Finite Element Analysis of 3 Posterior Fixation Techniques in the Lumbar Spine

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abstract

This study compared the biomechanics of 3 fixation techniques: bilateral pedicle screw (BPS) fixation, unilateral pedicle screw (UPS) fixation, and UPS supplemented with translaminar facet screw (UPS+TLFS) fixation. The study was conducted in an L3-L5 finite element model. Three different finite element models were created by adopting different fixation techniques after removal of the left L3-L4 and L4-L5 facet joints. A 500-N compressive preload combined with 8-NM moment were applied in 3 finite element models with 3 fixation techniques during different movements. Angular displacement and stress distribution were recorded. As described in this article, the UPS model had the most variation in angular displacement, the BPS model was intermediate, and the UPS+TLFS model had the least mobility. Most of the stress accumulated on the body and tail of the pedicle screws and the connecting rods in the UPS and BPS models, but stress accumulated on the rods and the part of the facet joint pierced by the TLFS in the UPS+TLFS model. The middle part of the pedicle screw endured little stress compared with the upper and lower parts. The maximum stress on the fixation devices was highest in the UPS model. The maximum stress in the UPS+TLFS model was the lowest among the 3 models. Biomechanically, UPS+TLFS fixation is superior to either UPS fixation or BPS fixation in improving stability and reducing stress. Bilateral pedicle screw fixation is intermediate, and UPS fixation is inferior.
Lumbar spinal disease is becoming more and more prevalent. Lumbar spinal disease encompasses a group of disorders, including spinal degeneration, bone hyperplasia, lumbar spinal stenosis, and lumbar spinal disk herniation. Compression and inflammation around the areas of the affected nerve roots cause severe neurologic pain. Surgical intervention is the most popular strategy for decompression and relief of symptoms.1

Transforaminal lumbar interbody fusion (TLIF) combined with bilateral pedicle screw (BPS) fixation has been widely used in the surgical treatment of lumbar spinal disease.2-6 This strategy could reduce perioperative and postoperative morbidity, decrease complications, and promote recovery. However, this procedure requires excessive paraspinal muscle dissection and retraction, and the muscle and soft tissue around the surgical area could easily be damaged during instrumentation. Meanwhile, the rigidity of the fixation arising from this procedure can increase stiffness and affect vertebral interbody fusion.7 Recently, unilateral pedicle screw (UPS) fixation has emerged as a major alternative to BPS. UPS has multiple advantages over BPS, including reducing bleeding, shortening the perioperative and postoperative periods, eliminating long-term complications, and reducing cost.8-11 However, the reduced spinal stability associated with UPS is a concern, especially during bending and rotation. To overcome this drawback, a novel internal fixation technique has emerged as a promising surgical option for patients with lumbar spinal disease. With this technique, UPS is supplemented with a contralateral translaminar facet screw (TLFS).12,13 This strategy produces a triangular structure that significantly enhances spinal stability and improves the efficacy of internal fixation. This technique is frequently used in lumbar spinal lesions involving a single segment. Biomechanical comparisons of the effect of different fixation techniques on patients with this condition have been frequently reported. Clinically, most lumbar spinal lesions involve multiple adjacent segments. Few studies have compared the effect of different fixation methods on patients with disease involving multiple adjacent segments.

The goal of the current study was to compare the biomechanical features of 3 different posterior fixation techniques in 2 levels with an intact L3-L5 finite element model and evaluate the effect of each method at the surgical levels in patients with lumbar spinal disorders involving multiple adjacent segments. The methods included BPS fixation, UPS fixation, and UPS supplemented with TLFS fixation. The study was performed in an intact finite element model. The current study shows that, biomechanically, the UPS+TLFS technique is superior to either the UPS technique or the BPS technique in terms of providing sufficient stability and reducing mechanical stress in adjacent lumbar segments. The BPS technique is intermediate, and the UPS technique is inferior to the other techniques.

**MATERIALS AND METHODS**

**Construction and Validation of an Intact Finite Element Model**

A 3-dimensional osseoligamentous nonlinear finite element model was created to simulate the lumbar spine with ANSYS version 11.0 (ANSYS Inc, Canonsburg, Pennsylvania). The vertebral geometry was adopted using computed tomography (CT) data of vertebral L3-L5 segments from a normal male volunteer (aged 33 years, height 170 cm, weight 70 kg). Congenital bone disease was ruled out by radiographic examination. CT scan was conducted with consent of the volunteer and approved by the Shanghai Zhongshan Hospital Ethics Committee. The CT images were imported into modeling software to create the 3-dimensional finite element model of the vertebral L3-L5 segments. The L3-L5 segments consisted of 3 vertebral bodies (L3, L4, and L5), 2 intervertebral disks (L3-L4 and L4-L5), end plates, posterior bony elements, and all 7 ligaments (anterior and posterior longitudinal ligaments, ligamentum flavum, inter- and supraspinous ligaments, facet capsular ligaments, and intertransverse ligments) (Figure 1). The materials used to construct each model were assumed to be linear and homogeneous. The ligaments were modeled as tension-only spring elements with nonlinear elastic properties. The nuclei pulposi were modeled as incompressible fluid-filled cavities. The facet joints could only transmit compressive forces. The joints had the same rigidity as the surrounding bone when in full closure. The material properties of different tissues were cited from the previous reported literature (Table).5,14-23

**Boundary and Loading Conditions**

The caudal elements of the L5 vertebral body were strongly fixed. It was assumed that all interfaces were perfectly

![Figure 1: The intact finite element model of lumbar spine (L3-L5) used in this study. Front view (a); lateral view (b); back view (c).](image-url)
bonded. The frictional coefficient between joint surfaces was set as zero. A 500-N compressive preload was applied to the superior surface of L3 to mimic upper body weight. An 8-NM moment was applied to the superior surface of L3 to mimic flexion, extension, lateral bending, and axial rotation, respectively. Range of motion (ROM) in these conditions was recorded. The model was validated by comparing ROM with previously reported values.

**Simulation of the Biomechanics of 3 Intact Finite Element Models With Different Fixation Techniques**

After validation of the intact L3-L5 finite element model, the left L3-L4 and L4-L5 facet joints were removed for decompression and fusion with TLIF. Conical titanium alloy screws and connecting rods were used. The length of all pedicle screws was 45 mm, and the diameter was 6.5 mm. The length of the TLFS was 45 mm, and the diameter was 3.5 mm. The friction coefficient among the screws, connecting rods, and bone was set as infinite. The devices were tightly bonded. In the model with UPS fixation (UPS model), the vertebral pedicle screw was implanted into the left side of L3-L5. In the model with BPS fixation (BPS model), vertebral pedicle screws were implanted into both sides of L3-L5. In the model with UPS+TLFS fixation (UPS+TLFS model), the vertebral pedicle screw was implanted on the left side of L3-L5 and supplemented with 2 contralateral TLFSs. The biomechanical features of the 3 finite element models with different fixation methods were studied to simulate postoperative conditions. The boundary and loading conditions were the same as described earlier. Detailed information is shown in Figure 2.

**Comparison of Biomechanical Parameters**

Intersegmental ROM was used to evaluate the stability of different fixation methods in these models. Angular displacement in flexion, extension, lateral bending, and axial rotation was recorded. The stress distribution was used to evaluate changes in internal mechanical force among screws and rods and to predict the incidence of loosening, removal or breakage. In principle, the greater the internal mechanical force, the greater the incidence of loosening, removal, or breakage. Maximum stress was used to predict the likelihood of fracture.

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**Table**

<table>
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<th>Material</th>
<th>Young's Modulus (MPa)</th>
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<td></td>
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</table>

Abbreviations: ALL, anterior longitudinal ligaments; CL, facet capsular ligaments; FL, ligamentum flavum; ISL, intersupraspinous ligaments; ITL, intertransverse ligaments; PLL, posterior longitudinal ligaments; SSL, supraspinous ligaments.

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**Figure 2:** Back views of the finite element models with 3 types of fixation. Bilateral pedicle screw model (a); unilateral pedicle screw and translaminar facet screw model (b); unilateral pedicle screw model (c).
ROM in the previous reports, especially the study of Li et al.\textsuperscript{24} This suggests that the finite element model is similar to other models and validates the current model (Figures 3A-C).

**Biomechanical Features of 3 Intact Finite Element Models With Different Fixation Techniques**

**Angular Displacement Analysis.** As shown in Figure 4, angular displacement during all modes of motion (flexion, extension, lateral bending, and axial rotation) differed in the 3 finite element models with different fixation methods. The rotation angles in all modes of motion in the UPS model were the greatest among all 3 finite element models. The UPS+TLFS model had the lowest rotation angles during all modes of motion. The BPS model was intermediate. In the UPS model, the rotation angle during lateral bending was nearly the same as that during axial rotation and was slightly larger during right lateral bending. In the UPS+TLFS model, the rotation angle increased during right lateral bending compared with left lateral bending. The rotation angle was similar during left and right rotations. In the BPS model, the rotation angle during lateral bending was nearly the same as that during axial rotation and was slightly larger during right lateral bending. In the UPS+TLFS model, the rotation angle during lateral bending was nearly the same as that during axial rotation and was slightly larger during right lateral bending. The rotation angle was similar during left and right axial rotations. In summary, angular displacement in the UPS model was significantly higher than that in either the BPS or UPS+TLFS model. It was intermediate in the BPS model. Angular displacement in the UPS+TLFS model changed slightly, with little differences among the different motion states in this model.

**Stress Distribution Analysis.** Mechanical forces and the tendency to fracture were analyzed by the stress distribution diagram from different motion states in 3 finite element models. The stress distribution diagrams showed that the areas where stress accumulated under external forces differed among the 3 models (Figure 5). The stress was mainly concentrated on the pedicle screws and the connecting rods in both the BPS and UPS models. The stress in the BPS model was greater than that in the UPS model. In the UPS+TLFS model, most of the stress accumulated on the surface of the connecting rods and the TLFS. The middle area of the pedicle screws had very little stress compared with the tail of the screws in 3 models. Figure 6 shows the maximum stress during different motions.
in 3 models. Compared with the maximum stress in the UPS model, stress was significantly decreased in the BPS model and drastically reduced in the UPS+TLFS model in all modes of motion. In the UPS model, stress during lateral bending and axial rotation was higher than during flexion and extension, with the highest stress found during right lateral bending. In the BPS model, stress increased during left lateral bending and left rotation.

**Discussion**

To simulate the biomechanics of 3 different posterior fixation techniques (UPS, BPS, and UPS+TLIF) in patients with lumbar spinal disorders involving multiple adjacent segments, the authors used an intact finite element model. To validate the intact finite element L3-L5 model, the authors compared ROM with that of 4 similar models reported previously.24-27 The current results are consistent with other reports. These findings validate the current finite element model and suggest that this model is beneficial.

Because of the structural symmetry in the BPS model, ROM in right lateral bending and rotation was similar to that in left lateral bending and rotation. However, because of the asymmetric structure in the UPS and UPS+TLFS models, ROM in right lateral bending was greater than that in left lateral bending under the same preload and moment. The left pedicle screw placement and the rigidity on the left side led to more stiffness on this side.

The ROM reported in the current study was similar to that reported by Li et al24 and slightly lower than that reported by another 3 groups.25-27 Possible reasons for this difference include: (1) the mechanical properties and ligament tensions were set slightly differently in current models than in previously reported models; (2) the degeneration of muscle, bone, and disks was completely neglected in this study; and (3) the initial preload and moment were slightly different from those in previous reports.25

In theory, angular displacement could predict the stability of a fixation technique before actual intervertebral fusion. The current study shows that angular displacement during all modes of motion (flexion, extension, lateral bending, and axial rotation) was significantly different among 3 finite element models with different fixation techniques. The rotation angles in all modes of motion in the UPS model were the greatest among the 3 finite element models. The UPS+TLFS model had the smallest rotation angles during all modes of motion. The BPS model was intermediate. Angular displacement in the UPS model significantly increased and initial stability decreased compared with either the BPS or the UPS+TLFS model. Angular displacement in the BPS model was greater than that in the UPS model and lower than that in UPS+TLFS model. Angular displacement in the UPS+TLFS model changed slightly compared with the UPS or BPS model. Because of the asymmetric structure from UPS fixation, initial stability in this model decreased significantly. The ability to resist lateral bending and rotation was more significantly reduced in this model. Initial stability in the BPS model was better than that in the UPS model, but worse than that in the UPS+TLFS model. Because of the strong stability of UPS supplemented with TLFS, stability in the UPS+TLFS model was the best among the 3 models. These results are in agreement with previous reports from other groups.13,28 TLFS fixation significantly improves the biomechanical properties of the lumbar spine. The facet joint plays a critical physiologic role against the rotation force during movement of the spine. The dual rod system arising from the standard BPS fixation generates a “parallelogram effect,” in which, regardless of the type of movement, there is always a tendency toward rotation, even during flexion and extension. The triangular structure is more stable than the quadrilateral structure. In the UPS+TLFS model, the fulcrum for lumbar movement is stable; therefore, this model significantly reduced angular displacement and other unnecessary movement. Clinically, caution should be used when adopting the UPS technique to treat spinal disorder involving multiple adjacent segments.

The maximum stress and stress distribution could predict the incidence of pedicle screw loosening, removal, or breakage during surgical fixation. The maximum stress in the UPS model was the highest among the 3 different models. It was the lowest in the UPS+TLFS model. The
maximum stress in the BPS model was intermediate. Decreased internal stability in the UPS model is a possible reason. Stress was negatively correlated with the stability of fixation, whereas screw breakage was positively associated with stress. Therefore, loosening, removal, and breakage are common with the UPS fixative technique. Conversely, the stress could be shared by supplementing the procedure with TLFS fixation. According to the theory of 3-column fixation, the majority of stress accumulates on the vertebral body surface, particularly on the anterior and middle columns. The TLFS is usually implanted across the posterior column. The transduction of stress is from the surface of L3 down to the bottom of the BPS. Therefore, more stress accumulates in these areas. The UPS+TLFS technique shows more biomechanical advantages over the BPS technique in terms of improving the initial stability of fixation and reducing internal stress among the surfaces of adjacent segments. In the meantime, because of the small surgical area and the convenience associated with this technique, UPS+TLFS is more popular than BPS in clinical settings.

The stress in the UPS+TLFS model in the current study (most generated during right lateral bending) was far less than that seen in the other 2 models. Most of the stress accumulated on the body and tail of the pedicle screws and the connecting rods in both the UPS and BPS models, but stress in the UPS+TLFS model accumulated on the connecting rods and the area of the facet joint pierced by the TLFS. These results are consistent with findings in clinical practice, in which pedicle screw breakage is commonly seen with BPS fixation. The areas are mostly in the interface of the connecting rod and the pedicle screw. The middle part of the pedicle screw endured little stress compared with the upper and lower parts. Stress transduction is always from the upper side to the lower side and deteriorates during transduction. However, under fixed forces, stress is concentrated on the middle part of the screw. This finding suggests that the middle pedicle screw could be substituted for other types of fixative materials, for example, a holding hook, as long as it can be tightly attached to the vertebral body. It is not necessary to use 3-column pedicle screw fixation.

By adopting the finite element model, the authors could accurately simulate the movements of the lumbar spine in all directions to investigate the changes in internal stress accumulated on multiple areas of the lumbar spine. The finite element model is useful and efficient. However, like any model, the current finite element model has limitations. First, for convenience, some of the conditions seen in clinical settings were ignored when the experimental parameters were set. For example, the authors supposed that the screw was fixed to the vertebral body flexibly, the friction coefficient between joint
surfaces was zero, and the effects from muscle and spine were zero. However, all of these conditions are present in actual patients during surgery. Second, postoperative events were not fully recognized or simulated in this model, including reduction of the vertebral body, relaxation of ligaments, and degeneration of the intervertebral disk. Third, all of the mechanical parameters were set under normal conditions. Despite these limitations, the current study was conducted under the same experimental conditions for all 3 types of internal fixation models. Therefore, the establishment of these models and the results are reliable. These achievements will provide useful guidelines for clinicians in the treatment of lumbar spinal disease.

**CONCLUSION**

Biomechanically, the UPS+TLFS technique is superior to either the UPS technique or the BPS technique in terms of improving initial stability and reducing mechanical distribution. The BPS technique is intermediate, and the UPS technique had the worst outcome. The authors do not recommend use of the UPS technique in patients with lumbar spinal disease involving adjacent segments because of poor stability and great stress. This procedure is associated with greater risk of treatment failure than the other 2 techniques. If it has to be done, it is recommended to extend the period of bed rest and the use of external fixation braces. Both BPS and UPS+TLFS techniques could be used for patients with adjacent segment diseases. However, the UPS+TLFS technique is superior to the BPS technique. It is recommended as the first choice to treat lumbar spinal disease involving multiple adjacent segments.

**REFERENCES**


