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Investigating the mechanical behavior of the human lumbar spine model by using finite element method

İnsan lomber omurgasının mekanik davranışının sonlu elemanlar yöntemi ile incelenmesi

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Abstract

Understanding the mechanical behavior of the human lumbar spine is important in spinal disorders and treatment. For this reason, spinal mechanics is examined in many biomechanical studies. The aim of this study is to examine the mechanical behavior of the human lumbar spine with the finite element method and to verify it by comparing it with experimental data in the literature. In addition, by trying different models, it is aimed to determine which structure in the spine functions under which loads and to show new researchers how these processes are applied. The human L1-L5 vertebrae were used. There were two models; one had facets as a single body in each without ligaments and the second one had facets as paired bodies at opposing bones with ligaments. Each intervertebral disc included nucleus pulposus, annulus fibrosus, and two end plates. Flexion, extension, left lateral bending, and right lateral bending loads were applied to the models with 4 Nm moment. The range of motions of each spinal segment in degrees were used as the analysis output and compared to the experimental data in the literature to validate the results. According to the results, modeling the facets as a single body caused excessive stiffness, while modeling them as facet pairs at opposing bones caused excessive movement. It can be said that using a model which, has paired facet joints and ligaments, provided converged range of motion values in each L1-L5 spinal segment under flexion/extension and left/right lateral bending moments.

Keywords: Lumbar spine, biomechanics, finite element method.

Öz

İnsan lomber omurgasının mekanik davranışının anlaşılması, omurga rahatsızlıklarında ve tedavisinde önemli bir yer tutmaktadır. Bu sebeple pek çok biyomekanik çalışmada omurga mekaniği incelenmektedir. Bu çalışmanın amacı, insan lomber omurgasının mekanik davranışını sonlu elemanlar yöntemi ile incelemek ve literatürdeki deneysel veriler ile karşılaştırarak doğrulamaktır. Ayrıca, farklı modeller deneyerek, omurgada hangi yapının hangi yükler altında işlev gördüğünü belirlemek ve bu süreçlerin nasıl uygulandığını yeni araştırmacılara göstermektir. Bu çalışmada insan L1-L5 omurgası kullanılmıştır. İlki, faset eklemlerin tek bir gövde olarak modellendiği ligamentsiz bir omurga modeli ve ikincisi faset eklemlerin karşılıklı kemiklerde iki farklı gövde çifti olarak modellendiği ligamentli omurga modeli olmak üzere iki farklı model incelenmiştir. Her bir intervertebral disk, nükleus pulpozus, anülüs fibrozus ve iki adet end-plate'ten oluşmaktadır. Modellere, fleksiyon, ekstansiyon, sola eğilme ve sağa eğilme yükleri 4 Nm'lik moment ile uygulanmıştır. Her bir spinal segmentin derece cinsinden dönme miktarı analiz çıktısı olarak kullanılmış ve doğrulama için literatürdeki deneysel veriler ile karşılaştırılmıştır. Sonuçlara göre, fasetleri tek bir gövde olarak modellemek aşırı direngenliğe neden olurken, karşıt kemiklerde faset çiftleri olarak modellemek aşırı harekete neden oldu. Fasetlerin karşılıklı kemiklerde faset çiftleri olarak modellendiği ve ligamentleri olan bir modelin, fleksiyon/ekstansiyon ve sola/sağa eğilme momentleri altında her bir L1-L5 spinal segmentinde deneysel verilere yakınsayan dönme miktarı değerleri sağladığı söylenebilir.

Anahtar kelimeler: Lomber omurga, biyomekanik, sonlu elemanlar metodu.

1 Introduction

The spine is a structure that helps to keep the human body standing and provides an ability to move in three axes. From the mechanical perspective, each vertebra in the spine act as levers, intervertebral discs and facet joints as pivots, ligaments as passive restrictors, and muscles as actuators. [1] Due to its location, the lumbar spine is the most load-bearing section of the spine. For this reason, the lumbar vertebrae have larger surface areas compared to other vertebrae. Intervertebral discs and facets, which serve as pivots, ensure force transmission and damping between the vertebral bodies. They enable the flexion and bending of the spine and assist in the absorption of shock impacts. There are seven different ligaments acting as connectors and restrictors in spinal movement.

Due to the large loads that they bear, spinal disorders and injuries are frequently observed in the lumbar vertebrae. Due to this, it has been an important topic for the studies [2-4]. The understanding of the mechanics of these disorders that occurs as a result of large loads on the lumbar spine is also crucial for treatment. To achieve this, experimental and numerical methods are conducted. Experimental studies are conducted in laboratory environments where the load-displacement behavior of spinal segment is simulated under physiological loading or many different loading conditions. In this type of studies, human or animal cadavers [5-7] or artificial bone samples [8] may be used. However, due to the complex geometry of the lumbar spine, it is generally difficult to investigate mechanical data such as stress and strain on spinal structures in experimental studies.

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Obtaining stress and strain data effectively and easily is achieved by implemented finite element (FE) method, which is a numerical procedure and allows the examination of the mechanical effects of material and geometric diversity of the structures. By using the FE method, it is possible to investigate the mechanical effects of various spinal disorders and deformities or surgical treatment methods of these disorders in a faster and easier manner [9-11]. From here, the aim of this study is to understand the mechanical behavior of the lumbar spine by examining it using the FE method and obtain a validated original FE model of the lumbar spine (L1-L5) by comparing it to experimental data from the literature. This validated spinal model is important for future numerical studies that may investigate the mechanics of disorders, deformities, or possible treatment methods of lumbar spine. The second aim of this study is to investigate the mechanical behavior of different spine models and thus determine which structure in the spine functions under which loading conditions. With this method, it is possible to have an idea about which structures are important in approximating the real spine mechanical behavior. The difference of this study from the other studies in literature is to compare different lumbar spine models and to explain to the new researchers what should do in obtaining a validated lumbar spine model in detail.

2 Materials and Methods

2.1 Generation of lumbar spine model

The 3D CAD model of the human spine can be created using various methods. In the most used approach, DICOM images obtained from CT (Computed Tomography) scans are converted into STL format using softwares such as Mimics Materialise (Materialise NV, Belgium) or 3D Slicer (3D Slicer, United States), and then transformed into a three-dimensional solid model. The present study investigates the mechanical behavior of the L1-L5 lumbar spine. The solid model of the lumbar spine examined in this study was created using an STL model obtained from CT scans which has been previously used in the study of Sengul et al [12]. The CAD model of the lumbar vertebrae was created by using Space Claim (Ansys Inc., US). Each step performed when creating the CAD model of the vertebrae from the STL model is shown in Figure 1 on the illustration of a single vertebra. The STL model of a single vertebra can be seen on Figure 1.A. The STL model shown here consists of a coarse mesh, so the creation of a solid may lead to inaccurate results in its current form. For this reason, the STL model was converted to a fine mesh STL model to better resemble an anatomically accurate bone structure. The fine STL model corresponds to the outer boundary of the cortical bone. This STL model was offset inward by 0.5 mm to create the inner boundary of the cortical bone. This offset value was assumed as 0.5 mm based on literature research [13-16]. Then, two 3D solid models were created for each vertebra by using these two boundary layers (Figure 1.B). Inner one of them represents to trabecular part and the other one represents to cortical part. To create the cortical shell around the trabecular bone, the intersection of two parts were subtracted from the cortical part. By this way, the cortical shell with 0.5 mm thickness and the trabecular bone inside were obtained (Figure 1.C).

Following to bones, intervertebral discs were created in each level between the two vertebrae. Each intervertebral disc was modeled with annulus fibrosus, nucleus pulposus, and two end-plates positioned above and below them (Figure 1.D.) The endplates were created like shell elements with the thickness of 0.5 mm [14]. Determining the size of the nucleus pulposus is crucial for accurately modeling the intervertebral disc structure. When the literature is examined, it can be seen that the ratio of the nucleus pulposus to the total volume of the disc varies approximately from 20% to 50% depending on the condition of the disc [17-20]. In several studies [1,17], it has shown that the numerical results converged to experimental ones in the literature when the ratio of the nucleus pulposus to the total volume of the disc was assumed approximately 40%. For this reason, the nucleus pulposus in each disc were modeled to occupy approximately 40% of the disc's volume. After modeling the intervertebral discs, the facet joints located posteriorly were modeled, appropriately.

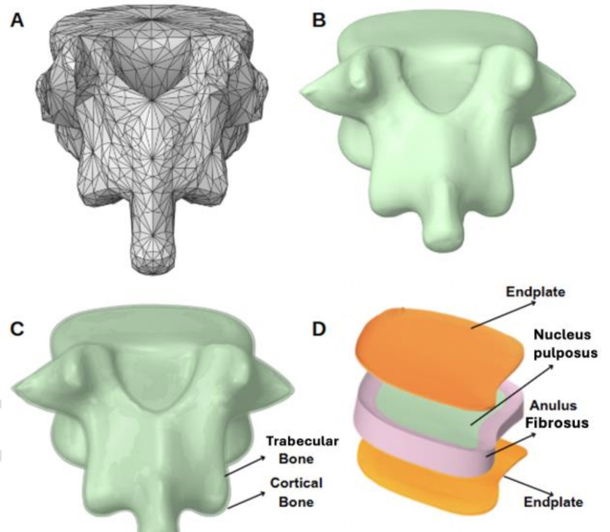


Figure 1. A) The coarse mesh STL model of a vertebra, B) the solid cortical bone and solid trabecular bone inside it, C) cortical shell and solid trabecular bone, D) the intervertebral disc.

In this study, two different spinal models were created to observe the effect of lumbar spine components on the mechanical behavior of spine. This approach allows for an understanding of which structures carry loads under specific loading conditions and provides foresights into which components should be included in the model to enhance its convergence with experimental data. Model 1 consisted of the L1-L5 spine, which included cortical and trabecular components of the bone, intervertebral discs comprising the annulus fibrosus, nucleus pulposus, and end plates, as well as facet joints that were modeled as single bodies each (Figure 2.A). In contrast to the first model, the facets of Model 2 were designed as two thin plates formed on the surfaces of two opposing bones that constitutes the joint, rather than as a single body (Figure 2.B). In this model, the distance between the opposing facet pairs was approximately 0.5 mm. Also, ligaments were added to Model 2. Six types of ligaments were added to the spine here including, anterior longitudinal ligament (ALL), supraspinous ligament (SSL), posterior longitudinal ligament (PLL), ligamentum flavum (LF), interspinous ligament (ISL), and capsular ligament (CL). These ligaments can be seen on Figure 2.C.

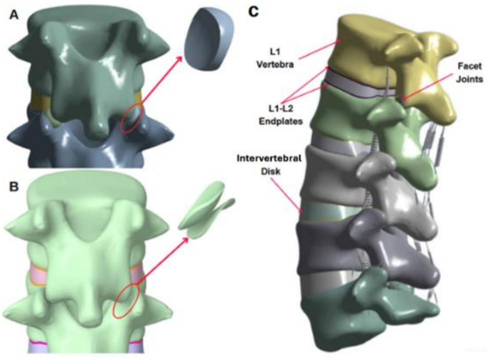


Figure 2. (A) Facet joint in Model 1, (B) facet joint in Model 2, and (C) L1-L5 spine with ligaments in Model 2.

2.2 FE analysis

In this study, all FE analyses were conducted using the Ansys Workbench (Ansys Inc., US) software. In this section, detailed information about the settings used in the analyses will be provided.

Boundary and loading conditions are important in the FE analysis. To apply them correctly, a coordinate system was defined first at top surface of the L1 vertebra as shown in Figure 3. In this coordinate system, the Z axis was gone through the instantaneous center of motion of the lumbar spine. With this way, the physiological loading conditions of the lumbar spine may be acquired. The bottom surface of the L5 vertebra was fixed to restrict its motion in six degrees of freedom (Figure 3). In the present study, the lumbar spine models were separately subjected to flexion, extension, right lateral bending, and left lateral bending loads through the upper surface of the L1 vertebra. To simulate the flexion and extension loading scenarios, +4 Nm and -4 Nm moments were applied along Y axis, respectively. Similarly, +4 Nm and -4 Nm moments were applied along X axis to simulate the right lateral bending and left lateral bending, respectively. These load values were taken from the literature [21].

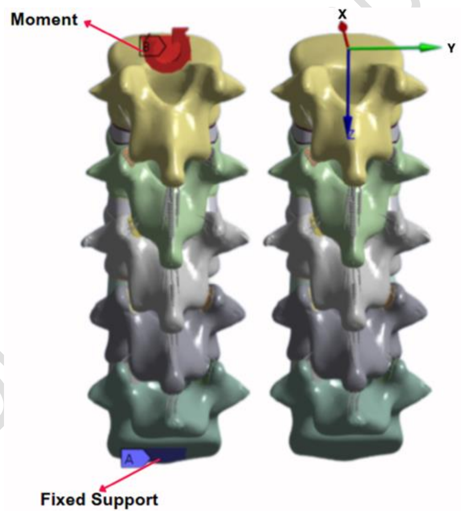


Figure 3. Boundary and loading conditions, the figure in left shows left lateral bending as an example.

The meshing of the model is another crucial part in the FE analysis because different mesh models may result totally different results. To increase the accuracy of the numerical results, the second-order tetrahedral, hexahedral, and pentahedral elements were used to create the mesh model in the present study. The mesh model of the vertebral bodies, discs, and facets predominantly comprised of the hexahedral elements, while the other two types of elements were used as necessary (Figure 4). In this study, Model 1 had 460539 nodes and 134806 elements whereas Model 2 used 487093 nodes and 142966 elements.

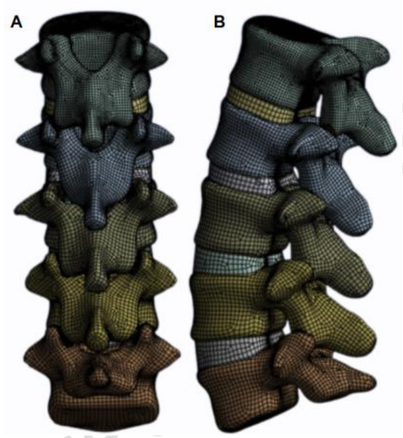


Figure 4. The mesh model of the L1-L5 spine from (A) posterior view and (B) lateral view.

Another important aspect of FE analysis is the assignment of appropriate material models to the structures being analyzed. There are many different studies in the literature for this purpose. In this study, a homogeneous, linear elastic, and isotropic material model was used for the cortical and trabecular bones, nucleus pulposus, end plates, and facets. For the annulus fibrosus, an isotropic Mooney-Rivlin material model was used. All the material models are presented in Table 1 with their references. The ligaments were modeled as linear spring elements that only carry tensile forces. The spring constants are also provided in Table 1.

Modeling contacts between structures correctly is critical for obtaining accurate analysis results. In all models of this study, a "bonded" connection type was used between cortical bone and trabecular bone, between endplate and cortical bone, between endplate and disc structures, between annulus fibrosus and nucleus pulposus, and between facets and cortical bone. Additionally, in Models 2, a frictional contact definition with a static friction coefficient of 0.1 was assigned between the opposing facet pairs.

2.3 Validation of the FE model

In their experimental study [21], Guan et al. have investigated the mechanical response of the L1-S1 vertebrae under flexion/extension and left/right lateral bending loads. They have applied moment up to 4 Nm and report the Range of Motions (ROM) of each spinal segment in degrees (°). In the present study, 4 Nm moment was applied to models. The ROM values obtained from each spinal unit were compared to the values ROM values of Guan and collogues to validate the results of the present study. For a specific spinal segment, if the ROM of the present study was in between the maximum and minimum values of ROM of their study, it is assumed that the segment was validated.

3 Results and Discussion

The primary aim of this study is to investigate the mechanical behavior of a lumbar spine model under physiological loading conditions using the FE method, and to validate the model with experimental data available in the literature. A validated spine model in this manner can be used in future studies. For example, with a validated FE model, a foresight can be obtained about the mechanical behaviors of different spinal instrumentation techniques in future numerical studies. Another aim of this study is to examine the mechanical behavior of different spine models and thus determine which structure in the spine functions under which loading conditions. With this method, it is possible to have an idea about which structures are important in approximating the real spine mechanical behavior. This is very important for the researchers who want to study the mechanical behavior of the lumbar spine with FE analysis to understand the key points of the subject and in this way, this study is intended to be a guide for them.

Here, it would be more beneficial to compare each model with the reference data from Guan et al. [21]. When the results of Model 1 examined carefully, Figure 5 shows that all segments, except L1-L2 in extension and left lateral bending and L4-L5 in extension, were not in the reference ranges of the Guan et al [21]. This showed that these segments were not validated under the applied loading conditions. These unvalidated segments showed less angular movement under applied conditions compared to the reference data of the Guan et al [21]. This means that these segments exhibit higher stiffness in the specified directions of movement compared to the reference. This also indicates that the lumbar spine, as a whole, behaves stiffer than lumbar spines examined in Guan et al [21]. The reason for this stiffer behavior exhibited by each segment and consequently the lumbar spine is attributed to the facet joints being modeled as a single body in Model 1. In reality, although facet joints restrict the movement of the spine, they allow a certain amount of frictional movement. However, modeling the facet joints as a single body in Model 1 means that such frictional movement cannot be simulated for Model 1.

As mentioned in the previous paragraph, modeling the facet joints as a single body restricted spinal movement. To converge the results with the experimental data of Guan et al [21], the lumbar spine needs to become more flexible. Before discussing the results of Model 2, strictly speaking, another model was tried in which facets were modeled as two facet pairs on the opposing bones. However, because of the excessive movement, no results could not be acquired. As a result, Model 2 is the ligament added version of this model with no results.

As can be seen in Figure 5, in the second model, the ROMs of each vertebral segment were in the range from the reference study [21]. Here, it can be said that the results of Model 2 were validated for each spinal level in every loading conditions. As a results, in the case of creating paired facets and adding the ligaments like in Model 2 resulted in a converged mechanical behavior to that of the real spine just in the study of Guan et al [21].

When comparing the Model 1, Model 2 and the other model which is the version of Model 2 without the ligaments, the results clearly showed that modeling the facets as a single body caused excessive stiffness, while modeling them as facet pairs at opposing bones caused excessive movement. In the first case, the results did not converge with the experimental data [21], while in the second case, no results could be obtained from the analyses due to excessive movement. Using the paired facets may solve the excessive stiffness by giving the spine extra movement. Moreover, adding the ligaments may overcome the problem of excessive movement by providing it sufficient stiffness. Consequently, the Model 2, which has paired facet joints and ligaments provided converged ROM values in each L1-L5 spinal segment under flexion/extension and left/right lateral bending moments. This validated FE model may be used in future studies.

4 Conclusions

This numerical study presents a validated FE model of the L1-L5 lumbar spine. This model may be used in the future studies. According to the results, modeling the facets as a single body caused excessive stiffness, while modeling them as facet pairs at opposing bones caused excessive movement. Using the paired facets may solve the excessive stiffness by giving the spine extra movement. Moreover, adding the ligaments may overcome the problem of excessive movement by providing it sufficient stiffness. It can be said that using a model which, has paired facet joints and ligaments, provided converged ROM values in each L1-L5 spinal segment under flexion/extension and left/right lateral bending moments.

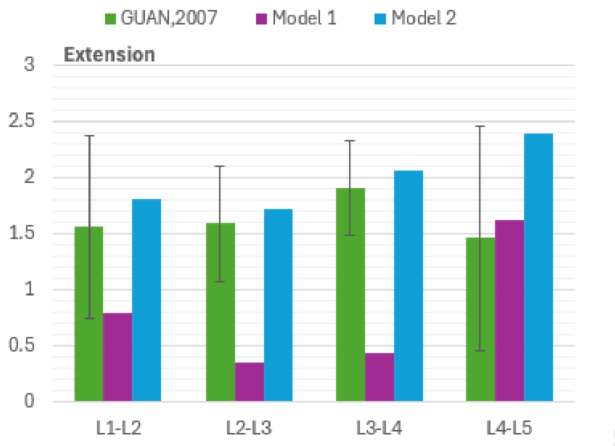
Table 1. Materials properties of the structures.

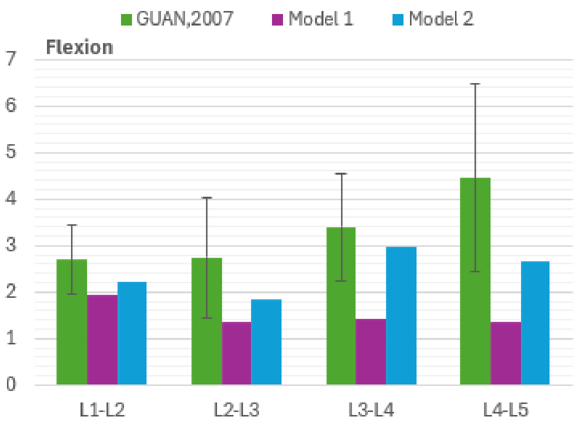
Structures	Young's Modulus (MPa)	Poisson's ratio	Element Type	References
Cortical Bone	12000	0.3	Hexahedral	[22]
Trabecular Bone	100	0.3	Hexahedral	[22]
Annulus Fibrosus	Mooney Rivlin: C_1=0.13, C_2=0.03, D=0.6		Hexahedral	[23]
Nucleus Pulposus	1	0.499	Hexahedral	[24]
Endplate	24	0.4	Hexahedral	[22]
Facet	11	0.499	Hexahedral	-
ALL Ligament	7.8	0.3	Springs	[22,25]
PLL Ligament	10	0.3	Springs	[22,25]
SSL Ligament	8	0.3	Springs	[22,25]
ISL Ligament	10	0.3	Springs	[22,25]
CL Ligament	7.5	0.3	Springs	[22,25]
LF Ligament	15	0.3	Springs	[22,25]

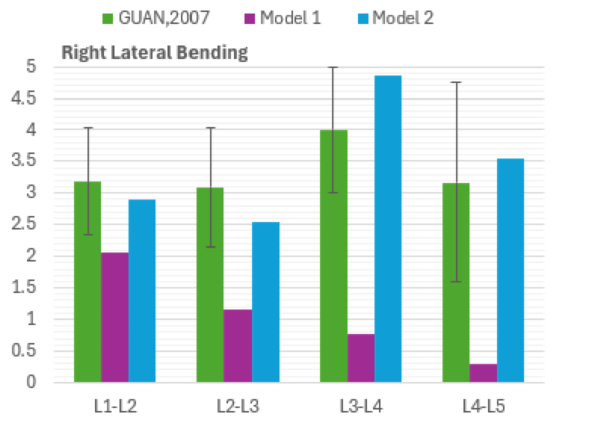
5 Acknowledgement

6 Author Contribution Statements

In the study carried out, Author 1 contributed to the review of literature, 3D designs, performing analysis, examination of the results, writing and critical review; Author 2 contributed to the idea formation, review of literature, examination of the results, writing and critical review, spellcheck and checking the contents of the article.







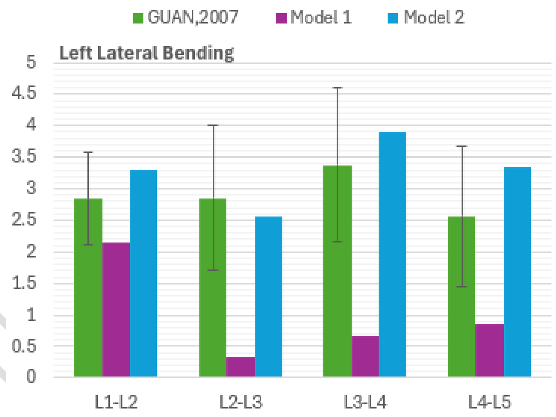


Figure 5. The ROM (°) values obtained from the analyses and the results of Guan et al [21]. The reference results of the Guan et al [21] were given with average values and standard deviations.

7 Ethics committee approval and conflict of interest statement

"For the present study, there is no need for ethics committee approval."

"For the present study, there is no conflict of interest with any person/institution."

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