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Research Article

Biomechanical Study of the Lumbar Spine: Finite Element Analysis

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Abstract

A normal disc is responsible for the flexibility and mobility of an entire spinal segment. Mechanical principles in the anatomy of the spine contribute to physicians in understanding the pathophysiology of the disease and in treatment planning. Data such as in vitro, in vivo and finite element (FE) models are used to understand and interpret the mechanism of the spine. In vivo studies help us understand the kinematics and muscle forces that occur in the lumbar spine. It also helps us find disc mechanics, disc injury mechanisms in finite element models and thus contributes to the clinical diagnosis and treatment models of lumbar spine problems. The aim of this study is to estimate the intervertebral disc stress values at L2-L2, L3-4 and L4-L5 levels by applying flexion, extension lateral bending, external rotation forces in the lumbar spine using the finite element. To create a three-dimensional finite element model, the lumbar spine of a healthy 40-year-old male individual was created by computerized tomography scanning. Tomography sections, L2-L5, 65 sections, 0.2 mm thick, were processed and processed into the program. By using the sections, the spine surface model was obtained up to the L2-L5 level. Analysis was performed by applying a force of 1 Nm to the spine in case of flexion. Spinal movements were observed along the L2-L5 vertebrae. In the flexion state, segmental movements observed at L2-3, L3-4, L4-5 vertebral levels were 4.45, 4.01, 3.08 degrees, respectively. During the right side bending, the applied force was 2.32, 2.95 and 2.75 degrees for the L2-3, L3-4, L4-5 vertebrae, respectively. The movements observed in external rotation were observed as 3.35, 3.75 and 2.88 degrees for L2-3, L3-4, L4-5 vertebrae, respectively. When lateral force was applied, the tension in the lumbar spine intervertebral disc was 1.23, 0.65 and 0.73 MPa for L2-3, L3-4, L4-5 intervertebral discs, respectively. When the axial rotation force was applied, 2.54, 2.13 and 2.05 MPa were observed for L2-3, L3-4, L4-5 intervertebral discs, respectively. L2-3 range of motion was found to be more flexible than L4-5. It was concluded that the contribution of the formed ligament structures to the stability was positive, and L4-5 intervertebral discs were more stable during the applied axial rotation movement. The finite element model we created is valuable in that it guides clinicians in terms of diagnosis, surgical planning, and follow-up treatment at a subjective-specific level.

Keywords: Lumbar Spine; Finite Element; Disc; Mechanics; Flexion; Extention

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Abbreviations

AF: Annulus Fibrosus; NP: Nucleus Pulposus; FE: Finite Element; Mn: Newton Meter; Mpa: Von Mises Force Per Area

Introduction

The spine structure has a complex structure in human anatomy. The intervertebral disc (IVD) structure consists of two main components. These are annulus fibrosus (AF) and nucleus pulposus (NP). AF forms the outer part of the disk, withstands heavy and complex loads. AF is the main load-bearing component of the intervertebral disc [1,2]. The main task of the nucleus pulposus is to provide flexibility on the corpuscles by distributing the pressure load [3]. A normal disc is responsible for the flexibility and mobility of an entire spinal segment [4]. Low back pain, which is one of the primary spinal problems, brings up the disability of the person in daily life [5,6]. Mechanical principles in the anatomy of the spine contribute to physicians in understanding the pathophysiology of the disease and in treatment planning [7-9]. Data such as *in vitro, in vivo* and finite element (FE) models are used to understand and interpret the mechanism of the spine [10]. Two techniques, animal and human cadaver models, can be used to study biomechanics [11-13]. The main disadvantages commonly observed in the examination of the lumbar spine are graphic-based, anatomical and structural-based physical feature variability [1]. *In vivo* studies help us to understand the kinematics and muscle forces that occur in the lumbar spine [14,15]. In a study, disc degeneration occurring during dynamic spine movement can be used to understand the mechanics of disc degeneration [16]. In another study, the human cervical spine finite element model provides a better understanding of biomechanics and this needs to be supported by clinical experimental studies [17-20]. It also helps us find disc mechanics and disc injury mechanisms in finite element models, thus contributing to the clinical diagnosis and treatment models of lumbar spine problems [21-24].

The aim of this study is to estimate the intervertebral disc stress values at L2-L2, L3-4 and L4-L5 levels by applying flexion, extension lateral bending, external rotation forces in the lumbar spine using the finite element.

Materials and Methods

In order to create a three-dimensional finite element model, the lumbar spine of a healthy 40-year-old male individual was created by computerized tomography scanning. Tomography sections, L2-L5, 65 sections, 0.2 mm thick, were processed and processed into the program (Mimics 20.0; Materialise Tecnologies, Leuven, Belgium). By using the sections, the spine surface model was obtained up to the L2-L5 level. This created model was combined using ANSYS 2022 R1 as shown in figure 1.

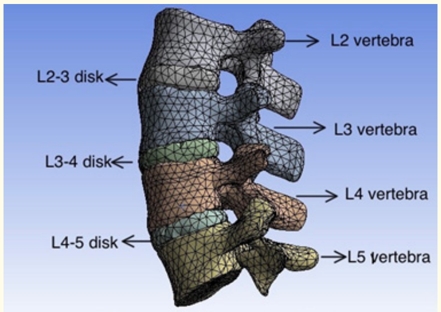

Figure 1: Finite element L2-L5 vertebrae model.

During the processing of the vertebrae into the program, the bone cortical thickness was processed as 0.5mm [25]. The anterior sides of the vertebrae are knitted using 8 focused elements, and the posterior sides of the vertebrae are knitted using tetrahedral elements due to anatomical irregularity. The element type and material properties used are shown in table 1.

In the analysis program, intervertebral discs were loaded as two separate data as annulus fibrosus and nucleus pulposus. Similarly, height levels were maintained at the front and rear of the disc [26]. In the created model, annulus fibrosus was determined as 62% and nucleus pulposus as 38% [26,27].

Ligament structures in the lumbar spine, anterior longitudinal ligament; ALL, posterior longitudinal ligament; PLL, interspinous ligament; ISL, ligamentum flavum; LF, capsular ligament; CL (Table 1).

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Section	Type	Young's modulus (MPa)	Poisson rate	Section area (mm2)
Bony structures				
Cortical bone		12,000	0.30	
Cansellous bone	Solid	450	0.30	
Posterior bone structure		3500	0.30	
End Plate		500	0.45	
Intervertebral disc				
Annulus fibrosus	Solid	3.5	0.45	
Nucleus pulposus		1.5	0.53	
Ligament structures				
ALL		32.0		7
PLL		25.0		6
ISL	Connection module	1.8		12
LF		1.9		13
CL		25.0		7

Table 1: Materials used in the lumbar spine and its properties.

The load-bearing area of the anatomical spine was determined as the intervertebral disc. Therefore, the front side is knitted tetrahedral. The average mesh element size for this model is 0.5 mm. The total knitting element in this model was 835,145.

In this study, four forces were applied to the spine: extension, flexion, right lateral bending and right external rotation. For each force, a force of 1 Nm was applied. These forces were applied to the L2 vertebra by keeping the L5 spine fixed. The applied forces are shown in figure 2.

Results and Discussion

After the finite element model of the lumbar spine was analyzed by creating a static load-bearing condition, the data obtained were compared with the experimental studies in the literature and the finite element analyzes created on the spine [17,23,28-31]. Physiological movements created in the lumbar spine and stress variables along the intervertebral discs were calculated.

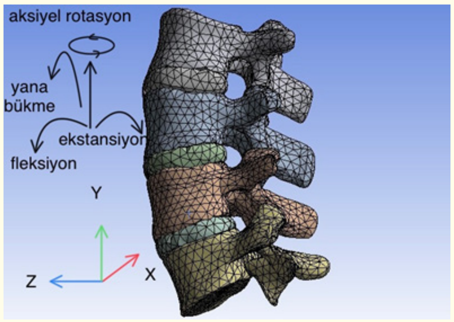
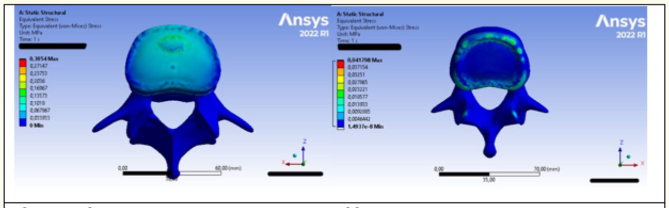


Figure 2: Forces applied to L2-L5 vertebrae (flexion, extension, right rotation, lateral bending).

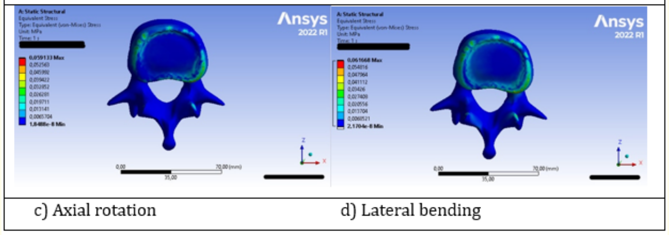
Analysis was performed by applying a force of 1 Nm to the spine in case of flexion. Spinal movements were observed along the L2-L5 vertebrae. In the flexion state, segmental movements observed at L2-3, L3-4, L4-5 vertebral levels were 4.45, 4.01, 3.08 degrees, respectively. During the right side bending, the applied force was 2.32, 2.95 and 2.75 degrees for the L2-3, L3-4, L4-5 vertebrae, respectively. The movements observed in external rotation were observed as 3.35, 3.75 and 2.88 degrees for L2-3, L3-4, L4-5 vertebrae, respectively.

The applied force and the maximum von Mises tension were calculated for the L2-3, L3-4, L4-5 vertebral levels. The calculated voltages are shown in figure 3. During flexion under force, a maximum of 0.65 Mpa for L2-3 intervertebral disc, 0.67 Mpa for L3-4 disc and 0.69 for L4-5 intervertebral disc was observed. The von Mises force observed during the extension force applied to the vertebrae was 0.57, 0.59 and 0.55 MPa for the L2-3, L3-4, L4-5 intervertebral discs, respectively. According to the literature, it has been reported that the stress on the intervertebral discs is less during extension [28]. Since the load bearing ratio of the discs will increase in the lower segments of the spine, ligaments and facet joints play an important role in spine flexion [19]. When lateral force was applied, the tension in the lumbar spine intervertebral disc was 1.23, 0.65 and 0.73 MPa for L2-3, L3-4, L4-5 intervertebral discs, respectively. When the axial rotation force was applied, 2.54, 2.13 and 2.05 MPa were observed for L2-3, L3-4, L4-5 intervertebral discs, respectively. Since the disc is the main bearing area during lateral applied force and rotation force, it has been observed that the tension is higher during external rotation, in line with the literature [1].

It was created to examine the anatomical movement of the lumbar spine in the vertebrae between L2-L5 with three-dimensional finite element analysis method. One of the main advantages of this



a) Flexion b) Extention



c) Axial rotation d) Lateral bending

Figure 3: Illustration of the load distribution on the discs according to the applied force.

study is that it can be compared with both *in vivo* and *in vitro* studies. Another point is that we compared our range of motion with the literature and determined our minimum and maximum range of motion [23,29,30,32].

In our finite element model, when compared to the literature, it was observed that it was 10 percent more flexible during the flexion movement at the L2-3 level. It was observed that it was 6 percent less flexible at the L3-4 vertebral level. A 15% higher flexibility was observed at the L4-5 vertebral level [28]. Lumbar spine movement was found to differ between 1.4 degrees in *in vitro* studies [32]. Compared to the literature, our study moves within the limits of all segments [23,29,32].

Compared to the literature, it was observed that our finite element model was 34 percent more flexible during the extension movement [28]. We observed that it was 15 percent stiffer at the L3-4 vertebral level. We observed that it was 8 percent more flexible at the L4-5 level [28]. L2-3 vertebra level was observed to be harder than the literature. It was observed to be within the limits according to published *in vitro* studies [29,32].

When we apply a side bending force in our finite element model, it is observed that there is a 30 percent higher flexibility in L2-3, 75 percent in L3-4, and 51 percent higher in L4-5, according to the literature [28]. According to the literature studies, when we apply a side bending force, we have seen that there are angles of 0.7 to 5.23 degrees. We observed that these values were within the limits according to the literature [29].

In vitro von Mises stress was applied to the intervertebral discs in our study and is shown in figure 3. L2-3 exhibited a lower tension in the intervertebral disc than in the other segments. L3-4-5 exhibited tension similarly to the literature. When the lateral bending force is applied, it has been observed that the resulting stress has a similar result compared to the literature. The rotation force created was determined as 2.5 MPa in L2-3, 2.89 in L3-4, and 3.03 in L4-5. It has been concluded that the stress differences that occur are due to the differences in the mechanical properties created [29].

Conclusion

In our study, the physiological movements of the vertebrae between L2-5 exhibit similar features with Finite element studies. L2-3 range of motion was found to be more flexible than L4-5. It was concluded that the contribution of the formed ligament structures to the stability was positive. When a side bending force is applied, the lower levels are higher in terms of flexibility of movement than the upper levels. It was observed that L4-5 intervertebral discs were more stable during the applied axial rotation movement. It was observed that the load on the intervertebral discs was higher in the lower segment discs. The finite element model we created is valuable in that it guides clinicians in terms of diagnosis, surgical planning, and follow-up treatment at a subjective-specific level.

Acknowledgements

None.

Conflict of Interest

The authors declare that there is no conflict of interest to disclose.

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