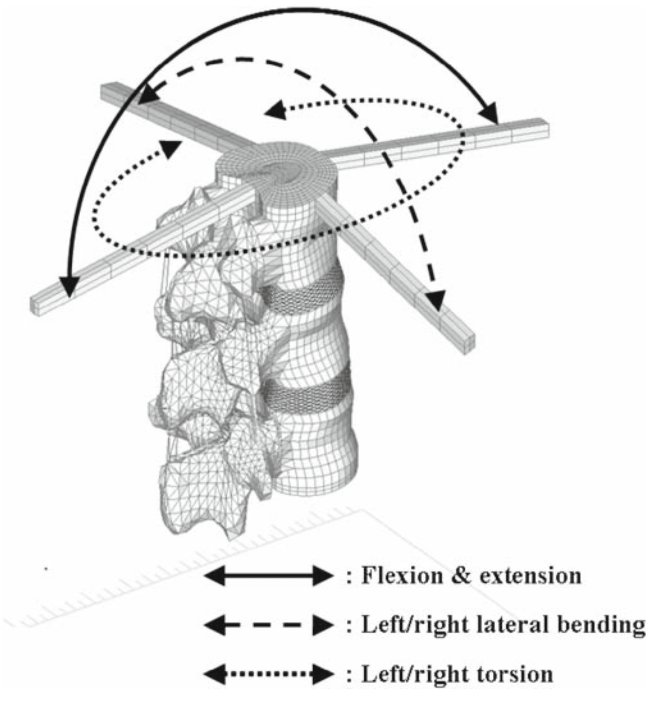


Fig. 3. Loading and boundary conditions for flexion/extension, left/right lateral bending, and left/right torsion

Results

The stiffness of the intact model correlated well with the experimental results (Fig. 4). For the case of one level (L1-L2) in the intact thoracolumbar spinal junction, the stiffnesses were 2.7, 2.8, 2.1, and 6.9 Nm/° for flexion, extension, lateral bending, and torsion, respectively, whereas the corresponding experimentally measure stiffnesses were 1.4–2.9, 2.1–3.7, 1.8–2.7, and 4.6–12.5 Nm/° (Fig. 4).[12–14] Similarly, for the case of the two levels (T12-L2) in the intact thoracolumbar spinal junction, the stiffnesses were 1.9, 1.6, 1.1, and 3.9 Nm/° for flexion, extension, lateral bending, and torsion, respectively, whereas the corresponding experimentally measured stiffnesses were 0.8–1.6, 0.8–2.0, 0.5–1.4, and 1.3–6.7 Nm/° (Fig. 4).[15,16]

All of the fusion models predicted higher stiffness values than the intact model in flexion, extension, and left/right lateral bending (Fig. 5). However, in torsion,

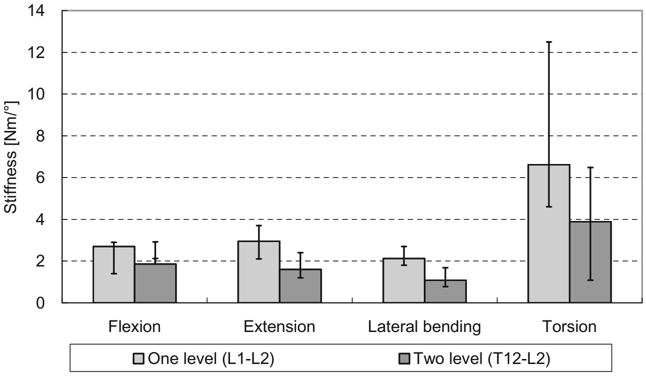


Fig. 4. Spinal stiffness of one- and two-level intact model for validation. *Bars* indicate the minimum and maximum values of previous experimental studies

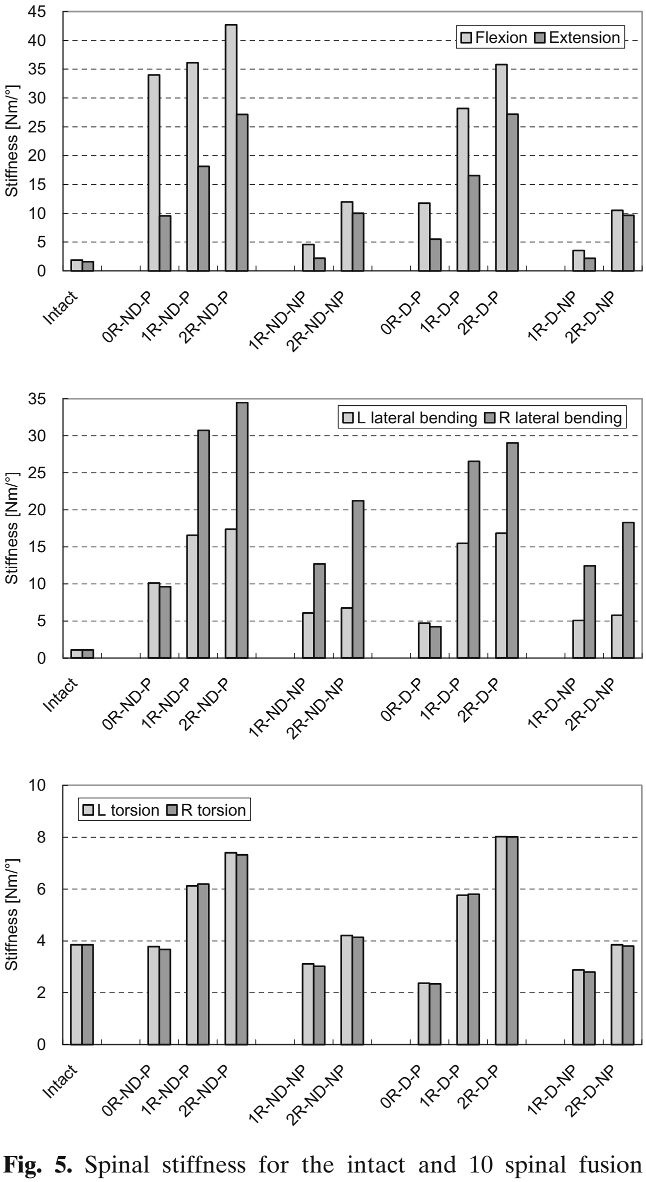


Fig. 5. Spinal stiffness for the intact and 10 spinal fusion models in flexion, extension, left/right lateral bending, and left/right torsion. *L* and *R* in the loading conditions indicate left and right directions of rotation

the stiffness of three models — 0R-D-P, 1R-ND-NP, 1R-D-NP — were lower than that of the intact model; whereas two models — 0R-ND-P, 2R-D-NP — had stiffness similar to that of the intact model (Fig. 5).

Influence of number of rods in the anterior fixation

The stiffness increased as the number of rods used in the anterior fixation increased, regardless of posterior fixation, mid-column decompression, or loading (Fig. 5). The effect of rod number on spinal stiffness decreased when additional posterior fixation was performed. For example, in the anterior fixation without posterior fixation under no mid-column decompression, the two anterior rod fixation case (2R-ND-NP) showed 161%, 354%, 67%, and 37% higher stiffness values in flexion, extension, right lateral bending, and right torsion, respectively, than those in one-rod fixation (1R-ND-NP). When adding posterior fixation, 2R-ND-P showed only slightly higher stiffness values than those in no rod fixation (0R-ND-P) or in one-rod fixation (1R-ND-P).

Influence of combined posterior fixation

Stiffness values of no posterior fixation cases were greatly increased by adding posterior fixation regardless of rod number, mid-column decompression, or loading (Fig. 5). The effect of posterior fixation on spinal stiffness decreased when the number of rods increased. For example, for two-rod anterior fixation with posterior fixation under no mid-column decompression (2R-ND-P), the stiffness increased by 257%, 172%, 62%, and 77% in flexion, extension, right lateral bending, and right torsion, respectively, compared with those without posterior fixation (2R-ND-NP); and the stiffness of 1R-ND-P increased by 690%, 724%, 142%, and 105% in flexion, extension, right lateral bending, and right torsion, respectively, in comparison with 1R-ND-NP.

Influence of mid-column decompression

Mid-column decompression reduced the stiffness values regardless of rod number, posterior fixation, or loading (Fig. 5). The effect of mid-column decompression was prominent in the cases of pure posterior fixation (0R-ND-P and 0R-D-P). The stiffness with 0R-ND-P was 189%, 74%, 127%, and 57% higher in flexion, extension, right lateral bending, and right torsion, respectively, than with 0R-D-P. The stiffness of the other models with mid-column decompression was slightly lower than those with no mid-column decompression.

Discussion

There are several surgical techniques currently employed to treat thoracolumbar burst fractures, including anterior fixation, posterior fixation, and combined anterior-posterior fixation. Biomechanical analysis of the various types of surgical techniques is therefore critical to enable selection of the appropriate surgical method for successful spinal fusion. However, the effects of various spinal fusion techniques on spinal stiffness have not been clearly defined, and the strengths and weaknesses of each fusion technique are still controversial.[1,2,17–20] In this study, the biomechanical effects of anterior rods and decompression of the mid-column on spinal stiffness in thoracolumbar burst fractures was evaluated after anterior fixation, posterior fixation, and combined anterior-posterior fixation. The finite element analysis was used to investigate the effects of various fusion methods on spine biomechanics owing to its convenience of controlling the variables related to the material and experimental environment.

Although all the fusion models predicted higher stiffness values than the intact model in flexion, extension, and left/right lateral bending, five models — 0R-ND-P, 0R-D-P, 1R-ND-NP, 1R-D-NP, 2R-D-NP — showed lower or similar stiffness when compared to the intact model in torsion. For spinal stability, the stiffness after fusion should be greater than the values of the intact spine under all loading conditions. Therefore, the use of two rods is recommended for anterior fixation without additional posterior fixation (2R-ND-NP and 2R-D-NP). Using one or two rods is also advantageous when posterior fixation is performed (1R-ND-P, 1R-D-P, 2R-ND-P, 2R-D-P). However, two-rod anterior fixation with posterior fixation (2R-ND-P, 2R-D-P), which provides much greater stiffness, should be used as a fusion technique only when necessary because too high spinal stiffness of the fused junction may result in adjacent segment disease owing to the excessive motion of adjacent spinal junctions.[2,3]

In this study, the number of anterior rods, mid-column decompression, and additional posterior fixation were examined as biomechanical factors for investigation of spinal stiffness. The effect of posterior fixation on spinal stiffness was substantially more pronounced than that of the number of anterior rods or mid-column decompression. For example, the stiffness of flexion, extension, right lateral bending, and right torsion in 1R-ND-P increased by 690%, 724%, 142%, and 105%, respectively, in comparison with those of 1R-ND-NP; and with 2R-ND-NP the stiffness of these factors increased by 161%, 354%, 67%, and 37% compared to 1R-ND-NP. In contrast, mid-column decompression had substantially less influence on spinal stiffness than did posterior fixation and anterior rod number even though decompression resulted in meaningfully lower stiffness.

Several clinical studies support the results presented here. Wood et al.[1] reported that anterior fixation resulted in clinical outcomes similar to those achieved with posterior fixation and significantly reduced the complication rate following anterior treatment of burst fractures. Schreiber et al.[19] reported that although the stiffness of flexion, extension, and lateral bending increased as significantly as a result of anterior fixation additional posterior fixation was still recommended because horizontal movement of vertebrae increased. In addition, Payer[20] reported that posterior fixation is a safe, reliable surgical method for spinal alignment, stability, and decompression in cases of neurological deficit. However, additional anterior fixation is recommended because instrument failure and recurrence of kyphosis have been reported when surgery is performed without vertebral body reconstruction.[19]

The developed intact model (T12-L2) was validated by comparing its stiffness with that in previous experimental studies for both one-level and two-level motion segments. All stiffness values were within experimental ranges regardless of the number of levels and the loading, except the stiffness in flexion for two-level motion segments (1.9 Nm/°), which was only slightly higher than the experimental range (0.8–1.6 Nm/°), so the difference may be negligible. In the future, developing a whole thoracolumbar spine model may provide more precise analysis. Additionally, the influence of other parameters on spinal stiffness, including the level of osteoporosity of each vertebra and the position and size of the implant, needs to be investigated.

There were a few restrictions and limitations in this study. The lumbar spine model was developed based on the CT data from one subject. It is necessary to investigate several subjects for a more clinically feasible conclusion because the geometry of vertebrae can affect the analysis result. Moreover, subject-specific material properties for bone, discs, and ligaments (instead of the properties based on previous literature) could increase the clinical relevance of the analysis. Muscle force also needs to be considered to simulate more realistic in vivo situation.

Conclusion

The results have shown that the stiffness of the fused spinal junction depends highly on the selection of additional posterior fixation. Mid-column decompression affected spinal stiffness, although this effect was much less than that of the application of posterior fixation and the number of anterior rods. In addition, two-rod anterior fixation without additional posterior fixation provides sufficient spinal stability, although one-rod anterior fixation with posterior fixation is preferred as it prevents excessive motions and ensures spinal stability. The present study indicates that careful consideration is necessary when choosing the number of anterior rods. Moreover, applying posterior fixation and mid-column decompression is necessary for surgical treatment of thoracolumbar burst fractures.

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