CLINICAL ARTICLE

Comparison of Biomechanical Properties of Single- and Two-segment Fusion for Denis Type B Spinal Fractures

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Objective: To compare the biomechanical properties of single- and two-segment fusion for Denis type B spinal fracture.

Methods: Two female patients with Denis type B L₁ vertebral fractures were studied. Both patients had achieved intervertebral fusion by 1 year postoperatively, at which time CT data were collected, including data of one patient before and after removal of pedicle screws and of another whose pedicle screws were not removed. The data were imported into Mimics software and T₁₁-L₂ three dimensional models established. After construction of the models, they were imported into ANSYS software. An axial load (260 N) and 10 Nm torque were loaded to simulate the flexion, extension, lateral bending and rotation of the spine, respectively.

Results: There was no significant difference in the average displacement of the spine motion between the two-segment and single-segment fusion patients without removal of pedicle screws. However, for all motion forms, the average displacement of the single-segment fusion patient's spine after removal of pedicle screws was significantly greater than that before removal of pedicle screws and that of the two-segment fusion patient. The average Von Mises stress of T₁₁-L₂ intervertebral disc of two-segment fusion patient was significantly greater than that of the one-segment fusion patient. Moreover, the average Von Mises stress of T₁₁-L₂ intervertebral disc of single-segment fusion patient was greater before than after removal of pedicle screws.

Conclusion: Provided there is satisfactory interbody fusion, removal of pedicle screws after one-segment fusion can increase spinal motion, reduce the stress on adjacent intervertebral discs and delay disc degeneration.

Key words: Biomechanics; Spinal fractures; Spinal fusion

Introduction

According to the fracture pattern and injury mechanism, Denis classified thoracolumbar burst fractures into five types, the commonest being type B, which accounts for 49.2% of all thoracolumbar burst fractures. Denis characterized Type B as a superior endplate fracture with intact inferior endplate caused by incomplete vertical force with slight flexion¹. However, Denis did not provide detailed descriptions of the state of the posterior columns in these five fracture types. In an

autopsy study, Willén *et al.* found that all thoracolumbar burst fractures have associated posterior column injury in the form of partial rupture of the posterior longitudinal ligament and/or vertebral arch fracture². A recent study suggested that the severity of thoracolumbar burst fracture is attributable to the nature of the posterior column injury, which is an indicator of clinical instability³. McCormack *et al.* proposed a "load-sharing" principle for thoracolumbar fractures⁴. According to this principle, unstable thoracolumbar burst fractures should

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be treated via anterior interbody support based on posterior reduction-fixation. Thus, a combined posterior and anterior approach rarely causes loss of kyphosis and the long-term stability of the spine is superior to that achieved by either an anterior or posterior approach alone⁵.

The commonly performed technique of anterior intervertebral fusion comprises resecting the involved vertebral body and its adjunct superior and inferior discs. Recent research on disc degeneration has shown that it is an irreversible process of gradual deterioration and that intervertebral fusion can accelerate this process because it affects the biomechanics of the spine⁶. According to the characteristics of Type B fracture, the inferior disc of the involved vertebral body is normal in morphology, signal strength of magnetic resonance imaging (MRI) and histology. Therefore, preservation of the inferior disc is indicated⁷. There is still a lack of clinical and basic research evidence as to whether single segmental intervertebral fusion comprising resection of only the injured superior disc can delay degeneration of the adjacent discs of the involved vertebra compared with the routinely performed double segmental intervertebral fusion, which involves resection of both the injured superior disc and the intact inferior disc.

We established surgical models of a combination anterior-posterior approach with single and double segmental fusion by applying a three-dimensional (3D) finite element method. We applied loading stress to each model with the goal of focusing on the different approaches to anterior column reconstruction to: (i) assess the spinal range of motion after the two types of surgical procedure; and (ii) evaluate and compare the biomechanical influences on degeneration of the adjacent discs.

Materials and Methods

Patient Data

The first study patient, a 45-year old woman, underwent double segmental fusion after sustaining an L₁ Denis Type B fracture in a traffic accident. She had no other injuries and her neurologic status was evaluated as Frankel grade B. The second study patient, a 41-year old woman, underwent single segmental fusion after sustaining an L₁ Denis B fracture caused by falling from a height. She had an associated with left pilon fracture and her neurologic status was evaluated as Frankel grade C.

Both patients were diagnosed as having L₁ burst fractures on the basis of plain radiographs and CT scans (to exclude the spinal congenital malformations and other damage). Their superior endplates and discs were damaged, whereas their inferior endplates and discs were intact. In both cases spinal cord compression and spinal stenosis were confirmed by MRI and the signals were normal for both inferior discs.

Surgical Approach and Outcome

Two-Segment Fusion

Under general anesthesia, the first patient was placed in a prone position and treated by open reduction and internal

fixation with pedicle instruments through a posterior approach. She was then moved into a right lateral position and the injured vertebral body and its superior and inferior discs were removed. After complete decompression, an appropriate titanium mesh was placed into the space between T₁₂ and L₂. Thus double segmental intervertebral fusion was achieved (Fig. 1a). The Cobb angle was reduced to 6° from the preoperative 28°. One year post surgery, grade D intervertebral fusion according to the imaging criteria of Brantigan and Steffee had been achieved⁸. Her neurologic function had improved to Frankel grade C and there was no loss of height between T₁₂ and L₂.

Single-Segment Fusion

Under general anesthesia, the second patient was placed in a prone position and treated by open reduction and internal fixation with pedicle instruments through posterior approach. She was then moved into a right lateral position and part of the injured vertebral body and only its superior disc were removed. Meanwhile, the inferior disc was preserved. After complete decompression, an appropriate titanium mesh was placed into the space between T₁₂ and the left partial body of L₁. Thus single segmental intervertebral fusion was achieved (Fig. 1b). The Cobb angle was reduced to 5° from the preoperative 24°. At one year postoperative follow-up, she had achieved grade E intervertebral fusion according to the imaging criteria of Brantigan and Steffee⁸. Her neurologic function had improved to Frankel grade D and there was no loss of height between T₁₂ and the left partial body of L₁. The posterior pedicle screw implants were accordingly removed (Fig. 1c).

Collection of CT Data

One year post surgery, both patients underwent CT scans (Sensation 64, Siemens, Erlangen, Germany; 120 kV, 200 mA, slice thickness 1 mm, gap 1 mm) from T₁₁ to L₂. All data were saved in Dicom format. The obtained data included 537 Dicom images of the case who had undergone double segmental fusion, 504 Dicom images of the case who had undergone single segmental fusion prior to and 492 Dicom images of this case after removal of posterior pedicle screw implants, which was performed one year after the initial surgery. In each image, the anterior vertebral edge was marked as a checkpoint for measuring spinal displacement under different loading conditions.

Establishing Surgical Models and Biomechanical Analysis

Three-Dimensional Reconstruction of CT Images

The above three sets of data were imported into the Mimics 10.01 system (Materialise, Leuven, Belgium) to produce 3D images, which in turn were imported into the Magics 9.9 system (Mimics remesher) through a finite element analysis (FEA)—remesher. The 3D images were then divided into plane-mesh models by the Magics 9.9 rigid-lattice division program of Mimics. Thus final optimized plane-mesh models,

Fig. 1 Diagrammatic representations of posterior approach and anterior segmental fusion. (a) Two-segment fusion. Both superior and inferior disc of L_1 were resected. Fusion was done between T_{12} and L_2 . (b) Single-segment fusion. Only superior disc of L_1 was resected and inferior disc of L_1 was preserved. Fusion was done between T_{12} and L_1 . (c) Removal of pedicle screws. Fusion was achieved between T_{12} and L_1 one year post surgery, and the posterior pedicle screws were removed. So the motion between L_1 and L_2 was preserved.

comprising a double-segment fusion model, single-segment fusion model and removal of pedicle screw model, were created.

Creation of Volume-Mesh Models

The above optimized plane-mesh models were converted into volume-mesh models with the Mesh tool of the ANSYS pre-processor (Canonsburg, PA, USA). The superior and inferior endplates of the intervertebral disc were set up by 1.0 mm thicknesses. The fibers of the fibrous annulus were built by the truss element, which can only bear tensile stress. The fibers travelled in a scissor-like fashion and the angles between the fiber and intervertebral disc plane ranged from 25° to 40° . The unit element was SOLID92 (tetrahedron with 10 nodes). The volume-mesh models were re-imported into MIMICS software to endow material properties. The elastic modulus and Poisson ratio of each part was selected according to universally accepted published material (Table 1)⁹.

Assembly Model

Each model unit was assembled by ANSYS software according to the spinal structure supplemented by the anterior longitudinal, supraspinous, interspinous, ligamentum flavum, capsular and intertransverse ligaments. A spring element was used to simulate the above ligament structures. Ligament elements with LINK 8 of 3D unit can bear only tensile stress without compressive stress.

Defining Contact and Interaction

The surface-to-surface contact mode was selected, each part assembled according to its dimensional position and the interface then defined according to the actual anatomical morphology. Contact between intervertebral disc and superior or inferior vertebral endplates were defined as in bonded mode without relative displacement. The superior and inferior endplates were chosen as the main planes, whereas the superior and inferior surfaces of the intervertebral disc were the auxiliary plane. Contact between superior and inferior joints was defined as standard sliding contact with a coefficient of friction of 0.2 and the superior joint surface as the main surface. Thus, a 3D finite element model was completely established (Fig. 2). The two-segment fusion model comprised 546,609 units and 877,237 nodes, the one-segment fusion model comprised 480,621 units and 769,041 nodes and the model of post pedicle screw removal after single segmental fusion comprised 434,404 units and 688,093 nodes.

TABLE 1 Material parameters for the normal finite element model

Structures	Elastic modulus (Mpa)	Poisson ratio	Sectional area (mm ²)
Titanium alloy	77,000	0.3	—
Bone and cartilage			
Cortical bone	12,000	0.3	—
Cancellous bone	100	0.2	—
Articular cartilage	10	0.4	—
Disc			
Endplate	1,000	0.4	—
Nucleus pulposus	0.2	0.5	—
Annulus fibrosus	450	0.3	0.2
Ligament			
Anterior longitudinal ligament	20	0.3	38
Ligamenta flava	50	0.3	60
Interspinous ligament	28	0.3	35.5
Supraspinous ligament	28	0.3	35.5
Intertransverse ligament	50	0.3	10
Articular capsule	100	0.3	40

Setting up Loads and Boundaries

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 any direction. The motion around the X-axis (anterior and posterior) was defined as flexion-extension, around the Y-axis (right and left) as lateral bending and around the Z-axis (superior and inferior) as rotation. Axial loads of 260 N and torque load 10 Nm were loaded to simulate flexion, extension, lateral bending and rotation of the spine. The movement of the anterior vertebral edge in each scanned layer was recorded, after which the average displacement of the spine and average Von Mises stress in the T₁₁₋₁₂ intervertebral disc were calculated and all the stress nephograms drawn.

Statistical Analysis

The data was statistically analyzed by SPSS 13.0 software package (SPSS, Chicago, IL, USA). One factor ANOVA was used

to evaluate the average displacement of the spine and average Von Mises stress in the T₁₁₋₁₂ intervertebral disc among the three models under different loading. If the difference was statistically significant, SNK-q pairwise comparison was used for intergroup comparison. The significance level was set at $P < 0.05$.

Results

Evaluation of Average Displacement of Spine in Six Motion Directions

General comparison of the average displacement of the spine in six motion directions among the three operation models showed some statistically significant differences ($P = 0.000$, Table 2). SNK-q pairwise test showed that there was no significant difference between the double-segment and single-segment fusion models in average displacement of spine

Fig. 2 A left lateral view of the 3D finite element model assembled by ANSYS software. (a) Two-segment fusion model. Both superior and inferior disc of L₁ were resected. Fusion was done between T₁₂ and L₂. (b) Single-segment fusion model. Only superior disc of L₁ was resected and inferior disc of L₁ was preserved. Fusion was done between T₁₂ and L₁. (c) Removal pedicle screws model. Fusion was achieved between T₁₂ and L₁ one year post surgery, and the posterior pedicle screws were removed. So the motion between L₁ and L₂ was preserved.

TABLE 2 Evaluation of displacement among three models (mean $\pm$ S.D., mm)

Models	Layer number	Flexion	Extension	Left lateral bending	Right lateral bending	Left rotation	Right rotation
Two-segment fusion	537	0.76 $\pm$ 0.66	1.24 $\pm$ 0.83	2.28 $\pm$ 1.11	2.37 $\pm$ 1.44	1.23 $\pm$ 0.94	1.05 $\pm$ 0.93
One-segment fusion	504	0.84 $\pm$ 0.67	1.29 $\pm$ 0.87	2.36 $\pm$ 1.16	2.46 $\pm$ 1.51	1.35 $\pm$ 0.96	1.15 $\pm$ 0.99
Removal of pedicle screws	492	2.05 $\pm$ 0.68	2.28 $\pm$ 0.90	4.08 $\pm$ 1.18	6.55 $\pm$ 1.58	2.94 $\pm$ 1.02	3.02 $\pm$ 0.92
F-value	—	584.886	230.223	392.907	1255.731	483.633	689.262
P-value	—	0.000	0.000	0.000	0.000	0.000	0.000

motion in the six directions ($P > 0.05$, Table 3). However, there were significant differences between the removal of pedicle screw and double-segment fusion models as well as between removal of pedicle screw and single-segment fusion models. Furthermore, the average displacement in the removal of pedicle screw model was greater than in the other two groups ($P < 0.05$, Table 3). With increasing stress loading, the whole spine model shows different colors in the ANSYS 3D window. The axis of color cursors from blue to red represents gradually increasing displacement of the spine. Blue represents no displacement of the fixed vertebral body whereas red represents the location of maximum displacement in the corresponding direction (Fig. 3a–f).

Evaluation of Von Mises Stress Loaded on T_{11–12} Disc

General comparison of average Von Mises stress loaded on T_{11–12} intervertebral disc in the six directions among the three operation models showed statistically significant differences ($P < 0.05$, Table 4). SNK-q pairwise test also showed significant

differences among these three models. The average Von Mises stress on the T_{11–12} disc in the double-segment fusion model was greater than in the removal of pedicle screw and single-segment fusion models. It was greater in the single-segment fusion model than in the removal of pedicle screw model ($P < 0.05$, Table 5). With increasing stress loading, the stress nephogram of T_{11–12} disc shows different colors in the ANSYS 3D window. The axis of color cursors from red to blue represents gradually increasing Von Mises stress. The greater the average Von Mises stress, the more load-sharing is borne by the disc (Fig. 4).

Discussion

Establishment of Operative Model of 3D Finite Element

The 3D finite element model is a reliable tool for studying spinal biomechanics^{9–12}. With this for high degree of simulation analysis method, the results of calculating 3D finite element depend strongly on the quality of the finite element

TABLE 3 SNK-q pairwise comparisons between within three models (q value)

Group	Flexion	Extension	Left lateral bending	Right lateral bending	Left rotation	Right rotation
Two-segment versus one-segment	0.000	2.632	1.956	1.521	2.813	2.441
Two-segment versus removal of pedicle screws	42.085*	28.775*	34.984*	63.480*	39.832*	46.095*
One-segment versus removal of pedicle screws	41.441*	25.759*	32.535*	61.021*	36.470*	43.001*
Note: * $P < 0.05$.						

TABLE 4 Evaluation of Von Mises stress loaded on T_{11–12} disc among the three models (mean $\pm$ S.D., MPa)

Groups	Node number	Flexion	Extension	Left lateral bending	Right lateral bending	Left rotation	Right rotation
Two-segment fusion	537	8.395 $\pm$ 52.00	4.01 $\pm$ 1.01	12.15 $\pm$ 3.04	16.71 $\pm$ 5.16	18.65 $\pm$ 5.42	17.16 $\pm$ 5.19
One-segment fusion	504	4.05 $\pm$ 1.93	2.39 $\pm$ 1.01	10.07 $\pm$ 2.92	12.76 $\pm$ 5.10	15.96 $\pm$ 5.35	12.44 $\pm$ 5.14
Removal of pedicle screws	492	2.65 $\pm$ 1.91	1.55 $\pm$ 0.98	8.11 $\pm$ 2.95	8.98 $\pm$ 4.94	12.49 $\pm$ 5.21	8.96 $\pm$ 4.95
F-value	—	3425.145	2259.441	665.251	836.459	481.797	940.520
P-value	—	0.000	0.000	0.000	0.000	0.000	0.000

Fig. 3 Displacement of 3D finite element model of the T₁₁₋₁₂ disc when left bending loaded by an axial load 260 N and 10 Nm torque. (a, b) Anterior and left lateral views of two-segment fusion model. (c, d) Anterior and left lateral views of single-segment fusion model. (e, f) Anterior and left lateral views of removal of pedicle screws model.

model (similarity with true structure), computer capabilities and degree of model meshing. It only provides accurate data for clinical purposes provided the sample model has been established at the anatomical level: this enhances the computer capacities and computational capabilities. In order to simulate the actual surgical conditions to a high degree, the procedure to establish this model was modified as follows:

1. The models were constructed directly from original post-operative CT data, thus circumventing the distortion of simulations produced by simply using a vertebral segment or segments with intervertebral fusion as an independent entity. In this model, vertebral and intervertebral segments were constructed as a whole and 3D models with pedicle screws were directly generated.
2. Because of the irregular geometry of the spine, it is difficult to distinguish boundaries between intervertebral disc and vertebral body as well as upper and lower small joints. In this study, a large number of manual segmentation methods were used in the modeling process. Just as a 3D model reconstructed by CT workshop is much closer to reality than one created by Mimics software, so manual segmentation model constructed from preliminary 3D CT-scan models combined with Mimics 3D window even more closely approximates the actual anatomical structures.
3. When the material attributes are endowed for finite element models, the properties of bone based on gray scale definition much more closely approximate reality than did models based on previous manually-assigned methods. The

TABLE 5 SNK-q pairwise comparisons within the three models (q value)

Group	Flexion	Extension	Left lateral bending	Right lateral bending	Left rotation	Right rotation
Two-segment versus one-segment	84.786*	61.044*	27.002*	29.342*	19.035*	35.890*
Two-segment versus removal of pedicle screws	111.70*	91.005*	52.396*	57.577*	44.059*	60.938*
One-segment versus removal of pedicle screws	27.215*	30.091*	25.353*	28.186*	24.672*	25.063*

Note: * $P < 0.05$.

Fig. 4 Stress nephograms of the T₁₁–L₂ disc when left bending loaded by an axial load 260 N and 10 Nm torque. (a) Two-segment fusion model. (b) Single-segment fusion model. (c) Removal of pedicle-screw model.

aim of modification is to improve the similarity between finite element models and the actual structure and eventually to establish a 3D finite element operative model that includes three spinal functional units (T₁₁–L₂).

Biomechanical Differences between Single- and Double-Segment Fusion

Influences on Spinal Mobility of Different Procedures for Fusion of Segments

Intervertebral discs play a major role in maintaining the initial stability during spinal flexion, extension, lateral bending, rotation and anteroposterior shear¹³. Preservation of the inferior disc of the injured vertebra can not only improve the mechanical stability of the spine, but also greatly enhance its mobility. Rigid internal fixation can lead to degeneration of the adjacent functional spinal units. In order to minimize this complication, a combination of effective fusion and preservation of spinal motion segment is clinically important. Provided intervertebral fusion is satisfactory, removal of pedicle screws releases a functional spinal unit, thus the mobility of the spine after pedicle screw removal was significantly better than that found in the other models under the above loading conditions. In the single-segment fusion model, the force was mainly transmitted through the posterior pedicle screw system and anterior mesh; however, the inferior intact disc of the injured vertebra only shares a small proportion of this stress. This inferior disc developed elastic deformation under all of the above stress conditions. Accordingly, the range of spinal motion was greater in the single-segment than in the double-segment fusion model. Compared with right lateral bending and right torsion, spinal mobility of the single-segment fusion and removal of pedicle screw models was reduced in left lateral bending and left torsion load. The explanation for these findings may be relate to the position of the implanted titanium mesh¹⁴.

Stress Loaded on Intervertebral Disc and Different Types of Fusion

Degeneration of the adjacent disc after intervertebral fusion has been receiving more attention with developments in spinal

surgery. Kummer¹⁵ and Bergmark¹⁶ took the ventral and dorsal structure of spine as a logical load distribution system. In an upright position, the anterior and middle columns of a normal spine bear 83% to 90% force, whereas the posterior column bears 10% to 17% force. After posterior pedicle screw fixation, the force mainly transmits through the internal fixation. In light of Wolff law, anterior stress shielding is not of benefit to fracture healing and long-term stability. Rather, transmission of force mainly through the dorsal portion of spine has an adverse effect. Because this is contrary to the normal logical load distribution system, post-traumatic disc degeneration will occur¹⁷. Segmental fusion significantly increases internal stress on discs, facet joints and the posterior longitudinal ligament, meantime, the mobility of the fixed segment transfers to the adjacent segments, so that the cumulative effect ultimately results in disc degeneration¹⁸. Our comparison among these three groups showed that as the average Von Mises stress increases, the load-sharing borne by the disc is greater; thus, the risk of disc degeneration increases. The stress loaded on the T₁₁–L₂ disc was less in the single-segment fusion and removal of pedicle screw models than in the double-segment fusion model. This is in line with the findings of Chen *et al.*, namely, that multi-segment fusion results in significantly greater stress on the adjacent discs than does single-segment fusion^{19,20}. In conclusion, removal of pedicle screws after anterior single-segment fusion can increase spinal mobility, reduce stress loaded on the adjacent disc, and be conducive to delaying disc degeneration.

Pondering over Clinical Issues

The appropriate surgical approach and internal fixation for Denis Type B fractures remains controversial. Xia *et al.* performed a study on the correction of loss of Cobb angle. In this study, the correction loss averaged 0.5 mm and 7.5° at 6 months after surgery in patients who had undergone posterior decompression, pedicle screws instrumentation and intertransverse or intervertebral bone grafting²¹. In contrast, patients who had undergone posterior pedicle screw fixation, anterior approach decompression and bone graft fusion, the spinal column sequence and physiological curvature returned to normal postoperatively, without obvious correction loss within the follow-up period. Different outcomes may be

associated with different degrees of support for the anterior column. The vertebral height recovers to some degree after distraction and reduction with a pedicle screw system; however, the trabecular structure of the vertebra does not recover simultaneously. The vertebral body loses its normal mechanical properties due to insertion of the nucleus pulposus. Therefore, the key to preventing correction loss is reconstruction of the anterior column²². In recent years, the rapid development of science and technology has created conditions for performing minimally invasive spine surgery. Ringel *et al.* used posterior short segment fixation coupled with endoscopy to reconstruct the anterior column: this not only enabled precise decompression but also avoided loss of the Cobb angle and the failure of internal fixation that can occur when only posterior fixation is performed²³. The corresponding clinical efficacy was better, further demonstrating that posterior and anterior three-column fixation is an ideal fixation method. However, minimally invasive surgery demands intensive support and the learning curve is relatively long, which restricts its widespread promotion and application. Thus, surgeons need to further strive to explore use of this technology.

Characteristics and Limitations in this Study

Because FEA is a theoretical type of analysis, its conclusions should be combined with other research data and clinical trials

in order to most accurately ascertain the truth. The biomechanical analysis with FEA performed in this study is a form of basic research. We are currently undertaking clinical research seeking to assess average spinal displacement and mobility under different stresses radiologically: this will provide a further objective and reliable evaluation. Pathological changes due to bone healing, ligament contraction, scarring and degeneration of intervertebral discs inevitably ensue after thoracolumbar surgery. However, in this study it was inappropriate to define all material properties based on normal human tissue. On the basis of reviewing various domestic and foreign published reports, researchers have reportedly redefined degenerative nucleus pulposus (Young's modulus 8.4 MPa, Poisson's ratio 0.45) and fiber ring (Young's modulus 8.4 MPa, Poisson's ratio 0.45)²⁴. However, because the extent of pathological changes after surgery varies, fixed values are also inappropriate. More accurate and realistic models rely on development of radiology to the point that it can reflect pathological changes by defined attributes based on gray scale.

This study has shown that, provided intervertebral fusion is satisfactory, removal of pedicle screws after single-segment fusion can increase range of motion, reduce stress loaded on the adjacent intervertebral disc and be conducive to delaying disc degeneration. Thus, treatment of Denis Type B burst fractures by anterior single-segment fusion combined with a posterior approach is indicated both theoretically and in practice.

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