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Research Article

The Effect of PEEK-Rod Fixation Systems on Finite Element Lumbar Spine Model

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Abstract

Orthopedic fixation devices have been employed in the treatment of spinal diseases. Special fixation devices have been developed to decrease the effect of spinal injuries and deformities and have been used to decrease the neurologic back pain of the patients. In this study, the finite element spine model of an adolescent idiopathic scoliotic patient was constructed. The titanium spinal implant system and the system of polyetheretherketone (PEEK) were compared regarding their stress distributions. The finite element lumbar spine model from L2 to L5 vertebra was obtained from computed tomography scan data. The three-dimensional spine model consisted of four lumbar vertebrae, three intervertebral discs, six facet joints, and the corresponding ligaments. Loading and boundary conditions were applied to the L2-L5 lumbar model. According to the subjected loads and bending moments on the model, stress distributions were evaluated especially on the intervertebral discs, and the screw-rod implant systems both for the titanium and the PEEK-based fixation systems. The disc structures were also analyzed for the effects of adjacent segment disease, which has been reported as a post-operative effect of fusion surgeries. Ansys software was used for the simulation processes of the models without the implant system and the models with different fixation systems. Comparative investigation between different fixation systems showed that the stress distribution values were decreased with the PEEK-based fixation system. Moreover, lower total deformation and equivalent stress values were recorded with the PEEK-based fixation system, especially on L3-L4 and L4-L5 intervertebral discs. Furthermore, both spinal implant systems allowed to decrease the overall loading stress on the whole spine models. And it was concluded that the PEEK-based spinal implant system was considerably reduced the load on the discs and ligaments, and also appeared as a better option in stress reduction and load sharing when compared to the titanium spinal implant system.

Keywords: Finite element analysis, Titanium rod, von Mises stress analysis, PEEK rod, Adjacent segment disease.

Sonlu Eleman Lomber Omurga Modelinin PEEK-Çubuk Sabitleme Sistemleri Üzerindeki Etkisi

Öz

Ortopedik sabitleme cihazları omurga rahatsızlıklarının tedavisinde kullanılmaktadır. Özel sabitleme cihazları omurga rahatsızlıklarının ve deformitelerinin etkilerini azaltmak ve hastaların nörolojik sırt ağrılarını hafifletmek için geliştirilmektedir. Bu çalışmada adolesan idiyopatik bir hastanın omurgasının sonlu eleman modeli elde edilmiştir. Titanyum ve polietereterketon (PEEK) omurga implant sistemleri stres dağılımları göz önüne alınarak karşılaştırılmıştır. Sonlu eleman lomber omurga modeli L2'den L5'e kadar bilgisayarlı

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tomografi verilerinden elde edilmiştir. Üç-boyutlu omurga modeli dört tane lomber omurundan, üç tane omurlararası diskten, altı tane faset eklemden ve bunlara karşılık gelen ligamentlerden oluşmaktadır. L2-L5 lomber modele yükleme ve sınır koşulları uygulanmıştır. Model üzerinde uygulanan yüklere ve eğilme momentlerine göre gerilme dağılımları, özellikle omurlararası disklerde ve vida-çubuk implant sistemleri üzerindeki etkileri titanyum ve PEEK-tabanlı sabitleme cihazlarının her ikisi için de değerlendirilmiştir. Disk yapıları ayrıca füzyon ameliyatlarının operasyon sonrası etkileri olarak rapor edilen komşu segment hastalığının etkileri açısından da araştırılmıştır. İmplantsız ve farklı sabitleme cihazlarının olduğu sistemlerdeki simülasyon işlemleri için Ansys programı kullanılmıştır. Farklı sabitleme sistemleri arasında yapılan karşılaştırmalı araştırma, PEEK-tabanlı sabitleme sisteminde daha düşük gerilme dağılımı değerlerinin olduğunu göstermiştir. Buna ek olarak, PEEK-tabanlı sabitleme sisteminde daha düşük toplam deformasyon ve eşdeğer gerilme değerleri, özellikle L3-L4 ve L4-L5 omurlararası disklerde kaydedilmiştir. Ayrıca her iki omurga implant sistemi, bütün omurga modeli üzerindeki toplam yükleme stresinin azalmasına imkan vermiştir. PEEK-tabanlı omurga implant sisteminin diskler ve ligamentler üzerindeki yükü önemli ölçüde azalttığı, ve de titanyum omur implant sistemi ile karşılaştırıldığında stres değerlerinin azaltılmasında ve yük paylaşımında daha iyi bir seçenek olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Sonlu eleman analizi, Titanyum çubuk, von Mises gerilme analizi, PEEK çubuk, Komşu segment hastalığı.

1. Introduction

Adolescent idiopathic scoliosis, which is an abnormal curvature of the spine, requires surgical correction with the attachment of rods to the spine by using screws inserted into the vertebral bodies [1]. By the application of compressive forces across the intervertebral disc spaces, a reduction in the deformity has been observed and the effect of various surgical corrective forces on the level of deformity has been investigated [2].

In recent years, with the degeneration of intervertebral disc structures, facet joints, and ligaments [4], the rate of degenerative scoliosis has been increasing [3]. Moreover, this degeneration causes the misalignment of the spinal column in the coronal plane [3]. Furthermore, osteoporosis can be the reason for this degeneration of the vertebral column [4].

Since the nerve roots are affected by compression and inflammation, it is very difficult for patients to endure this severe neurologic pain. Spinal degeneration affects adjacent segments. Surgical procedure is the most preferred strategy to decrease this pain [5]. A few studies compared the effect of different fixation techniques involving the models composed of various adjacent segments [5]. As the traditional stabilization systems, rigid rod and pedicle screw fixation systems including titanium and stainless steel have been employed for the fusion process in the lumbar region. A rigid rod system has been used to provide stability with decompression of the neural regions [8] and allow equal load sharing between the ligaments (anterior and posterior longitudinal ligaments) during the fusion into the bony segments [6-7].

In this study, a lumbar model including L2-L5 vertebra was developed and subjected to the compressive loads and lateral bending moments. The objectives of this study were to investigate the efficacy of two different spinal (titanium-rod and PEEK-rod) implant fixation systems and compare the biomechanical effects of these systems on the discs, screws, and rods of the L2-L5 lumbar spine model.

2. Material and Method

2.1. Construction of the model

In the first step of the three-dimensional (3D) reconstruction, it is essential to have CT images in the file format of DICOM (Digital Imaging and Communications in Medicine). CT images were measured from a patient with scoliosis using a CT scanner (Siemens/Somatom Definition As) with a slice thickness of 1.50 mm. Mimics Materialise software was used for the construction of the spine model between L2-L5. The construction process of the models was carried out as in the previous studies [9-11]. After transferring the data, the software was employed to convert two-dimensional data into 3D images in different planes (axial, coronal, sagittal). For the reconstruction of the vertebral bone structures, preset thresholds were used in the software. The range of the threshold begins from 226 HU and goes to a certain value that depends on the mineral density of the bone in that region. With a very low threshold value, it is not easy to distinguish different bones. If this value is very high, then there will be bony defect regions in the 3D model of the bone.

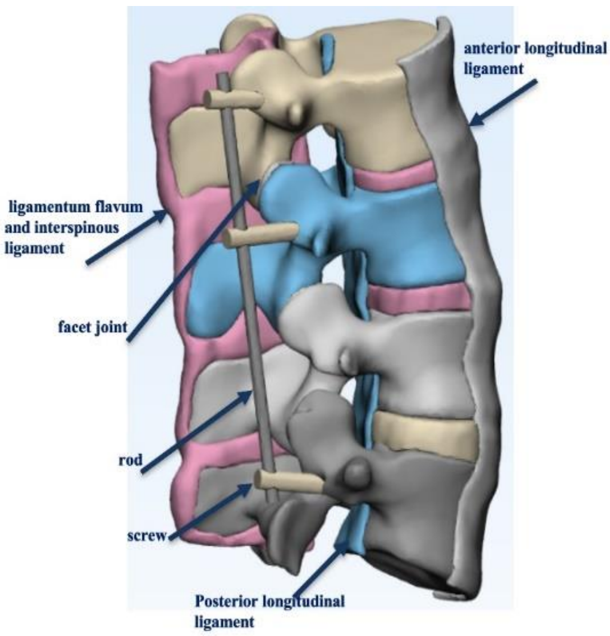

Figure 1. The L2-L5 model with the rod-screw implantation system. Different colors indicate different segmentation masks for different components in the spinal column.

Since the segmentation of the whole structure is not possible, the manual editing tools including cropping the mask, morphology operations, multi-slice, and 3D mask editing was used to control the full segmentation. Four lumbar vertebrae (L2-L5), three intervertebral discs (L2-L3, L3-L4, and L4-L5), six facet joints, and the corresponding ligaments (ligamentum flavum, interspinous ligaments, anterior and posterior longitudinal ligaments) were constructed in Mimics software. Since the intervertebral discs were constructed as one part, their complete mechanical feature was considered as annulus regions. The elastic modulus and Poisson's ratio of the annulus region were given in Table 1.

In this process, several segmentation masks were used according to the Hounsfield unit (HU) of the spinal structures in the CT scan data. The threshold value of the bone (HU units from 226-3200) is easier to distinguish in the segmentation process. Because of the low attenuation values in soft tissues, it is not easy to apply the same techniques to the intervertebral discs and the facet joints.

Thus, the segmentation of these parts was done manually in the study. After completing the manual segmentation process, the whole model with the intervertebral discs and facet joints was obtained (Fig.1).

2.2. Construction of the screw-rod system

The pedicle screws were constructed as cylinders. Also, the interface between screw and bone was assigned to be fully constrained. The pedicle screws were inserted through the pedicles of the vertebrae bilaterally (Fig. 2). The approach for creating a screw trajectory is explained in Fig. 2. A total of six pedicle screw trajectories on the first, second, and fifth lumbar vertebrae were formed (L2, L3, L5). First, a cylinder was created using the analyze section in Mimics software, and then the starting and the ending points were decided. The construction of the rods and screws was completed as in the previous studies [9-11].

In addition to manual adjustment of the screw trajectory in the three-dimensional reconstructed object, the simulation of the screw trajectory was also adjusted in each plane including sagittal, coronal, and axial regions. Besides, radius (2.8 mm for each screw), color, length (48 mm for each screw), and also the preoperation angles of the simulated object were adjusted at this point. The material properties [9] of the screws and the rods (Table 1) were assigned before the finite element analysis in Ansys Workbench. PEEK and titanium rods, and titanium screws were used in the study.

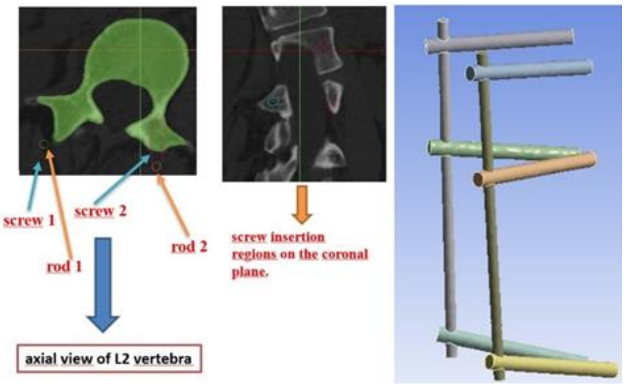

Figure 2. The representation of the screw and rod development.

2.3. The meshing procedure

The meshing procedure for surface and volume meshes was completed in 3-Matic software. Tetrahedral elements were used in the meshing of each spinal component that was constructed.

L2-L5 model without the implant system was consisted of 234482 nodes and 1261852 elements, whereas the model with the fixation system was composed of 243363 nodes and 1296458 elements in their 3D structures. After transferring the whole model from 3-Matic to Ansys software, the essential mechanical properties were taken from the cadaveric studies in the literature [3, 4].

The following table (Table 1) is related to the materials that were assigned to the corresponding spinal components in the models [3, 5, 12].

The axial compression force, 800 N preload, and 10.6 Nm moment were transferred through the L2-L5 spine model with titanium and PEEK rods.

Table 1. Mechanical properties of materials.

Material	**Elastic Modulus (MPa)**	**Poisson's Ratio**	**Element Type**
vertebra	12000	0.3	isotropic, tetrahedral elements
facet joints	11	0.2	isotropic, tetrahedral elements
intervertebral disc	4.15	0.47	isotropic, tetrahedral elements
anterior and posterior longitudinal ligaments	20	0.3	isotropic, tetrahedral elements
ligamentum flavum, interspinous ligament	15	0.3	isotropic, tetrahedral elements
titanium screw	112.400	0.34	isotropic, tetrahedral elements
titanium rod	112.400	0.34	isotropic, tetrahedral elements
PEEK rod	3600	0.3/tensile strength (17 MPa)	isotropic, tetrahedral elements

3. Results and Discussion

Total deformation and equivalent stress results showed that the use of the PEEK-rod fixation system led to less stress and shear values compared to the titanium-rod system (Table 2).

The corresponding load sharing was given in Figure 3. The model without any implantation was compared with the models with two different material types of fixation rods. There was not a significant difference in total deformation between the two fixation systems.

The PEEK-rod fixation system allowed to decrease the maximum total deformation by 15%. Also, it was observed that the bending structure of the rods was greater in the titanium rod system after the application of preload and moment. In addition, equivalent (von Mises) stress was reduced by %53 in the PEEK implant system by the effect of axial loading applied to the top vertebra and also lateral bending movements of the model.

The results also showed that total deformation and stress values were higher in the titanium fixation model. The PEEK-rod system decreased stress values on the adjacent discs (L3-L4 and L4-L5) of the finite element model.

In the PEEK-based system, total deformation and stress values were decreased on L3-L4 and L4-L5 intervertebral discs when compared to the titanium fixation model. The maximum stress values were calculated especially on the rods and also the screw-rod interfaces in all models. Furthermore, both of these fixation systems allowed to stabilize the L2-L5 lumbar spine model.

Table 2. Mechanical response of the spinal unit models.

The analysis	L2-L5 without implants (MPa)	Titanium-rod system (MPa)	PEEK-rod system (MPa)
maximum equivalent (von Mises) stress	81.873	241.24	115.17
maximum shear stress	45.573	137.75	58.84

We observed that total deformation, equivalent stress, and maximum shear stress were reduced with the PEEK rod fixation system.

The possibility of the adjacent segment disease was much higher in the titanium-rod fixation system because the PEEK rod system allowed the model to endure high stress and better load sharing with the reduction of stress at the bone to screw interface.

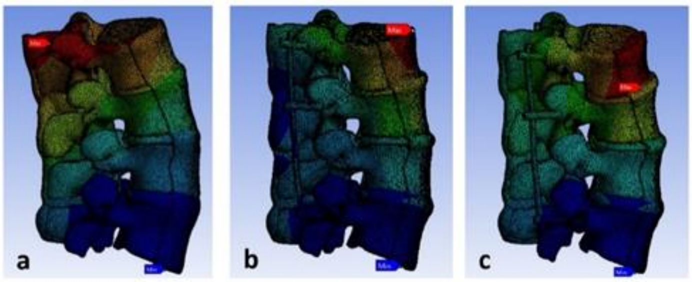

Figure 3 Total deformation of the L2-L5 model (a) without the fixation system, (b) with titanium-rod, and (c) with PEEK-rod fixation implant systems.

4. Conclusions and Recommendations

It was concluded that both fixation systems decreased the loading on the finite element model, especially on the discs and ligaments.

In conclusion, PEEK rod fixation systems provide a prominent alternative to titanium-based implantation systems.

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