ABSTRACT

The main goal of the presented study is to understand the mechanical behaviour of a lumbar functional spine unit (FSU) L4-L5 with spondylolisthesis pathology. For the study of the healthy FSU the process includes the 3D reconstruction of the lumbar spine geometry from computer tomography (CT) images, finite element (FE) mesh definition and simulation of the spine mechanics under different load cases. The pathological model was built applying a posterior displacement of 6.81mm. The study of the two FE models, one healthy and the other with pathology, allowed identifying significant differences on the mechanical behaviour.

Keywords: Biomechanics, finite elements method, lumbar spine, vertebrae L4-L5, spondylolisthesis.

INTRODUCTION

Low back pain is the most diffuse pathology and represents one of the top causes of missed work. This pain is a universal human experience as almost everyone has it at some point. Fortunately, low back pain often gets better on its own. When it doesn't, there are effective treatments.

Some authors (Weinstain, 2010; Moramarco, 2010) explain that low back pain can arise due to idiopathic degeneration of any mechanical component of the column spine, like discs, ligaments and facet joints. In most cases, surgery is the unique effective solution to the problem. Surgery should only be considered if a patient's ability to participate in everyday activities is unacceptably reduced and a concerted effort to relieve symptoms through non operative techniques has been unproductive. Any treatment of lumbar spine injuries aims at returning to a more active and pain free lifestyle, decreasing of any neurological deficit and prevention of further disability. Furthermore, surgical treatment has some advantages like the immediate stability and the possibility for early mobilization.

Nowadays most of the orthopaedic surgeries are essentially based on the experience of the surgeon, who demands the best situation for each patient (Moramarco, 2010). Although CT and magnetic resonance techniques allow the doctor to observe the current state of the patient spine degeneration, it is not possible to predict the behaviour of the spine after surgery. The use of computer models to study the biomechanical alterations of the cervical spine is a powerful tool to understand the mechanisms of injury. The finite element method is an excellent tool for studying the biomechanical behaviour of the spine, as it allows spine motion analysis(Guan, 2006; Little, 2007); it makes possible to find the best solutions helping
clinicians to make the best decision in planning surgical interventions. In the last years, several models were created, with the goal to create prosthesis for a particular problem, (Eberlein, 2001; Guan, 2006; Little, 2007; Moramarco, 2010; Rodrigues 2012; , 2013).

The main goal of this study is to perform the development of a non-invasive method to obtain truly dynamic behaviour of the spine under specific loads. A healthy model of a lumbar L4-L5 FSU is created and an iterative calibration process was performed in order to find an ideal but realistic combination of mechanical properties. Then a pathological model is built applying a posterior displacement equal to 6.81 mm, corresponding to a lumbar spondylolisthesis. Using the commercial software Abaqus Explicit, the characterization of each FSU model is made in order to compare the behaviour of the healthy and non-health FE models under different loading types; results show that for the same load, stresses of the non-healthy intervertebral disc are higher, which can lead to greater disc injury.

METHODS

The spinal segment L4-L5 under consideration consists of two vertebral bodies, the intervertebral disc, spinal ligaments and facet joints. The intervertebral disc and ligaments contribute to the general flexibility of this spinal segment, having an important role in the spine kinematics. For the definition of the healthy FSU geometry, vertebrae, intervertebral discs (nucleus pulposus, annulus fibrosus and fibres), endplates, ligaments and facet joints were considered (Little, 2007).

The construction of the vertebrae was established using CT scan data, and the finite element mesh of the vertebrae was created using the commercial finite element package Abaqus/Cae (Rodrigues, 2012).

The intervertebral disc was designed with its components, such as nucleus pulposus and annulus fibrosus bounded by two endplates (Jieun, 2012; Rodrigues, 2012). Due to its lower density, the intervertebral discs are not visible in a CT and disc geometry was defined using the lower surface of L4 and the upper surface of L5. Fig. 1 shows the disc geometry with the two different regions, the inner nucleus pulposus and the peripheral annulus fibrosus taking into account the volumetric ratio 3:7.

![Fig. 1 - 3D finite element of the intervertebral disc and Layers 1-2 and 7-8 of collagen fibres](image)

The annulus fibrosus is a viscous substance reinforced by a network of collagen fibres. The arrangement of the elastic fibres plays a very important role in the overall mechanical properties of the annulus fibrosus. The stiffness of the fibre proportionally decreased from
outside to inside for every two fibre layers and the proportion varied from 1 to 0.65 (Xu, 2013). The fibres were modelled as tension-only truss elements, T3D2 and embedded in the viscous matrix of the respective annulus layer as shown in Fig. 1. The definition of the cartilaginous plates was performed considering the first and last layer elements, respectively. With the aim to decrease the thickness of the plate, the nodes were moved.

In order to model the intervertebral joints, facet joints were created in the contact area of the two vertebrae. These facet joints were treated as a three-dimensional contact problem using surface-to-surface soft contact with exponential-pressure-over closure option available in ABAQUS. Finally the anterior longitudinal ligaments (ALL), the posterior longitudinal ligaments (PLL), the supraspinous ligament (SSL), the interspinous ligaments (ISL), the intertransverse ligaments (ITL), the ligamentum flavum (LF) and the capsular ligaments (CL) were considered, and modelled with tension-only spring connector elements (truss elements T3D2), similar to the definition of the collagen fibres. The complete model is presented in Fig. 2a).

![Fig. 2 - 3D finite element: (a) healthy model; (b) pathologic model](image)

In FE modelling of spinal motion segments generally it is considered that the segment is supported rigidly along the inferior endplate of the lower vertebra, L5, and the loads are applied on the superior endplate of the upper vertebra. The loads can be applied as static or dynamic loads. In this study static loading situations were considered and all the loads were applied in the superior surface of L4 through a reference node. The choice of mechanical properties was performed by an iterative calibration process; considering a compression load case a realistic combination of mechanical properties was obtained taking into account results found in literature (Rodrigues, 2012). Elastic behaviour was considered for all FSU elements (Rodrigues, 2012), except the nucleus pulposus and the viscous annulus that were considered as hyper elastic materials. The vertebral bodies were taken as rigid bodies, thus there was no difference between cortical and trabecular bone.

The pathological model, shown in Fig. 2b, was built applying a posterior displacement of 6.81 mm. The characterization of each model was performed using Abaqus Explicit: the two models were subjected to pure moments and forces in the three anatomical planes. In order to compare the mechanical behaviour of the two units, the maximum displacement and stress fields were calculated.
RESULTS

Two movements were analysed such as flexion and torsion. For each load case the axial displacement field of the L4-L5 FSU, and the minimum principal stress distribution in the intervertebral disc were analysed. Considering load cases flexion and torsion, moments of +20 Nm and +11.45 Nm were applied respectively.

![Fig. 3 - Axial displacement field (flexion load): (a) healthy model; (b) pathologic model](image)

Figure 3 shows similar displacement fields for the healthy and non-healthy models, considering flexion load; the healthy model presented a smaller axial displacement and in both models the largest axial displacements are observed in vertebrae apophysis.

![Fig. 4 - Stress distribution considering torsion load: (a) healthy model; (b) pathologic model](image)

Figure 4 shows the minimum principal stress distribution on the disc considering load case flexion for healthy and pathological discs, respectively. As expected results show compression at the anterior zone and traction at the posterior zone. Considering compression, the maximum stress values are -0.5607 MPa and -1.238 MPa for the healthy and pathologic
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discs respectively. Concluding, the pathological model presents higher stresses and is more prone to deformations.

![Fig. 5 - Axial displacement field (torsion load): (a) healthy model; (b) pathologic model](image)

Figures 5 and 6 present the displacement field and the minimum principal stress distribution considering torsion load. As in the previous load case the healthy model presents smaller axial displacements. Stress distribution is uniform in the healthy model, however, in the disease model, the intervertebral disc is under traction on the right side and under compression on the left side. In both models the critical zone is under compression. The healthy model presents a maximum value equal to -0.2396 MPa while for the pathological model maximum value is equal to -0.476 MPa. Once more the FSU model with pathology presents higher stresses (almost twice) than the healthy one.

![Fig. 6 - Stress distribution considering torsion load: (a) healthy model; (b) pathologic model](image)

CONCLUSIONS

The obtained results, as clinically expected, show that pathologic model present the highest compressive stresses for the two studied load cases. Concluding patients with spondylolisthesis will have greater possibility of disc degeneration and herniation. Furthermore greater deformation of the disc and large axial displacements of contiguous segments, will lead to neurological injury.

The obtained results with static load conditions allow the prediction of the most loaded parts of the discs related to the most susceptible zones of damage. Although the finite element
model developed for this study is still not fully complete, as muscle forces and initial stresses of the ligaments were not considered it proved to be a useful tool for understanding the biomechanical behaviour of the cervical spine, and may help clinicians to understand the initiation and progression of disc degeneration and to treat lumbar discopathy problems even more effectively.

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REFERENCES