Research Square

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Biomechanical comparison of two surgical techniques for the treatment of the ossification of the ligamentum flavum: A finite analysis

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Abstract

Objective: Thoracic ossification ligamentum flavum (TOLF) is considered a significant factor in thoracic myelopathy, and surgery is the main treatment method. The purpose of this study was to compare the biomechanical effects of two internal fixation techniques on spinal stability, range of motion (ROM), stress on internal fixation devices, and adjacent segment degeneration after TOLF treatment using finite element analysis.

Methods: CT data were imported into MIMICS software and further processed with Geomagic software to establish a three-dimensional model of T8-T12. Subsequently, two internal fixation schemes were established using SolidWorks software: laminoplasty and in-site regrafting (LPIR) and laminectomy + spinal canal decompression + pedicle screw internal fixation technique (LSPT). The ROM, ROM distribution, adjacent segment ROM, Von Mises stress on adjacent intervertebral discs and internal fixation devices were analyzed.

Results: Among the two groups of internal fixation techniques, LPIR had the highest overall ROM, which was 1.58°, while the overall ROM of LSPT was only 0.40°. The LPIR group experienced greater stress on the adjacent intervertebral discs at the proximal and distal ends, which were 2.30 MPa and 1.79 MPa, respectively. In the LSPT group, the Von Mises stress on the adjacent intervertebral discs at the proximal and distal ends was 2.12 MPa and 0.87 MPa, respectively. In the LPIR group, the titanium plate and screws bore greater stress, which was 363.06 MPa. In all types of movements, the maximum stress on the plate-screw connection site near the laminectomy boundary of the plate was observed. In the LSPT group, the screws showed the maximum Von Mises stress during flexion, which was 60.51 MPa.

Conclusion: Laminectomy and pedicle screw internal fixation provide better stability but reduce spinal flexibility. LPIR retains better spinal flexibility and is a feasible treatment strategy for TOLF.

1. Background

Thoracic ligament ossification (TOLF) is a chronic degenerative disease of the thoracic vertebrae, also known as ligament ossification. It was first proposed by Polgar in 1920 [1], characterized by the transformation of fibrous tissue within the ligament into bone tissue. It is the main cause of thoracic spinal stenosis and ultimately leads to thoracic spinal cord disease [2, 3]. TOLF is most common in Asian individuals aged 40–70, with a predilection for the lower thoracic vertebrae, particularly between thoracic vertebrae 10 and 11 [4, 5]. Currently, the pathogenesis of TOLF is unclear. Studies have shown that the occurrence of TOLF is related to multiple factors, such as mechanical factors, genetic factors, endocrine and trace element factors [6, 7].

The clinical symptoms of TOLF patients are complex and diverse, mainly including lower limb muscle weakness, numbness and sensory disorders, as well as walking dysfunction. In severe cases, it may even lead to paraplegia, thus potentially being mistaken for lumbar spine diseases, thereby reducing the

opportunity for early diagnosis [8–10]. Surgery is the most effective treatment for TOLF. Studies have shown that thorough surgical decompression for symptomatic TOLF patients is effective, while non-surgical treatment is usually ineffective. Moreover, early diagnosis and treatment can lead to better clinical outcomes [11, 12]. Common traditional surgical methods include laminectomy, laminoplasty, intervertebral foramenotomy, and single-door laminectomy [10, 12, 13]. However, during the operation, it may stimulate the spinal cord and aggravate the compression, resulting in serious complications such as deterioration of spinal cord function. Additionally, spinal instability caused by laminectomy usually requires pedicle screw fixation [10, 12, 14]. In recent years, many new surgical methods, including laminoplasty suspension [15], zone laminectomy [16], bridge crane technology [17], floating island laminectomy [18], and minimally invasive surgical techniques such as total endoscopic decompression [19], have been used for the treatment of TOLF. However, the average incidence of complications in surgical treatment for TOLF is 24%, mainly including cerebrospinal fluid leakage (19%) and neurological deterioration (5%) [20]. Currently, there is no unified standard for the best surgical method for TOLF. How to use a simple, safe and effective method to treat TOLF and reduce the occurrence of complications and improve the quality of life is a problem urgently needed to be solved in clinical practice [10].

In previous studies, our research team reported a surgical approach called Laminoplasty and In-site Regrafting (LPIR), which not only preserved the mobility of the spine, reduced the possibility of thoracic kyphosis deformity, but also prevented recurrence. Moreover, we conducted a retrospective study on the clinical effects of 8 consecutive patients with TOLF who received LPIR surgery, and no serious complications occurred, indicating that LPIR treatment for TOLF has high safety and feasibility [14]. However, the biomechanical characteristics of the spine and the biological changes of adjacent intervertebral discs after LPIR and laminectomy + pedicle screw fixation surgery for TOLF patients remain unclear. Therefore, the aim of this study is to evaluate whether there are differences in the stability of the spine and the biomechanical characteristics of adjacent intervertebral discs between LPIR surgery and the classic laminectomy + pedicle screw internal fixation surgery for TOLF patients, and to compare the reliability of the two surgical methods, providing a theoretical basis for clinical application.

2. Materials and Methods

2.1 Construction of the Complete T8-T12 Finite Element Model

A 23-year-old healthy male volunteer was selected and given informed consent. Spinal fractures, deformities, tumors, infections, and history of spinal surgery were excluded. This study was approved by the Medical Ethics Committee of Zunyi Medical University Affiliated Hospital (KLL-2024-316). Using 64-slice spiral CT plain scan, two-dimensional CT images of the T5-L3 segments of the volunteer were obtained and saved in DICOM format. The data were imported into the 3D modeling software Mimics (Materialise, Leuven, Belgium) to establish a 3D spinal model of T8-T12 vertebrae; then the model was

imported into the Geomagic software (Geomagic, Cary, North Carolina, USA) for further processing, including surface smoothing, filling of model holes, and completion of the reconstruction of the 3D model of T8-T12. The model was then imported into the Solidworks software (Solidworks Corporation, Boston, Massachusetts, USA) for further reconstruction of the solid model. The structures of cortical bone, cancellous bone, nucleus pulposus, annulus fibrosus, articular cartilage, and articular cartilage end plate were respectively constructed [21]. Finally, the model was imported into the ANSYS (Pennsylvania, United States) software to complete material assignment, ligament establishment, and meshing, and to construct the complete T8-T12 vertebral body finite element model (Finite Element FE), as shown in Fig. 1.

2.2 Construction of the complete finite element model for T8 to T12

In this study, the cortical bone thickness was set at 1 millimeter, and the endplate was set at 0.5 millimeter. A model based on the vertebral endplate, cancellous bone, and intervertebral disc was established. This model also included the annulus fibrosus and tetrahedral elements with 10 nodes, such as the pedicle, endplate, isthmus, spinous process, facet joint, and transverse process. The nucleus pulposus was defined as an incompressible liquid-like substance, and the volume ratio of the annulus fibrosus to the nucleus pulposus was set at 6:4 [21]. The anterior longitudinal ligament, posterior longitudinal ligament, supraspinous ligament, interspinous ligament, interspinous ligament, ligamentum flavum, and ligamentum nuchale of the finite element model were all simulated using nonlinear spring elements that only withstand tension [22, 23]. The positions, cross-sectional areas, and lengths of the elements were based on the actual anatomical structure. The bone was assumed to be uniform and isotropic. The internal fixation system was set as titanium alloy. Bone contact was applied in the vertebral body, endplate, and intervertebral disc. Frictionless contact was used to simulate the sliding contact between articular cartilage. Fixed contact was set between the vertebral body and the screw, and between the screw and the rod. The material parameters of the finite element model are shown in Table 1 [21, 23, 24].

structure	Young's Modulus (MPa)	Poisson's Ratio
cortical bone	12000	0.3
cancellous bone	100	0.2
Endplate	1000	0.3
posterior bone structure	3500	0.25
Cartilage	50	0.3
Nucleus pulposus	9	0.4
Annulus fibrosus	5	0.45
Plates、screws、and screws	110000	0.28
Anterior ligaments	20	0.3
Posterior ligaments	20	0.3
Flavum ligaments	19.5	0.3
Supraspinal ligaments	59	0.3
Interspinal ligaments	15	0.3
Intertransverse ligaments	12	0.3
Capsular ligaments	75	0.3

Table 1 Element Types and Material Parameters of the Finite Element Model for T8-T12

2.3 Establishment of Two Internal Fixation Models

LPIR: Firstly, the T9 (T11 vertebral body segment) is regarded as the lesion segment of TOLF. The centerlines of the bilateral facet joints are defined as the bilateral decompression boundaries. The medial lamina is removed along the decompression boundaries, and the ossified ligamentum flavum is fully treated. Then, a pre-bent titanium plate is fixed onto the lamina, and the length of the titanium plate needs to cover the origin of the spinous process, lamina and transverse process (as shown in Fig. 2a). Vertebral Plate Resection (LSPT): Using the centerlines of the bilateral facet joints as the boundary, the vertebral plate, spinous process, ligamentum flavum and interspinous ligament are completely removed. Two 5.5*45mm pedicle screws and two 90mm rods are respectively placed at the bilateral pedicles of T9, T10 and T11 (as shown in Fig. 2b). All the models are drawn using SolidWorks software.

2.4 Boundary and Load Conditions

The bottom of the T12 vertebra is constrained in the x, y, and z directions, with no displacement or rotation in any direction. A load of 500N is applied vertically above the T8 vertebra, and a load of 7.5N.m is applied on the upper surface of the T8 vertebra to simulate movements including flexion, extension, bending, and rotation.

3. Results

3.1 Verification of the Finite Element Model

In this study, we established a complete spinal model of T8 (T12 vertebrae) and applied a torque of 7.5 N.m to simulate body movements. The range of motion (ROM) values for the T8 (T12) segment during flexion were 5.26°, extension were 5.60°, left flexion were 4.35°, right flexion were 4.52°, left rotation were 2.07°, and right rotation were 2.18°. These results were similar to those reported by Zhang [21] and Basaran [25] et al. (as shown in Table 2). Therefore, the finite element model in this study is highly realistic and can be applied to this research.

	Present Study	Zhang et al.	Basaran et al.
Flexion	5.26	5.3±1.0	4.5±0.9
Extention	5.60	5.3±1.0	4.5±0.9
Left bending	4.35	4.3±0.1	4.2±0.8
Right bending	4.52	4.3±0.1	4.2±0.8
Left rotation	2.07	2.1±0.2	2.3±0.6
Right rotation	2.18	2.1±0.2	2.3±0.6

Table 2 Range of Motion in the T8-T12 normal model compared with models from previous studies

3.2 Range of motion (ROM) of T8 (T12 vertebral bodies under two surgical methods

The overall maximum ROM of T8 (T12 vertebral bodies in both internal fixation groups was found during flexion movement. The overall ROM was the highest in the laminaoplasty and in situ replantation (LPIR) group, at 1.58°, while it was 0.40° in the lamina resection (LSPT) group. Specific data (as shown in Table 3 and Figure 3) are provided.

	LSPT	LPIR
Flexion	0.40	1.58
Extention	0.03	0.17
Left bending	0.23	1.03
Right bending	0.25	1.17
Left rotation	0.27	0.66
Right rotation	0.26	0.67

Table 3 Maximum range of motion ROM of T8-T12 overall（°）

3.3 ROM Distribution of Fixed Segments

In both LPIR and LSPT internal fixation methods, the maximum ROM of the fixed segments (T9 and T11 vertebral bodies) were 1.14° and 0.20° respectively. In LSPT, the percentage of the fixed segment's ROM in the overall ROM was the lowest, at 50%. This indicates that the stability of LSPT is higher than that of LPIR. The ROM of the fixed segments was reasonably distributed across all segments, avoiding concentration on the fixed segment vertebrae.

3.4 Range of Motion of Adjacent Segments

The results of this study show that the range of motion of the proximal adjacent vertebral segments in the two internal fixation methods is greater than that of the distal adjacent vertebral segments. The range of motion of the proximal adjacent vertebral segments in the LPIR and LSPT groups was 1.58° and 0.40° respectively. While the range of motion of the distal adjacent vertebral segments was 0.43° and 0.05° (as shown in Figure 4). The maximum range of motion occurred in the LPIR group at 1.58°, and the range of motion of the adjacent vertebral segments in the LSPT group was the smallest, at 0.05°.

3.5 Von Mises stress on adjacent intervertebral discs

Similar to the ROM results of the adjacent segments, the Von Mises stress of the proximal intervertebral disc was higher than that of the distal intervertebral disc. In the LPIR and LSPT groups, the maximum stress of the proximal intervertebral disc occurred during forward flexion, being 2.30 MPa and 2.12 MPa respectively; the maximum stress of the distal intervertebral disc occurred during forward flexion and left flexion, being 1.79 MPa and 0.87 MPa respectively. The Von Mises stress values of adjacent intervertebral discs and the cloud diagrams (as shown in Figures 5 and 6) are presented.

3.6 Von Mises stress on screws and plates

In the LPIR and LSPT groups, LPIR showed the maximum Von Mises stress when rotating to the right, which was 363.06 MPa. For all types of movements in the LPIR group, the maximum stress of the plate occurred near the plate-screw connection area near the lamina resection boundary; in the LSPT group, the maximum Von Mises stress was shown when flexing forward, which was 60.51 MPa. For all types of movements in the LSPT group, the maximum stress of the pedicle screw was found at the connection point between the pedicle screw and the rod. Stress maps of the titanium plate and pedicle screws in LPIR and LSPT (as shown in Figure 7).

4. Discussion

TOLF has an insidious onset and progresses gradually. Although the symptoms are mild, it may cause severe spinal cord compression [26]. When TOLF patients present with progressive neurological deficits, conservative treatment is usually ineffective, and decompression surgery should be performed as soon as possible to prevent irreversible spinal cord injury. Currently, there is no unified standard for the surgical treatment of TOLF. Posterior open laminectomy (with or without internal fixation and fusion) is the most commonly used surgical method because it can achieve complete decompression of the

ossified area [27]. However, traditional open laminectomy requires the removal of a large amount of ligamentous tissue and facet joints, which may lead to spinal instability and postoperative complications, including instability of the operated segment, secondary thoracic kyphosis, deterioration of neurological function, and degeneration of adjacent segments [28, 29]. In previous studies, our research team reported an improved surgical technique called laminoplasty and in situ reimplantation (LPIR), and the results indicated that LPIR is safe and feasible for the treatment of TOLF [14]. However, the biomechanical characteristics of spinal stability and adjacent segment intervertebral disc degeneration after LPIR and posterior open laminectomy in TOLF patients remain unclear. Therefore, the purpose of this study is to analyze the biomechanical characteristics of spinal stability and adjacent segment intervertebral disc degeneration after LPIR and laminectomy in TOLF patients, compare the reliability of the two surgical methods, and provide a theoretical basis for clinical application.

Firstly, in this study, we compared the overall range of motion (ROM) and ROM distribution of T8 (T12) in two surgical methods, LPIR and LSPT, to investigate the stability of the spine after fixation. Previous studies have shown that the main cause of postoperative instability of the lumbar spine is the loss of posterior structure support and fixation, resulting in a decrease in the ability to resist rotation and shear [30]. Minamide [31, 32] et al. believed that total or partial laminectomy, especially when the spinous process, bilateral laminae, and bilateral facet joints are destroyed, often affects lumbar spine stability, leading to postoperative low back pain, weakness, and eventually spondylolisthesis, requiring reoperation. Therefore, a strong fixation system after surgery is essential. Strong fixation can provide immediate stability to the surgical segment, promote fusion, enable patients to get out of bed early, and improve their quality of life. In this study, as shown in Table 3, Fig. 3, and Fig. 4, under the fixation of both LPIR and LSPT surgical methods, regardless of the type of movement, the overall ROM of LSPT was smaller, and the proportion of ROM of the fixed segment vertebrae to the overall ROM of T8 (T12) was also smaller. This indicates that the spine has better stability after LSPT, and the ROM distribution is more reasonable, which can prevent excessive abnormal movement of the spine. In contrast, the stability of LPIR is slightly worse, and the ROM distribution is also not ideal. This is mainly because after laminectomy, long-segment pedicle screw fixation systems bear most of the load, providing sufficient stability to the surgical segment and limiting its movement. Although laminectomy can provide better stability, it also limits the flexibility of the spine.

Adjacent segment degeneration is a common complication after spinal internal fixation. A recent study found that patients who underwent spinal fusion surgery had an increased incidence of adjacent segments due to the increased pressure caused by fixation and the loss of the posterior ligament complex [33]. Another study showed that excessive posterior spinal internal fixation would increase the pressure at both ends of the fixation structure, thereby accelerating the degeneration of the intervertebral discs in adjacent segments and leading to the occurrence of transitional kyphosis [34]. In addition, clinical studies have shown that although laminectomy is the most commonly used spinal cord decompression surgery for TOLF and achieves good spinal cord decompression, it is prone to dural tear, postoperative kyphosis, and intersegmental instability and other complications [29]. Therefore, an appropriate surgical method and internal fixation technique should not only provide sufficient fixation

strength to maintain spinal stability but also reduce the stress on adjacent segments to lower the possibility of adjacent segment degeneration. In our study, it was observed that in the LPIR group, the maximum stress on the adjacent intervertebral discs of the surgical segment was 2.30 MPa and 1.79 MPa, respectively, both occurring during flexion. In the laminectomy (LSPT) group, the maximum stress on the adjacent intervertebral discs was 2.12 MPa and 0.87 MPa, respectively, occurring during flexion and left bending. This is because the intervertebral discs and facet joints have poor resistance to rotation and lateral bending during the transition from the coronal plane to the sagittal plane. Overall, the intervertebral discs in the LPIR group bore higher stress, indicating a higher risk of adjacent segment degeneration. This may be due to the fact that LPIR uses titanium plates to reimplant the lamina in situ without using pedicle screws for fixation, so the patients undergoing LPIR surgery have higher mobility to maintain spinal flexibility, and the intervertebral discs bear relatively greater stress.

Furthermore, in this study, we compared and analyzed the von Mises stress of the pedicle screw internal fixation system and the titanium plate under different motion conditions for the two groups of internal fixation methods. From the stress cloud diagrams, it can be observed that LPIR showed the maximum von Mises stress when rotating on the right side, which was 363.06 MPa. In the laminectomy group, the maximum von Mises stress was shown during flexion, which was 60.51 MPa. The results indicate that the von Mises stress under LPIR internal fixation is high regardless of the motion condition. This is because the LPIR procedure uses titanium plates for fixation, and the titanium screws used are shorter, resulting in greater spinal mobility. The stress concentration in the adjacent segments leads to greater stress being borne by the adjacent intervertebral discs and the titanium plate, which is consistent with the above results. After laminectomy, since most of the posterior structures of the spine are removed, pedicle screws are needed for fixation to provide sufficient stability. The pedicle screws can withstand a certain amount of load stress, thereby reducing the stress borne by the internal fixation devices and reducing the risk of screw fracture or loosening [35]. As shown by the stress cloud diagram distribution, the maximum stress of the pedicle screws all occurred at the connection point between the pedicle screw and the rod, which is consistent with the location of most clinical screw fractures. Although the titanium plate in the LPIR internal fixation procedure bears a large stress, the maximum stress is far less than the yield strength of the titanium alloy material. The maximum stress that the titanium alloy plate and screws can withstand is 795 MPa [36].

This study also has some limitations. Firstly, the finite element analysis can only simulate the movement of the spine in six directions, which may not fully represent all the characteristics of the human body. Additionally, the biomechanical properties of different fixation techniques may vary due to anatomical factors and other factors. For instance, this study did not consider the role of muscle soft tissues, which play a role in pulling and stabilizing the spine during movement. Moreover, the geometric shapes of intervertebral discs and facet joints vary among different patients, which may lead to errors in the stiffness and mechanical stress of the model compared to the actual situation in the body. In future research, we plan to conduct a clinical, randomized, double-blind, controlled study to test the safety and usability of our research results.

5. Conclusion

In this study, there were no significant differences between the two internal fixation techniques in terms of the overall ROM of the T8 (T12 vertebral body), the ROM distribution of the fixed segment, the ROM of the adjacent segments, and the stress of the adjacent intervertebral discs. Compared with LPIR, although the laminectomy + pedicle screw internal fixation technique can provide better stability, it reduces the flexibility of the spine. The spine after LPIR has better flexibility, so the stress borne by the adjacent intervertebral discs is greater, thereby increasing the possibility of degeneration of the adjacent segments, and the titanium plate also bears greater stress, but it is far less than the yield strength of the titanium alloy material. Therefore, we believe that LPIR is a feasible treatment strategy for TOLF.

Declarations

Author Contribution

Author contributions: Bao CS, Chen F: Data measurement, data analysis, main contributors to writing the paper.Wei GH, Liao SL, You TY, He L , Qin JP :Participated in study conception, supervised data measurement, and data analysis . Ao J and Qian H Participated in study design, data analysis, and paper revision. All the authors read and approved the final manuscript.

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Figures

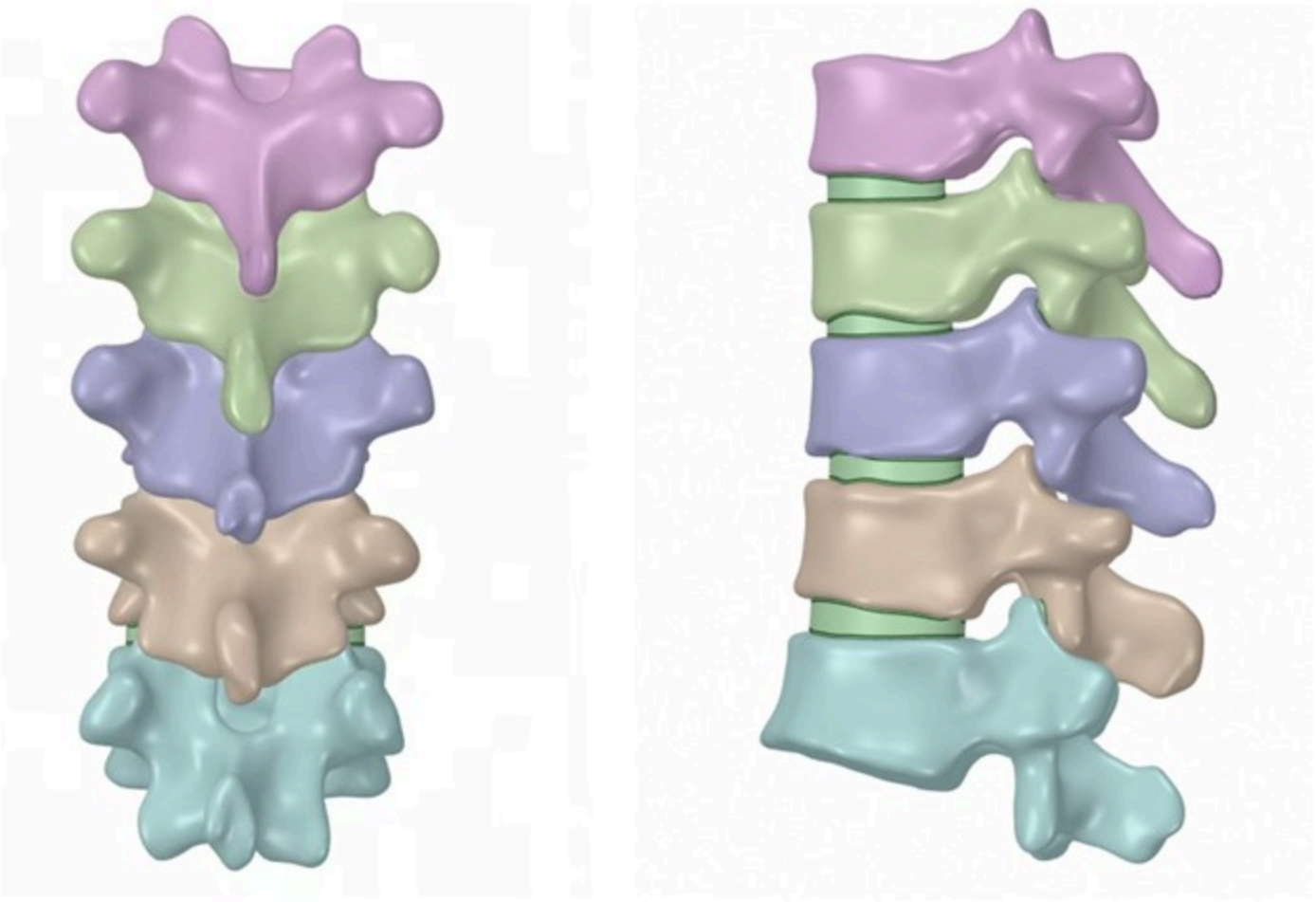


Figure 1

Complete finite element model of T8 to T12 vertebrae

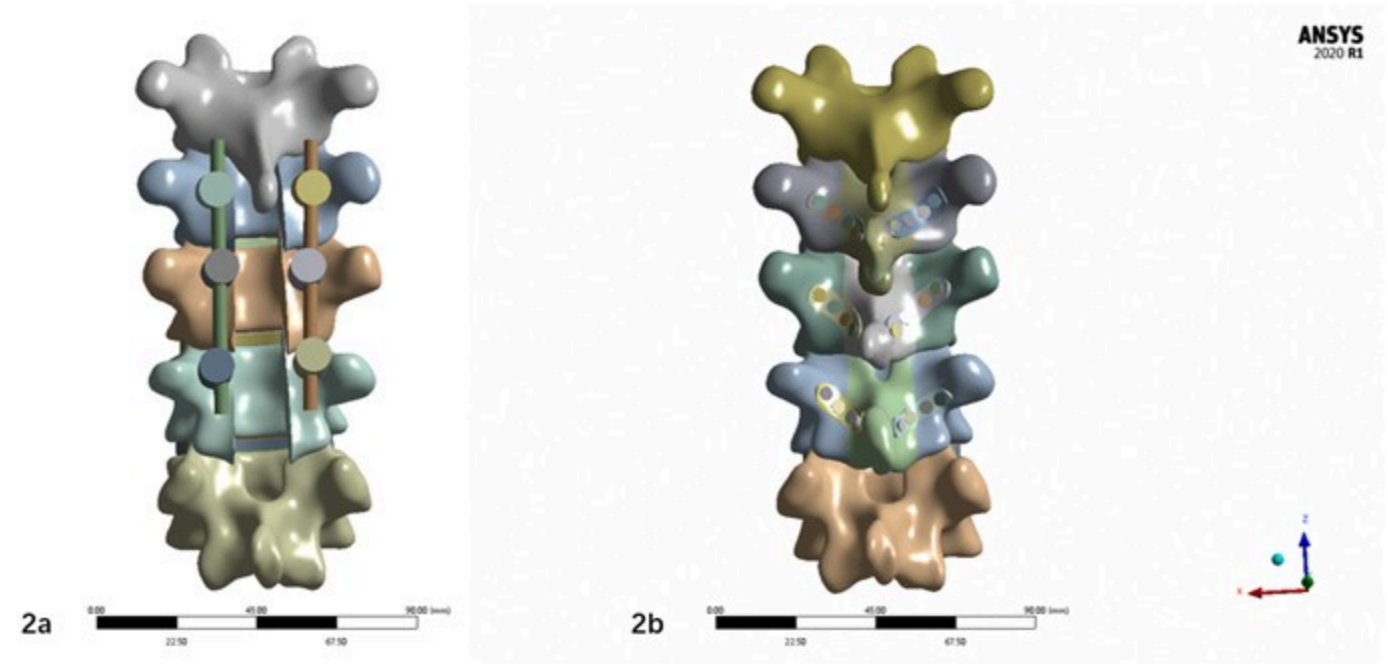


Figure 2

Two models of surgical internal fixation schemes, 2a is LPIR and 2b is LSPT

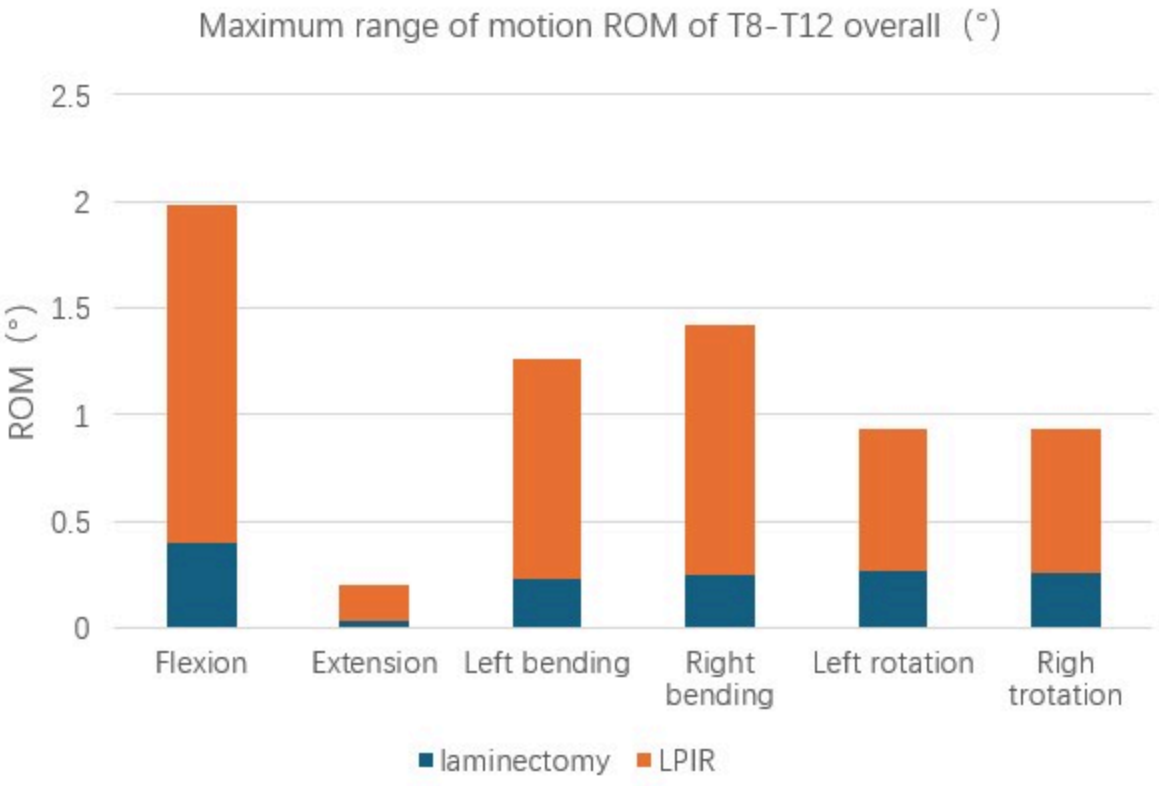


Figure 3

Maximum range of motion ROM of T8-T12 overall□°□

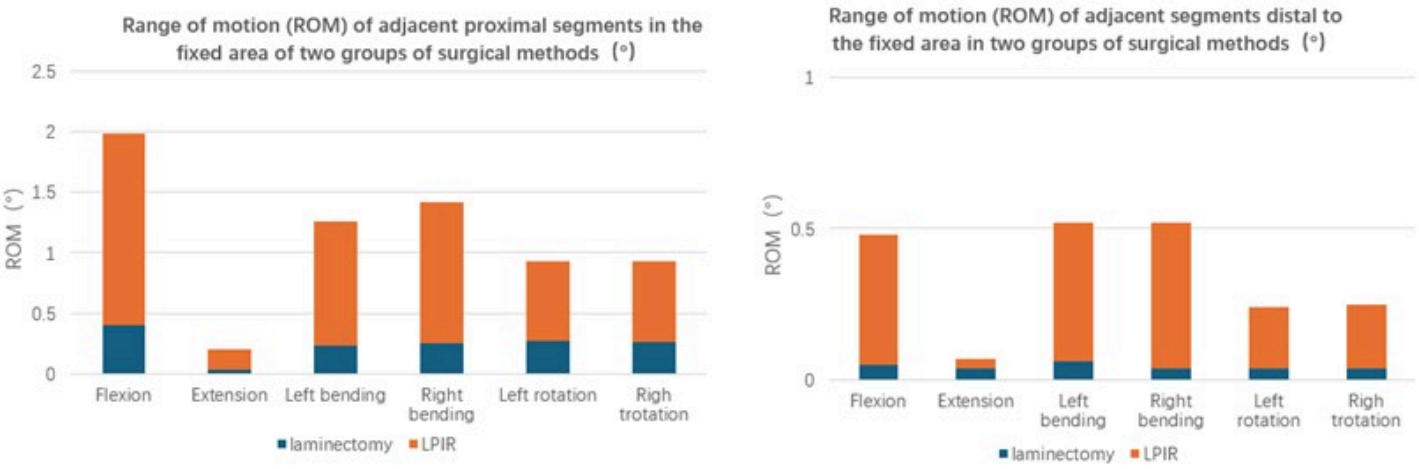


Figure 4

The ROM of adjacent segments in the fixed areas of the two groups of surgical methods □°□

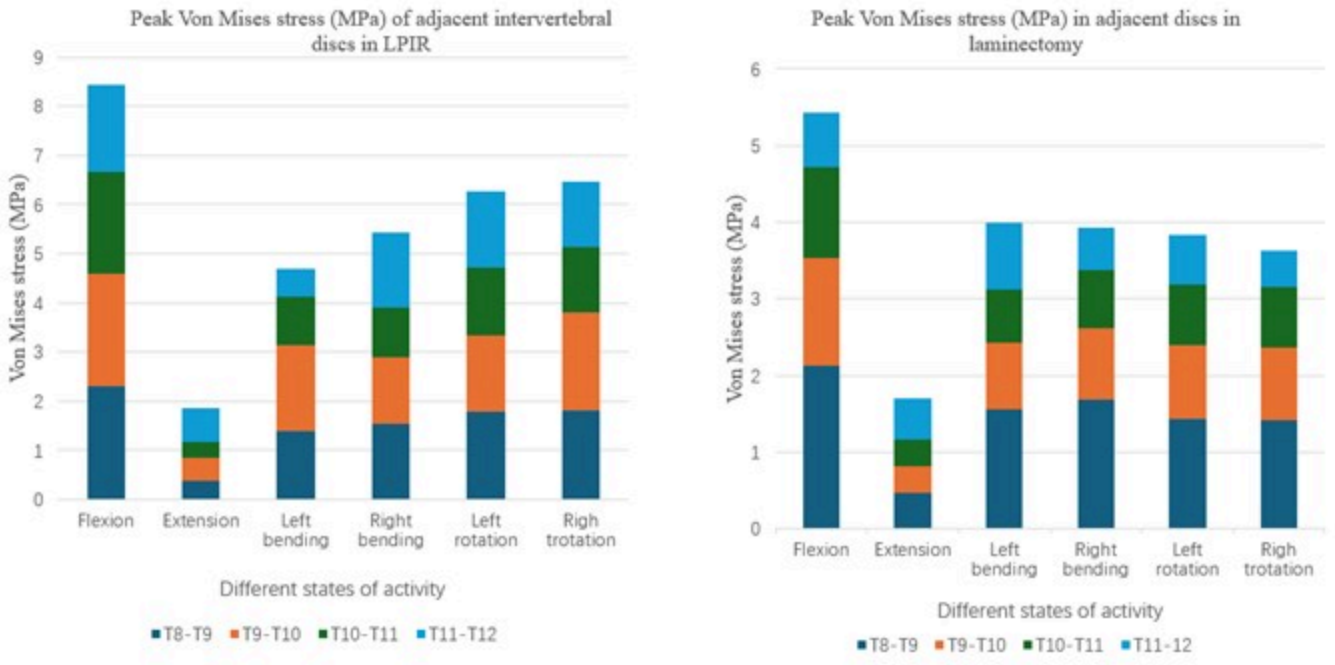


Figure 5

Von Mises stress values of adjacent intervertebral discs for the two groups of surgical methods

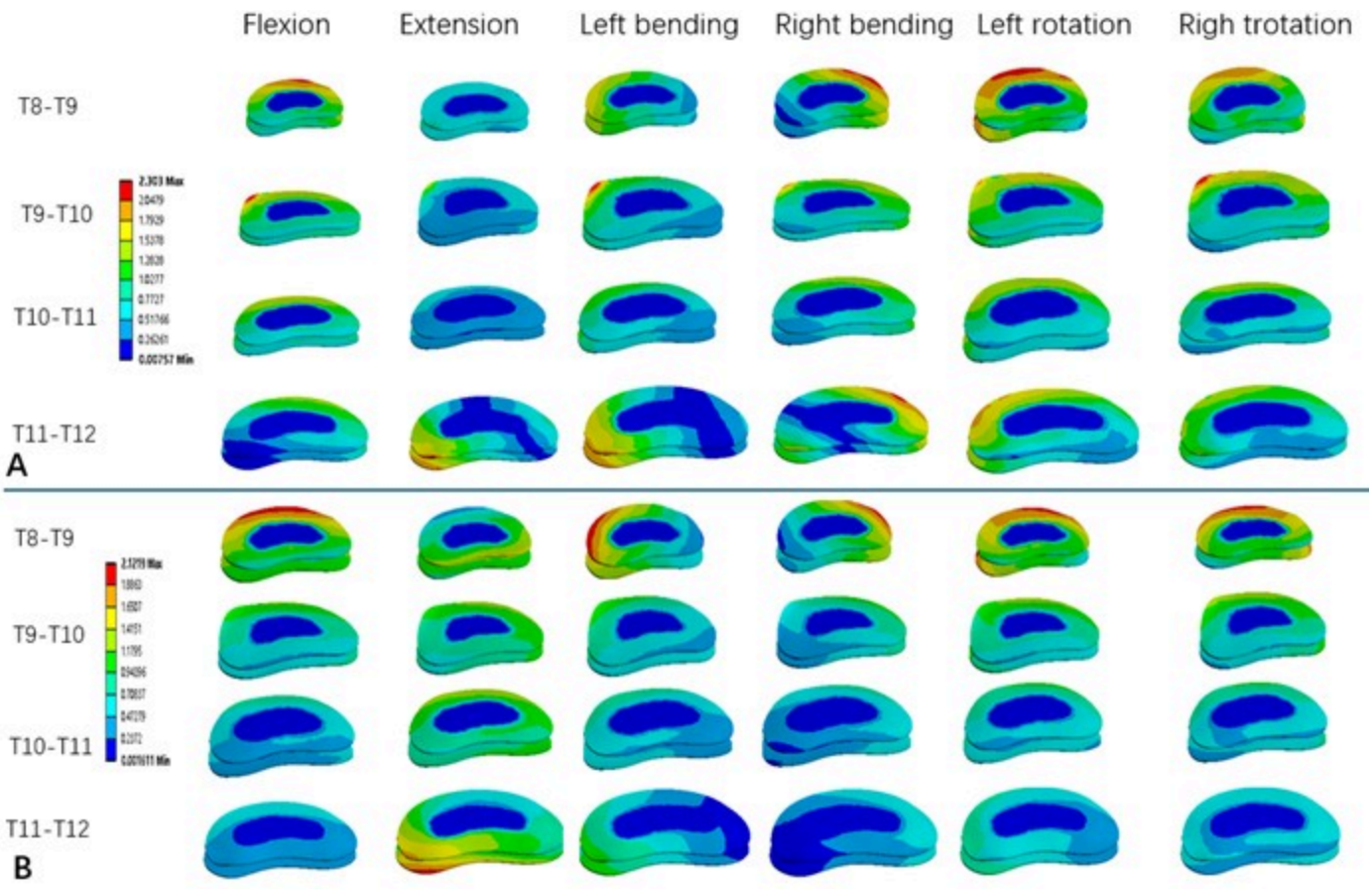


Figure 6

Von Mises stress distribution maps of adjacent intervertebral discs for the two groups of surgical methods; A: LPIR, B: LSPT

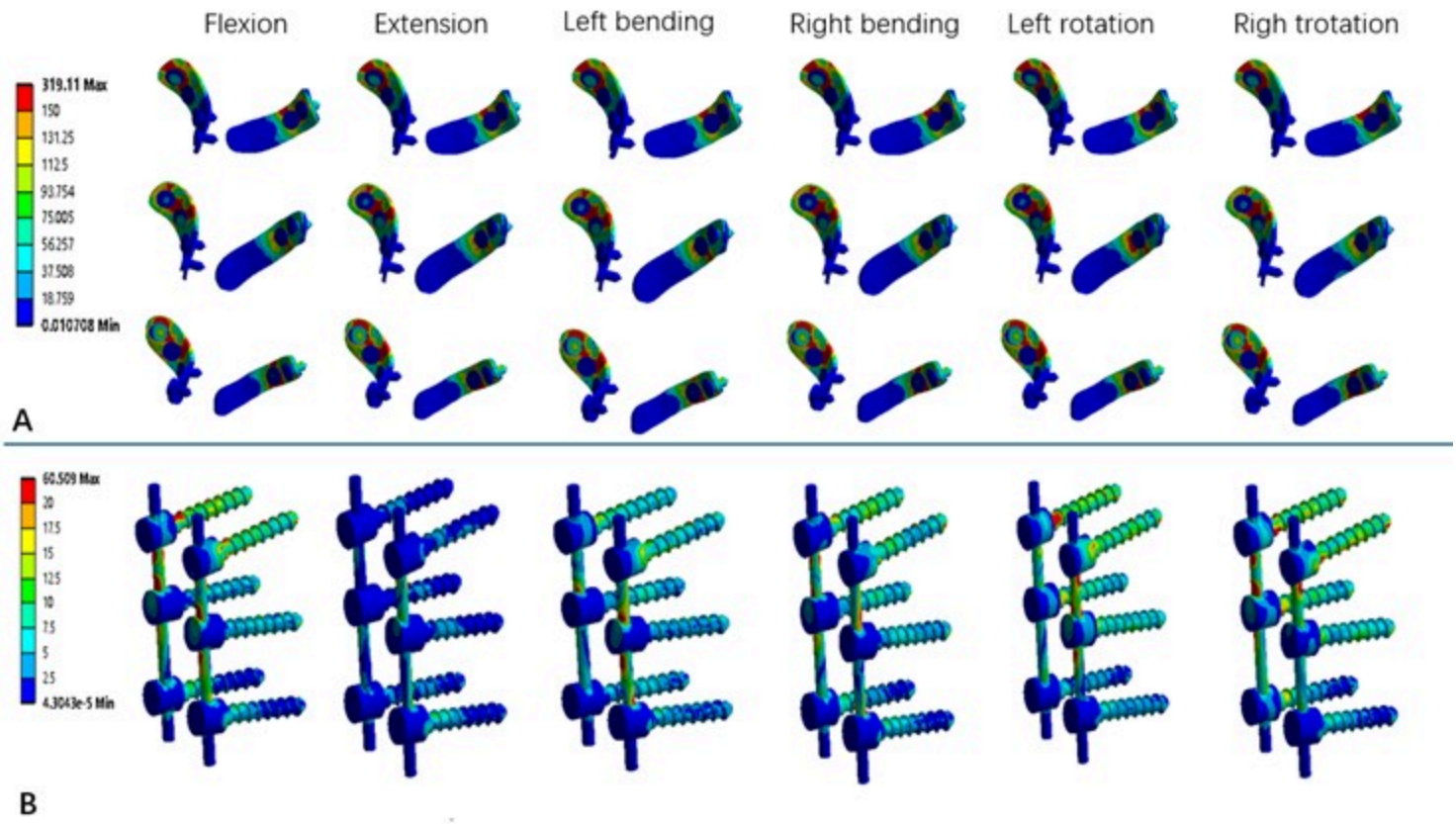


Figure 7

Von Mises stress distribution maps of internal fixation devices for the two groups of surgical methods; A: LPIR, B: LSPT