



Biomechanical Effects of Thoracic Flexibility and Stiffness on Lumbar Spine Loading: A Finite Element Analysis Study

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■ **OBJECTIVE:** To determine the effects of thoracic stiffness on mechanical stress in the lumbar spine during motion.

■ **METHODS:** To evaluate the effect of preoperative thoracic flexibility, stiff and flexible spine models were created by changing the material properties of ligaments and discs in the thoracic spine. Total laminectomy was performed at L4/5 in stiff and flexible models. A biomechanical investigation and finite element analysis were performed preoperatively and postoperatively. A hybrid loading condition was applied, and the range of motion (ROM) at each segment and maximum stress in the discs and pars interarticularis were computed.

■ **RESULTS:** In the preoperative model with the stiff thoracic spine, lumbar disc stress, lumbar ROM, and pars interarticularis stress at L5 increased. In contrast, as the thoracic spine became more flexible, lumbar disc stress, lumbar ROM, and pars interarticularis stress at L5 decreased. All L4/5 laminectomy models had increased instability and ROM at L4/5. To evaluate the effect of thoracic flexibility on the lumbar spine, differences between the stiff and flexible thoracic spine were examined: Differences in ROM and intervertebral disc stress at L4/5 in flexion between the stiff and flexible thoracic spine were respectively 0.7° and 0.0179 MPa preoperatively and 1.5° and 0.0367 MPa in the L4/5 laminectomy model.

■ **CONCLUSIONS:** Biomechanically, disc stress and pars interarticularis stress decrease in the flexible thoracic spine. Flexibility of the thoracic spine reduces lumbar spine loading and could help to prevent stress-related disorders.

INTRODUCTION

Increased stress in the lumbar spine can cause a variety of lumbar spine disorders.

Thickening of the ligamentum flavum, which causes lumbar spinal canal stenosis, can occur due to increased mechanical stress according to finite element (FE) analysis and animal model studies.^{1,2} In young people, excessive increased lumbar stress from sports can cause various sports-related lumbosacral stress injuries.³ In addition, after lumbar spine surgery, braces are worn and rehabilitation instruction is provided to reduce lumbar stress. It is possible that reducing lumbar stress may prevent the development of lumbar stress-related disorders.

In general clinical practice, attention tends to be focused on only the affected area. For example, in the case of lumbar diseases, the lumbar spine is the focus of diagnosis and treatment. However, in diagnosis and treatment, not only the affected area but also the adjacent joints are important to consider. In the joint-by-joint theory proposed by the American physical therapist Gray

Key words

- A finite element analysis study
- Biomechanical study
- Flexibility
- Joint by joint theory
- Lumbar
- Stiffness
- Thoracic

Abbreviations and Acronyms

F(25): a 25% decrease in thoracic ligament and disc flexibility
F(50): a 50% decrease in thoracic ligament and disc flexibility by 50%
FE: finite element
La-F(50): laminectomy performed in the F(50) model at L4/5
La-Intact: laminectomy performed in the Intact model at L4/5
La-S(50): laminectomy performed in the S(50) model at L4/5
LBP: Low back pain

ROM: range of motion Intact intact finite element model

S(25): a 25% increase in thoracic ligament and disc stiffness

S(50): a 50% increase in thoracic ligament and disc stiffness

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Gook,⁴ focus is placed on the movement of each joint, including adjacent joints. Moreover, the joints are categorized as stability joints or mobility joints depending on their function and can present alternately. According to this theory, the lower cervical and lumbar regions of the spine contain stability joints and the thoracic region consists of mobility joints. The joint-by-joint theory has been applied in rehabilitation, and it has been suggested that not only treatment of the affected lumbar spine but also improvement of flexibility in the thoracic spine can reduce LBP.⁵ Therefore, we believe that it is important to consider movement of the thoracic spine that is adjacent to the lumbar spine. However, the importance of the relationship between the lumbar and thoracic spine is not as well understood as that between the lumbar spine and hip joint, as typified by the hip-spine syndrome.⁶ Moreover, there has been no biomechanical validation of the relationship between the lumbar spine and the thoracic spine.

Therefore, the purpose of this study was to evaluate the effects of thoracic flexibility on mechanical stress in the lumbar spine by three-dimensional (3D) FE analysis. Our hypothesis was that improving the flexibility of the thoracic spine would help to prevent the development of lumbar stress-related disorders by reducing the lumbar spine loading during motion.

MATERIALS AND METHODS

Intact Finite Element Model

A nonlinear ligamentous FE model was developed based on computed tomography (CT) imaging of a healthy patient with no abnormalities, degeneration, or deformities. MIMICS software (Materialise, Leuven, Belgium) was used to construct the 3D geometry of the bones. The model contained a rib cage, thoracolumbar spine, pelvis, and both femurs (Figure 1) and was fixed at the base.⁷⁻¹⁰ Spine discs were created by filling the space

between each pair of vertebrae based on the CT images. Then, Geomagic Studio software (Raindrop Geomagic Inc., USA) was used for smoothing in preparation for meshing. IAFEMESH software (University of Iowa, Iowa City, IA) was used for meshing the spinal discs, while HyperMesh software (Altair Engineering, Inc., Troy, MI) was used for meshing the vertebrae and pelvis. Nodes and elements were generated after meshing. Nodes were used to measure range of motion (ROM) for each functional spine unit, which was calculated by subtracting the angular displacement of the upper vertebra from the lower vertebra. We call this the “Intact” model and have used it in previous biomechanical simulations of a variety of surgical procedures and instrumentation systems, and the details of the model and validation data are well documented.¹¹

The vertebral bodies were modeled as a cancellous bone core surrounded by a 0.5-mm-thick cortical bone shell, both of which were modeled as a linear elastic isotropic material.¹⁰ The intervertebral discs were simulated as composite structures that included a solid matrix embedded with fibers in concentric rings. This structure simulated the annulus fibrosis surrounding a pseudo-fluid nucleus, which in turn was simulated as a linearly elastic material. Three-dimensional (3D) hexagonal elements were used to define the ground substance, and the REBAR “no compression” behavior option was used to define the reinforced fibers oriented at alternating angles of 30° to horizontal.⁸⁻¹⁰ The facet joints were simulated using three-dimensional gap elements with an initial defined clearance of 0.5 mm. All ligamentous structures were modeled as hypoelastic materials with the “tension only” property. The material properties used in the human thoracic-pelvic FE model were obtained from the published literature⁷⁻¹⁰ and are listed in Table 1. The thoracic spine consisted of 104,450 elements and 121,045 nodes, the lumbar spine consisted of 49,441 elements and 56,679 nodes, and the pelvis consisted of 31,307 elements and 39,673 nodes.

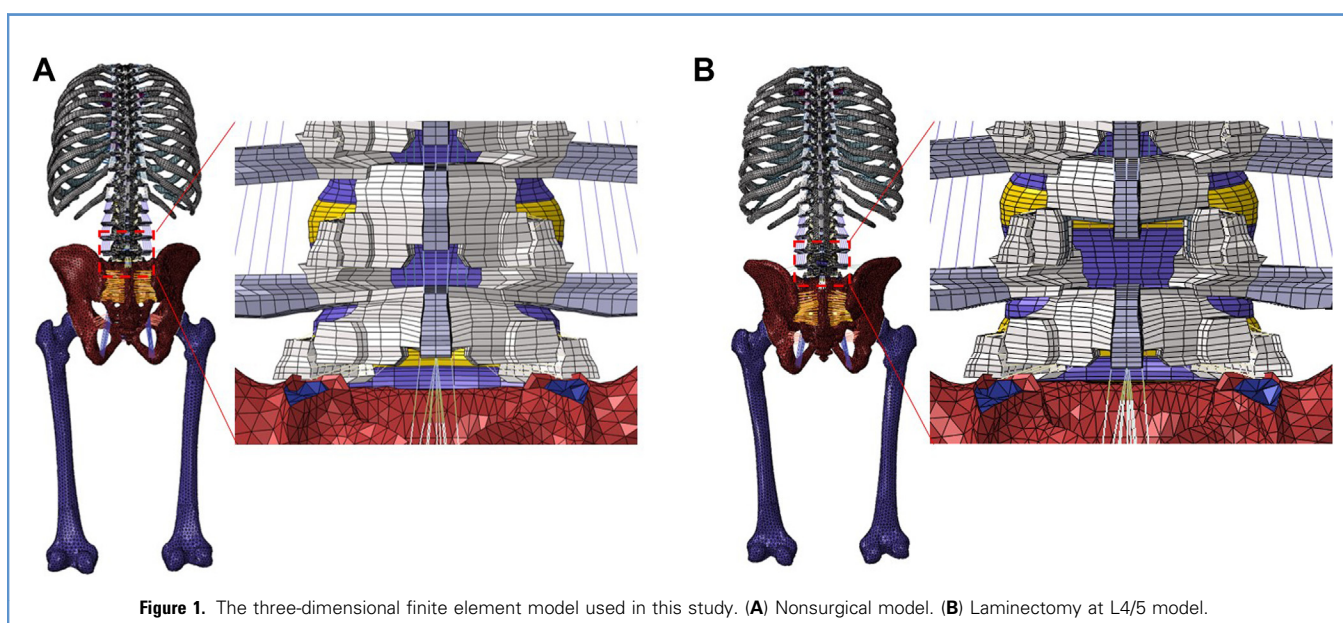


Figure 1. The three-dimensional finite element model used in this study. (A) Nonsurgical model. (B) Laminectomy at L4/5 model.

Table 1. Relevant Material Properties Applied to the Finite Element Model Obtained From the Literature

Bony Structure	Material model/Element Type	Young's Modulus	Poisson's Ratio
Cortical bone	Isotropic, elastic/hexahedral elements	12,000	0.3
Cancellous bone	Isotropic, elastic/hexahedral elements	100	0.2
Intervertebral disc			
Annulus ground substance	Isotropic, elastic/hexahedral elements	4.2	0.45
Annulus (fibers)	Rebar	357–550	0.3
Nucleus pulposus	Incompressible, isotropic, elastic/hexahedral elements	9	0.4999
Ligaments			
Anterior longitudinal	Tension-only, truss elements	7.8 (<12%), 20.0 (>12%)	0.3
Posterior longitudinal	Tension-only, truss elements	10.0 (<11%), 20.0 (>11%)	0.3
Ligamentum flavum	Tension-only, truss elements	15.0 (<6.2%), 19.5 (>6.2%)	0.3
Intertransverse	Tension-only, truss elements	10.0 (<18%), 58.7 (>18%)	0.3
Interspinous	Tension-only, truss elements	10.0 (<14%), 11.6 (>14%)	0.3
Supraspinous	Tension-only, truss elements	8.0 (<20%), 15.0 (>20%)	
Capsular	Tension-only, truss elements	7.5 (<25%), 32.9 (>25%)	0.3
Joint			
Apophyseal joints	Non-linear soft contact, GAPPUNI elements		
Instrumentation			
PEEK (interbody cage)	Isotropic, elastic/hexahedral elements	3500	0.3
Titanium (rods)	Isotropic, elastic/hexahedral elements	120,000	0.3
Pedicle screws (Ti alloy)	Isotropic, elastic/hexahedral elements	110,000	0.3

Stiff and Flexible Thoracic Models

The stiff and flexible thoracic spine models were based on the model of Kiapour et al.,¹² who reproduced a flexible and stiff lumbar spine by creating flexible and stiff lumbar ligament and annulus fibrosus elements. Therefore, in this study, to create the stiff thoracic spine model, the ligament and annulus fibrosus elements of the thoracic vertebrae were stiffened. The thoracic ligament and annulus fibrosus elements with a 25% increase in stiffness were defined as the Stiffness 25% [S(25)] model, and those with a 50% increase in stiffness were defined as the Stiffness 50% [S(50)] model. On the other hand, the thoracic ligament and annulus fibrosus elements with a 25% increase in flexibility were defined as Flexibility 25% [F(25)], and those with a 50% increase in flexibility were defined as Flexibility 50% [F(50)].

Physiological loading was simulated by a follower load based on upper body mass and muscle contractions at different vertebral levels and was applied via wire connectors attached to the left and right sides of each vertebral body following the curvature of the spine.¹³ A 4-nm moment was applied to the superior surface of the T1 vertebra of the intact spine to simulate flexion, extension, left/right bending, and left/right axial rotation (Figure 2).¹¹

A hybrid loading protocol was simulated in the rigid and flexible models and included the follower load plus a gradually increasing bending moment applied to the top of T1.¹² The moment was increased until the overall motion of the T1-S1

segment matched that of the intact spine. The biomechanical data, including the hybrid moment, segmental kinematics, intradiscal pressure, and peak stress in the pars interarticularis across the segments were analyzed and compared between cases.

Bilateral Laminectomy Models

The Intact, S(50), and F(50) models were modified to simulate bilateral laminectomy models. The medial aspects of the facets and the adjacent lamina were removed on both sides, as was the ligamentum flavum. The supraspinous and interspinous ligaments and half of the spinous process were removed (Figure 1). This decompression surgery was performed at L4/5 in the Intact, S(50), and F(50) models and for the purposes of this report is referred to as laminectomy in the Intact [La-Intact], S(50) [La-S(50)], and F(50) [La-F(50)] models.

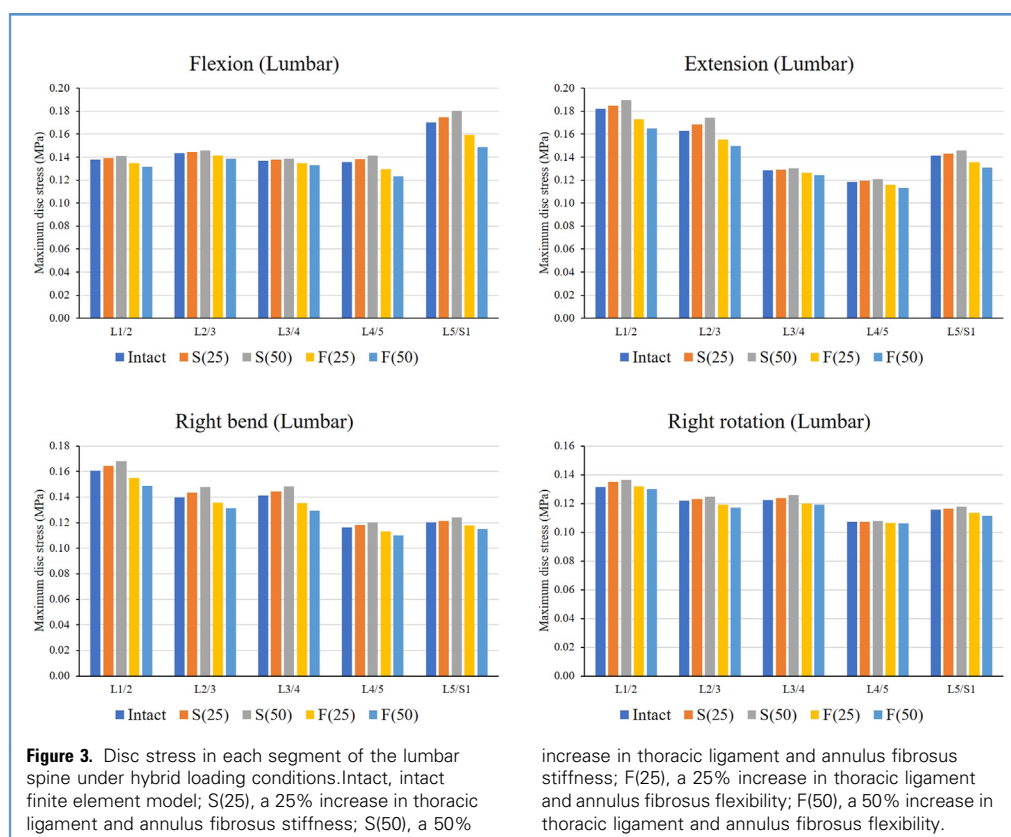
RESULTS

Nonsurgical Model

We applied angular motion displacement of Intact model at 4 Nm to the other models for hybrid loading. The ROM of each lumbar vertebra increased in the S(25) and S(50) models and decreased in the F(25) and F(50) models (Figure 2).

Figure 3 shows the maximum stress on the intervertebral discs during motion of the spine under hybrid loading conditions. In the Intact model, the mean maximum intervertebral disc stress





was 0.137 MPa during all flexion, extension, lateral bending, and axial rotation movements at L5/S1. Similarly, the mean intervertebral disc stress was 0.139 MPa in the S(25) model and 0.142 MPa in the S(50) model. Stiffening the spine increased the intervertebral disc stress to 101.4% in the S(25) model and 103.7% in the S(50) model. In contrast, the intervertebral disc stress in the F(25) and F(50) models decreased to 96.1% (0.132 MPa) and 92.4% (0.127 MPa), respectively.

Figure 4 shows the maximum stress on the pars interarticularis during spine motion under hybrid loading conditions. Because spondylolysis most commonly occurs at L5,¹⁴ we evaluated the maximum stress on the pars at L5 in extension; this level has the highest incidence of spondylolysis. The maximum stress of the pars at L5 in the Intact model was 57.6 MPa. Compared with the Intact model, stiffening the thoracic spine increased the pars stress to 106.2% (61.1 MPa) in the S(25) model and 111.5% (64.1 MPa) in the S(50) model. In contrast, the pars stress in the F(25) and F(50) models decreased to 92.5% (53.2 MPa) and 82.8% (47.7 MPa), respectively.

Bilateral Laminectomy Models

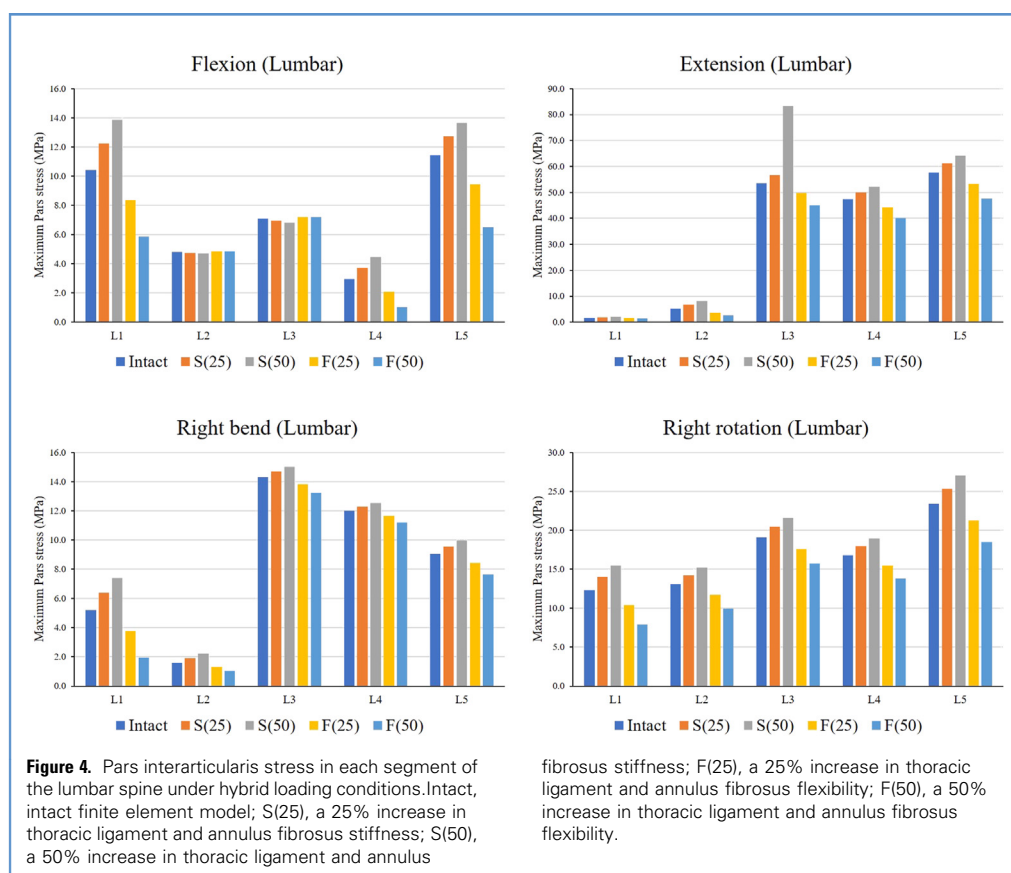
The effect of laminectomy at L4/5 was investigated under hybrid loading. Laminectomy has little effect on bending and rotation movements, and the Intact and La-Intact models, the S(50) and La-S(50) models, and the F(50) and La-F(50) models had nearly identical ROM in lateral bending and rotation (**Figure 5**). However,

laminectomy led to instability at L4/5 particularly during flexion but also during extension. In flexion, the ROM of the Intact, S(50), and F(50) models were 3.5°, 3.7°, and 3.0°, while that of the La-Intact, La-S(50), and La-F(50) models was 5.1°, 5.2°, and 3.5°, indicating increased postoperative ROM. Showing the effect of thoracic flexibility on the lumbar spine, the difference between S(50) and F(50) and that between La-S(50) and La-F(50) were 0.7° and 1.5°, respectively. In extension, the difference between S(50) and F(50) and that between La-S(50) and La-F(50) were 0.4° and 0.5°, respectively. The effect of thoracic spine stiffness on ROM in flexion and extension was stronger postoperatively.

The effect of thoracic stiffness on intervertebral disc stress in flexion and extension was also stronger postoperatively (**Figure 6**). In flexion, the difference between S(50) and F(50) and that between La-S(50) and La-F(50) were 0.0179 MPa and 0.0367 MPa, respectively. In extension, the difference between S(50) and F(50) and that between La-S(50) and La-F(50) were 0.0075 MPa and 0.0090 MPa, respectively.

DISCUSSION

It is well known that rehabilitation started preoperatively and continued postoperatively is the key to a favorable surgical outcome.⁵ It is also important to implement rehabilitation based on sound theory. However, patient education regarding LBP tends to focus on stabilization of the lumbar spine, and these



patients are often required to wear a lumbar brace. Currently, awareness of the need for thoracic flexibility is much less than that regarding the importance of lumbar stabilization.

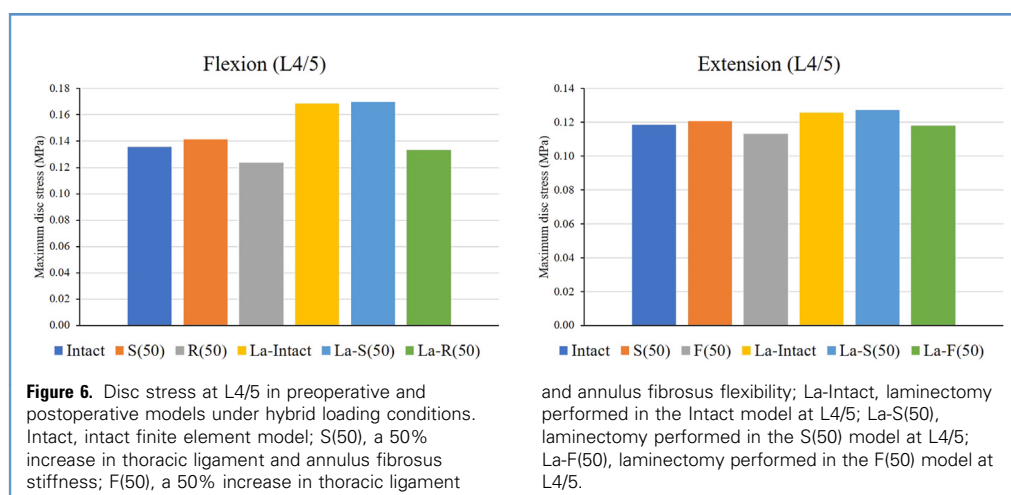
However, the thoracic spine is adjacent to the lumbar spine and is considered to be as important to the lumbar spine as the relationship between the lumbar spine and the hip joint, which is typified by the hip-spine syndrome.⁶ Heo et al. reported that flexibility training at the thoracic spine level reduced LBP.¹⁵ Furthermore, Park et al. found that LBP was relieved to a greater extent by thoracic flexibility training than by lumbar stabilization.¹⁶ Therefore, we believe it is important to approach not only the affected region but also adjacent regions.

Gray Cock's original joint-by-joint theory⁴ defines joints that are suitable for large movements as mobility joints and joints that are not suitable for large movements as stability joints and considers that these mobility and stability joints are present alternately. Mobility joints, such as those at the hip and shoulder, are ball and socket joints and highly mobile. In contrast, the elbow and knee joints, which are stability joints, are hinged or condyloid and have a limited ROM. In the spine, the thoracic level is considered a mobility joint while the lumbar and lower cervical levels are considered stability joints. However, many clinicians believe that the lumbar spine is a mobility joint and the thoracic spine is a stability joint. Thus, the joint-by-joint theory that the

thoracic spine is a mobility joint seems contradictory. However, investigation of the actual ROM of the spine has shown that the thoracic spine has a greater ROM than the lumbar spine in extension, lateral bending, and rotation.^{17,18} Moreover, these adjacent joints need to cooperate with each other to exert force.

In this biomechanical investigation, we applied the same ROM in the Intact model to other models. In our model of a stiff thoracic spine, ROM, disc stress and pars stress were increased at all levels of the lumbar spine whereas in our model of a flexible thoracic spine, ROM, disc stress and pars stress were decreased. In the lumbar spine, this effect was greater in the S(50) and F(50) models than in the S(25) and F(25) models. During all flexion, extension, lateral bending, and axial rotation movements in the Intact model, the mean maximum stress on the intervertebral discs at L5/S1 was 0.137 MPa; similarly, the mean stress was 0.139 MPa in the S(25) model and 0.142 MPa in the S(50) model; stiffening of the spine increased the intervertebral disc stress to 101.4% and 103.7%, respectively, and the stress in the F(25) and F(50) models decreased to 96.1% (0.132 MPa) and 92.4% (0.127 MPa). Pars stress also showed the same tendency. This finding indicates that the load on the lumbar spine increases with increasing stiffness of the thoracic spine. Conversely, the more flexible the thoracic spine, the less the potential for stress on the lumbar spine. These findings indicate that flexibility of the





thoracic spine is important for preoperative reduction of lumbar stress, and physical therapy for the thoracic spine may reduce the frequency of degenerative lumbar diseases or spondylolysis.

In this study, we modeled laminectomy at L4/5, which is most common lumbar surgery,¹⁹ and conducted a postoperative evaluation. Interestingly, we found that the effect of flexibility of the thoracic spine was greater postoperatively than preoperatively. This effect was particularly shown during flexion. The difference in ROM at L4/5 between S(50) and F(50) before surgery was 0.7°. However, the difference in ROM of La-S(50) and La-F(50) after laminectomy was 1.5°. Also, in the assessment of L4/5 disc stress, the difference between S(50) and F(50) was 0.0179 MPa, whereas the difference between La-S(50) and La-F(50) was 0.0367 MPa. This tendency was also seen during extension. These results suggest that thoracic flexibility is more important postoperatively than preoperatively. In the postoperative period after laminectomy, although it is of course important to focus on the stability of the lumbar spine, it is equally important to pay attention to the flexibility of the thoracic spine in the rehabilitation process. Currently, various methods are used to improve thoracic spine flexibility, such as supine posture with a ball or pole placed on the back used to extend the thoracic spine, Pilates, and exercises to move the thoracic spine.^{15,16,20,21} However, it is still unclear which exercises are the most efficient, and further research is needed.

This study had several limitations. First, the FE model was based on computed tomography images obtained for a healthy subject without any spinal disease. Therefore, changes in spinal alignment and material were not considered. Second, the flexibility of the paravertebral muscles and tendons was not considered. Finally, the relationship between the lumbar spine and the hip joints was not evaluated. However, it is probable that improved motion at the hip joints would reduce lumbar stress.

CONCLUSION

Individuals with a stiff thoracic spine would be at increased risk of developing a stress-related spinal disorder. Our findings indicate that improving the flexibility of the thoracic spine could help to reduce LBP and alleviate lumbar stress after surgery.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Masatoshi Morimoto: Conceptualization, Data curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Sudharshan Tripathi:** Methodology, Writing – original draft, Writing – review & editing. **Manoj Kodigudla:** Software. **Emi Motohashi:** Conceptualization, Formal analysis. **Junzo Fujitani:** Conceptualization, Formal analysis. **Vijay K. Goel:** Supervision. **Koichi Saiyo:** Supervision.

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