Comparative Study of Biomechanical Model of the L4-L5 Lumbar Section with Mechanical Fixation

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Abstract. The risk of fixation loosening by the pedicle failure during or after the screw insertion surgery is high, causing fracture of the bone tissue due to the high stress concentration. The purpose of this paper is study the influence of osteoporosis on the bone-screw interface, based on a 3D biomechanical model of the lumbar section. The Finite Element (FE) method was used. Mechanical properties in health vertebra (HV) and osteoporotic vertebra (OV) were defined. A compression load of 500 N and a moment of 7.5 Nm were assumed in four load scenarios: compression, flexion, flexion-extension and axial rotation. The bone-screw interaction zone and the posterior of vertebra and pedicles were susceptible to bone tissue failure, because the higher equivalent stress were close to bone failure stress. The HV stresses were higher than OV stresses. The higher stress was 8.83 MPa. Opposite to stresses results, the strains were higher in OV than in HV, being the OV strain more than 2 times higher than HV strain.

Keywords: L4-L5 lumbar section · Biomechanics · Mechanical fixation

1 Introduction

Trans-pedicular vertebral fixation is a common technique used in the treatment of vertebral disorders [1]. Its purpose is to obtain a solid arthrodesis to relieve the patient's pain [2]. In this technique, the pedicle screws are inserted in the vertebral body and are joined to bars to create a solid union and release an injured section (vertebra or intervertebral disc).

This procedure has gained acceptance for the treatment of degenerative diseases of the lumbar spine and it has shown advantages in the decompression of nerves and the restoration of the intervertebral disc, the stabilization and the reinforcement of the damaged region of the spine [3–5]. However, in osteoporotic patients the risk of pedicle failure during or after the screw insertion surgery is high [4], causing fracture of the bone tissue due to the stress concentration.

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The study of the behavior of the bone-screw interface allows the anticipation of possible failures. The objective of this work is to study the influence of mechanical properties of vertebrae in the bone-screw interface, based on a 3D biomechanical model of the L4-L5 lumbar section.

2 Materials and Methods

The Finite Element Method (FEM) was used to analyze the biomechanical model. The geometry, material and loads and boundary conditions were taken into account for model definition, which allowed the succeeding analysis (post - processing) [6].

2.1 3D Geometry of the Model

The L4-L5 lumbar section was selected as the region under analysis. For geometrical reconstruction, images in DICOM format from the Computed Tomography Scanner GE LightSpeed VCT (120 kV/89.40 mAs, pixel 0.773 mm, 512 × 512, slice 5 mm) installed on the National Institute of Rehabilitation of México were used.

In order to obtain the geometric model, it was used the 3D-Slicer software (http://www.slicer.org) while the medical images manipulation and the 3D geometry reconstruction were made. The meshed surfaces with triangular elements were generated and exported in STL file extension [7].

The Blender software (http://www.blender.com) was used in the transformation of the meshed surfaces of the vertebrae into an editable polygon model. The smooth surfaces were also conducted. The intervertebral disc was obtained from both delimited surfaces and the contour of L4 and L5 vertebral plates. In order to avoid parts interferences, a Boolean operation was executed.

A generic hardware (bar and screw model) was selected. Assembly was conducted in Solidworks Premium 2018 (Dassault Systemes SOLIDWORKS Corp., MA, USA).

2.2 Loads and Boundary Conditions

Four load scenarios were defined: compression, flexion, flexion-extension, and axial rotation (see Fig. 1), according to criteria of Rohlmann et al. [8]. A compression load of 500 N and a moment of 7.5 Nm were assumed. The compression was applied at the upper plate of the L4 vertebra and the rotation at a reference point of the same vertebra. All degrees of freedom in the screws head were restricted.

2.3 Mechanical Properties

A linear elastic model was used. The mechanical properties (modulus of elasticity and Poisson's coefficient) in healthy vertebrae (HV) bone were 12 GPa and 0.3 respectively [9–11], while in osteoporotic vertebrae (OV) bone they were 4.014 GPa and 0.3 [12]. The mechanical properties of a titanium base material (7074) were used.

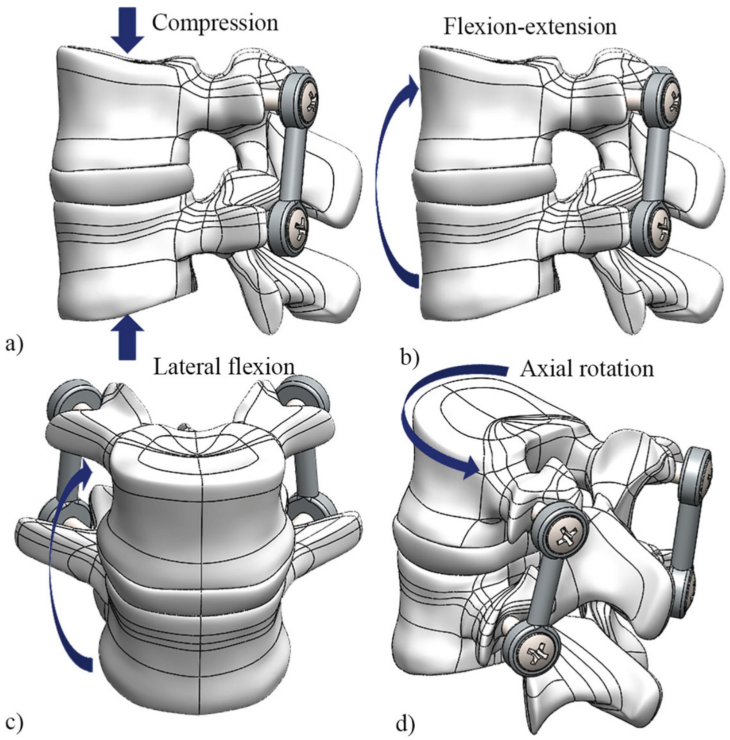

Fig. 1. Loads scenarios defined to the model. (a) Compression load, (b) Flexion-extension, (c) Lateral flexion, and (d) Axial rotation.

2.4 Mesh

The assembly was meshed by using an automatic mode. The high order tetrahedral elements of 1.5 mm were used. The 16-point Jacobian formulation was also used. A total of 426613 nodes and 299453 elements was obtained, with an aspect ratio less than 5 in all the elements.

3 Results and Discussion

In the geometry of the intervertebral disc, the stress was maximum in the compression scenario, 3.45 MPa in the osteoporotic vertebrae (OV) and 3.29 MPa in the healthy vertebrae (HV). Stress was distributed towards the edge, leaving the nucleus pulpous free (Fig. 2). This result could be influenced by the boundary conditions imposed on the model, which simulate a total rigidity of the hardware. The stress in the lateral flexion was 3.18 MPa (OV) and 2.91 MPa (HV). In the rotation and the flexion-extension, the stress did not reach 50% of the previous results.

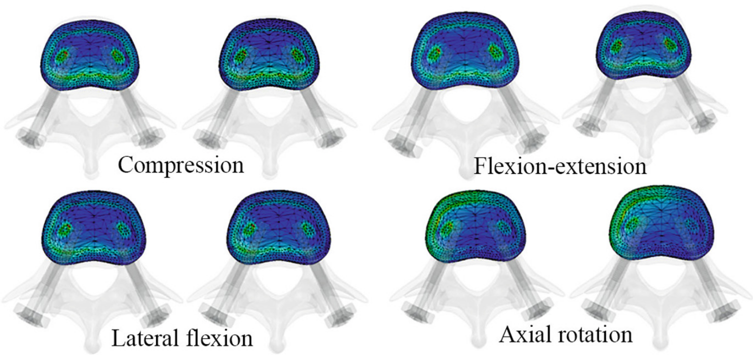

Fig. 2. Equivalent von Mises stress in the intervertebral disc in the four loads scenarios.

In the geometry of vertebrae under compressive loads, the higher stress 8.02 MPa (HV) and 5.81 MPa (OV) was located in the posterior region and in the pedicles of the vertebrae. This result coincides with Xu et al. [9]. Stress was located below the bone-screw interface of L4 vertebra, while it was in the upper plate of L5 vertebra. The zone that contained the highest stress was the one located between the mechanic fixation (from upper screws to the lower screws) (Fig. 3a).

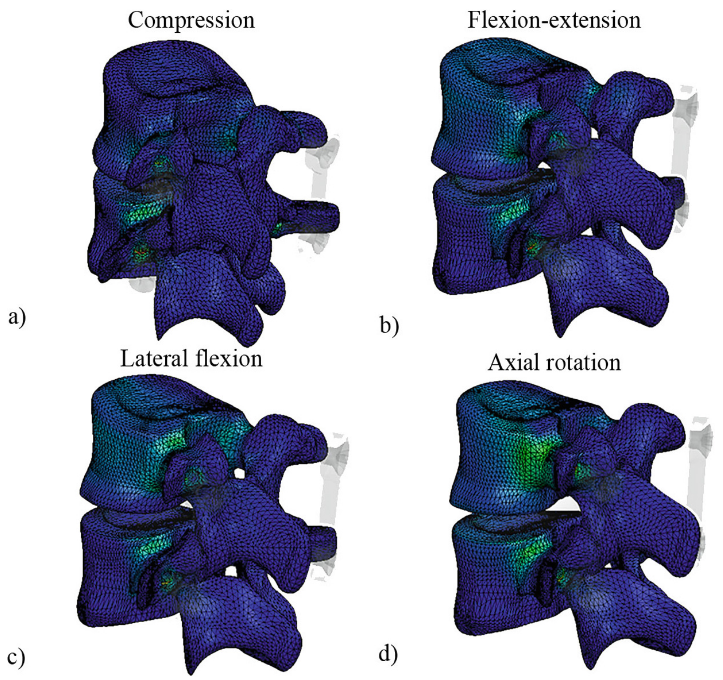

Fig. 3. Distribution of von Mises equivalent stress in the four scenarios and in health bone. Posterior vertebra and pedicle was the higher stress zone: (a) compression load, (b) flexion-extension, (c) lateral flexion, and (d) axial rotation.

In the flexion-extension movement, L5 vertebra experimented higher equivalent stress than L4 vertebra. It was 3.63 MPa in HV and 3.34 MPa in OV (Fig. 4). It reached the maximum value of stress in the zone of the bone-screw interface (Fig. 3b), which agrees with Cheng et al. [13].

In lateral flexion movement, the stress exceeded the compression scenario, 8.83 MPa (HV) and 6.05 MPa (OV) (Fig. 4). The zone near to bone-screw interface and near the direction of movement experienced higher stress than the rest of the posterior part of the vertebra. The pedicular channels were the most affected (Fig. 3c). In this scenario, the vertebrae movement occurred in one direction and it is dangerous because a complex system of loads appeared. In the rotation scenario, the stress was higher in the left of the sagittal plane (orientation of the loads) (Fig. 3d). It was 1.97 MPa in HV and 1.39 MPa in OV (Fig. 4).

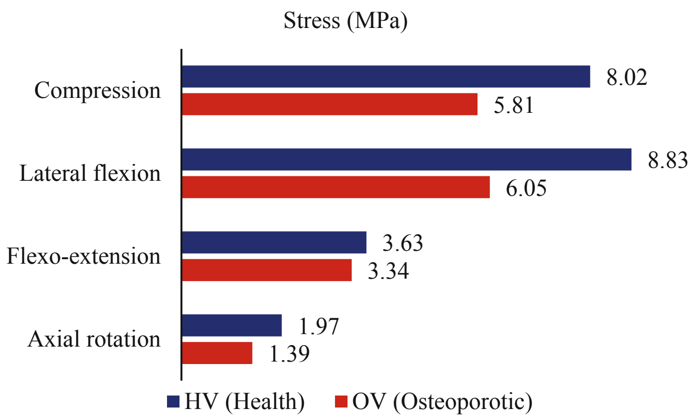

Fig. 4. Results of equivalent von Mises stress in the four scenarios. Compression and lateral flexion of health bone showed higher state of stress.

Notice that HV stress was higher than OV stress (Fig. 4). This was due to the lower modulus of elasticity of the OV bone. Those stresses were in the range reported in the literature (2 to 10 MPa) [14, 15].

When the patient experiences a flexion or axial rotation movement of the spine, the screws may come out of the bone. In addition, the patient's weight produces a perpendicular load to the screws axis and it may fail at shear stress. Furthermore, if the patient carries out heavy activities, the forces acting on the mechanical fixation may increase its magnitude, producing equivalent stress higher than the failure limit of the bone. In consequence, the contact area in the bone-screw interface is susceptible to bone failure.

According to the results of the stress analyses, the patients should be oriented not to carry out heavy activities, as should be considered a risk factor for the treatment stability, directly affecting the functionality of the arthrodesis system. In this respect, it is compulsory to avoid the occurrence of stresses close to the failure limit because high stress may produce the loosening of the screw-bone interface, extraction, and insufficiency of the instruments after the lumbar arthrodesis (the catastrophic screw or hardware failure), three of the common problems of the implant's failure [16].

A bone modifies its structure to supports load conditions (Wolff's Law). The stress, strain and deformation energy density influence the bone adaptation. Then, strain is an important factor to consider because this mechanical signal constitute the trigger of bone remodeling [17, 18].

Opposite to stresses results, the strains were higher in OV than in HV, being the OV strain more than 2 times higher than HV strain (Fig. 5). In the compression load scenario, the strain was 0.000508 in HV when the stress was 8.02 MPa. While it was 0.00134 in OV (2.63 times of HV strain), when the stress was 5.81 MPa, just the 72% of HV. In flexion-extension scenario, the strain was 0.000249 (HV) and 0.0007 (OV). OV strain was 2.81 times higher than HV (Fig. 5). The influence of strain was highly perceptible on the left pedicular channels and at the center on the upper plate of L4 vertebra.

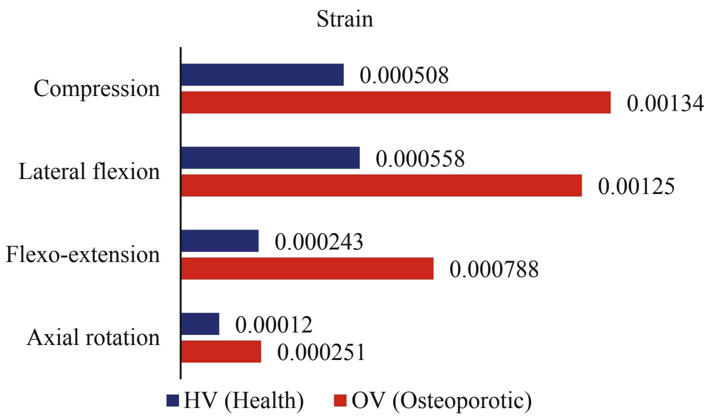

Fig. 5. Results of maximum strain in the four load scenarios. Compression and lateral flexion showed higher strain in osteoporotic bone.

In lateral flexion, the strain was 0.00055 in HV and 0.00125 in OV (2.72 times of HV strain), following similar stress-strain dependence such as in the two previous cases. In the rotation movement, strain was 0.00012 in HV and 0.00025 in OV (2 times of HV strain).

In regards to the displacements, they were 0.0116 mm (HV) and 0.0219 mm (OV) in compressive load. The zone of the highest displacements was the posterior region of the vertebra, while the smallest displacement was identified in the apophysis. The displacements in flexion-extension were 0.0144 mm (OV) and 0.00711 mm (HV). Once again, the influence of the displacements had more risks in the diseased vertebra; the value was 10 times higher in OV. In lateral flexion, displacement have the same direction of the applied load, while the values were even higher than the case of compression 0.0141 mm (HV) and 0.031 mm (OV) (Fig. 6).

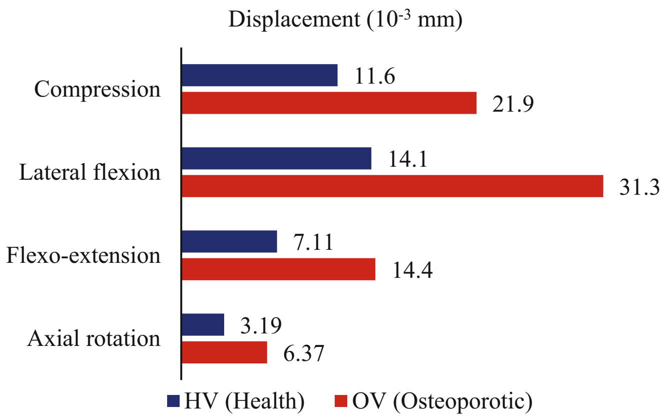

Fig. 6. Results of maximum displacements in the four load scenarios. Compression and lateral flexion showed higher displacement in the osteoporotic bone.

Several biomechanical models have been used in the simulation of spine regions. Von Farell et al. [19] studied a lumbar section with different levels of intervertebral disc degeneration. They assigned mechanical properties to the cancellous bone through a density-stiffness relationship and they defined homogeneous mechanical properties to the cortical bone. They did not use mechanical fixators. Rohlmann et al. [8] investigated the influence of an implant on the intervertebral rotation, the facet joint forces, and intra-disc pressure. They did not take into account the vertebrae displacement and defined a rigid model of the vertebrae, supposing that most of the spinal movement occurred in the intervertebral discs. Elmasry et al. [10] performed the study of the thoracolumbar region with different fixation systems. They defined constant mechanical properties in both cortical and trabecular bone.

In this work, we used a model of a posterior mechanical fixation which differs from the ones used by Elmasry et al. [10] and it is similar to the spine fixation hardware used by Rohlmann et al. [8]. The mechanical properties were not dependent to bone density as stated in the study by Von Farell et al. [19], but constant as stated by Elmasry et al. [10]. However, a comparison of healthy and osteoporotic behavior of the vertebrae was carried out by defining not only two mechanical properties for each one the healthy and the osteoporotic bone, but also four load scenarios: compression, flexion, flexion-extension and axial rotation. In further analysis, adjacent segments of the spine, mechanical properties and bone density relationship and the effect of fatigue through cyclic loads should be included.

4 Conclusions

In this paper, the L4-L5 lumbar section under four scenarios of loads and two mechanical properties (Health Vertebra HV and Osteoporitic Vertebra OV) of the bone was simulated. The model was sufficiently refined to accurately represent the geometry. The bone-screw interaction zone and the posterior of vertebra and pedicles were susceptible to bone tissue failure, because the higher equivalent stress was close to bone failure stress. The HV stress was higher than OV stress. The higher stress was 8.83 MPa. Opposite to stress results, the strain was higher in OV than in HV, being the OV strain more than 2 times higher than HV strain.

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Conflict of Interest. The authors declare no competing interests.

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