BIOMECHANICAL STUDY OF IDIOPATHIC SCOLIOSIS

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ABSTRACT

The spine is one of the most complex structures of the human skeleton. Spine develops several pathologies due to trauma or degenerative diseases, as scoliosis and sometimes is necessary to resort to a surgical correction. The finite element method (FEM) is a well-known and widely used numerical method to study spine structural behaviour. This paper presents a computer-aided methodology for creating a 3D model of the Idiopathic scoliosis using spinal vertebrae reconstructed from medical images. The presented analysis can help physicians to predict the outcome of intervention with different surgical procedures and be considered as a first step in creating a complete model owing to study the biomechanics of the surgical treatments of scoliosis pathology.

Keywords: biomechanics, spine, scoliosis, finite element method.

INTRODUCTION

The spine is considered as a firm and flexible beam, offers stability and mobility to the human body due to its 26 individual vertebrae connected by joints and stronger ligaments dynamically supported by the surrounding musculature. Being a multifunctional structure subject to different loads, the occurrence of a wide range of pathologies including scoliosis is common. Scoliosis is a three-dimensional (3D) deformation of the human spine, characterized by a lateral displacement, accompanied by axial rotation of the vertebrae. In upright postures of the trunk of humans who have structurally normal spines, the vertebrae lie along a nearly straight vertical line; otherwise scoliosis is present when, in upright positions of the trunk, the spine curves to the side for unknown reasons. Even though most scoliosis curves will stabilize without treatment, a few will get worse. Especially during the rapid growth period of adolescence, lateral curves in the spine tend to become clinically significant. It most commonly develops during the growth spurt of puberty and early adolescence, usually between the ages of 10-12 for girls and 11-16 for boys. About 1 in 40 children have some degree of scoliosis.

Mild scoliosis affects about the same number of boys and girls. However, moderate or severe scoliosis is more common in girls. Mild scoliosis curves create psychosocial problems for the children who have them as result in cosmetic deformities of the trunk. On the other hand, severe scoliosis curves result in trunk deformities of magnitudes that eventually become life-threatening. Most cases of scoliosis, called idiopathic cases, have no known cause.

There is an extensive literature inquiring into the causes of idiopathic scoliosis. Weaknesses or other abnormalities in the muscle of the trunk have often been said to be a cause of idiopathic scoliosis (Nachemson, 1977). The tests performed by Portillo (Portillo, 1983)
provided no evidence that the strengths of any of the major muscles of the trunk are different in populations of girls with idiopathic scoliosis and age-matched population of girls with structurally normal spines. Furthermore once a curve to the side exists in a spine, the weight of the body segments superior to that curve in upright positions of the trunk creates a lateral bending moment that tends to increase scoliosis.

When unbalanced lateral moments are imposed on a spine, its involved motion segments will take on lateral tilts. Some investigations (Schultz, 1984) have shown that when spines of structurally normal animals are held in laterally curved positions for several weeks, the lateral tilts of the vertebrae become semi-permanent. Reuber (Reuber, 1983), suggests that it would be the tendency of disc lateral tilts to increase and become semi-permanent which would dominate the tendency for idiopathic scoliosis progression.

In order to classify scoliosis the Cobb angle was originally used to measure coronal plane deformity on anterior-posterior X-ray images; now Cobb angle is used as a standard measurement to determine and track the progression of scoliosis. It is a measure of the curvature of the spine in degrees and a Cobb angle of 10 degree is regarded as a minimum angulation to define scoliosis. Those who have curves between 40 and 50 degrees are often considered for scoliosis surgery. The goal is to make sure the curve does not get worse, but surgery does not perfectly straighten the spine. 3D models of the spine reconstructed from medical images allow the prediction of installed stresses and strains. As scoliosis is a condition defined in mechanical terms, biomechanical studies are relevant. Previous research (Kim, 2009) showed that the use of commercial software is a good tool to get detailed investigation on the biomechanics of the spine with scoliosis.

The aim of this study was to create a 3D finite element model of the spine with adolescent idiopathic scoliosis using computed tomography data (CT); the principal objective was to get a model able to predict scoliosis surgical results as displacements and stresses in order to be able to plan and optimize the surgical correction of scoliosis. The use of computational models is increasing with the biomechanical study of several existing pathologies in the human spine. Finite element models present low costs and no risks of biological tissue (bone), and are able to provide data on some measures that are impossible to acquire in a cadaver body, such as pressure on the disc. This work also intends to reduce the number of spinal X-ray images required for the study of idiopathic spinal deformities at adolescents.

METHODS AND RESULTS

This work consisted of the 3D construction of a spine with adolescent idiopathic scoliosis (AIS) using computed tomography data of a patient aged 14, obtained at Vila Nova de Gaia Hospital in Portugal. Once the CT images obtained had no sufficient resolution for the reconstruction of the vertebrae geometry, the 3D model has been obtained as follows: vertebra geometry was obtained from a database (Physiome Space Portal, 2014); in order to create the model, vertebrae were positioned according to the obtained CT images.

For this purpose, commercial codes MIMICS and FEMAP were used. The 3D model of the spine curvature with adolescent idiopathic scoliosis was built using MIMICS software and CT images. Then with FEMAP software vertebrae obtained in a database were positioned according to the 3D model obtained in MIMICS. Fig. 1 presents the CT image and the obtained 3D model.
Due to its lower density, intervertebral discs are not visible in a CT image. The geometry of each disc was defined using the lower surface of the above vertebra and the upper surface of vertebra situated below. Each disc was partitioned into two regions: the inner nucleus pulposus and the peripheral annulus fibrosus taking into account the volumetric ratio 3:7. Fig. 2 shows the disc geometry with the different regions of the nucleus pulposus and annulus fibrosus and the FE mesh consisting of eight-noded hexahedral elements with a hybrid formulation C3D8H.

Cartilaginous plates were defined considering the first and last layer elements, respectively and nodes were moved in order to decrease the thickness of the two plates. The annulus is a viscous substance reinforced by a crisscrossing network of collagen fibres. The reinforcing fibres, attached to each of the annular layers were modelled as tension-only truss elements,
T3D2, between the diagonally opposing nodes of the frontal faces of each hexahedral element (Fig. 2). These fibres were embedded in the viscous matrix of the respective annulus layer.

Fig. 3 - Front view (a) and lateral view (b) of 3D model: vertebrae, intervertebral discs and ligaments: supraspinous ligaments (green), interspinous ligaments (pink), intertransverse ligaments (orange), longitudinal ligaments (yellow)

Then, all the considered ligaments, supra/inter-spinous, intertransverse and longitudinal ligaments, were modelled with tension-only spring connector elements (truss elements T3D2), similar to the definition of the collagen fibres. Fig. 3 illustrates some intervertebral discs, and ligaments of the 3D model of the spine with AIS. In this study vertebrae meshed with four node tetrahedral elements C3D4 were modelled as rigid bodies once its order of deformation is low when comparing with the deformation of the disc and muscles were not considered.

<table>
<thead>
<tr>
<th>Anatomical structure</th>
<th>E [MPa]</th>
<th>Poisson's Ratio</th>
<th>Type Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertebral body</td>
<td>12000</td>
<td>0.3</td>
<td>SOLID 4-noded</td>
</tr>
<tr>
<td>Nucleus pulposus</td>
<td></td>
<td></td>
<td>Hiperelastic SOLID, 8-noded</td>
</tr>
<tr>
<td>Annulus (viscous substance)</td>
<td></td>
<td></td>
<td>Hiperelastic SOLID, 8-noded</td>
</tr>
<tr>
<td>Collagen Fibers</td>
<td>500</td>
<td>0.3</td>
<td>Beam 2-node</td>
</tr>
</tbody>
</table>
The choice of mechanical properties shown in Table 1 was performed according to the literature (Kim 2009; Little, 2013; White, 1990). The nucleus pulposus, mainly composed of water, was considered isotropic, almost incompressible and a hyperelastic model was considered to characterize the behavior of its gelatinous material. All ligaments and collagen fibres were modelled considering elastic behaviour.

CONCLUSIONS AND FUTURE WORK

This paper presents a methodology for developing a 3D model of the human scoliosis using CT images. The main goal of this study was to create a finite element model able to understand the biomechanics of the surgical treatment of this pathology allowing, in future, assessment and treatment plans and optimization of scoliosis surgeries.

Obtaining the 3D model of the spine in scoliosis had some limitations arising from quality and resolution of the supplied medical CT images that only allowed a spatial visualization of the spine with AIS. In scoliotics studies CT images are usually employed in order to decrease the time of exposure to radiation, unnecessary for the diagnosis of this pathology. However, obtaining a 3D structure of the vertebrae in a database and repositioning the vertebrae according to the CT images of the spine with AIS, a good approximation was achieved.

ACKNOWLEDGEMENTS

The authors acknowledge the collaborative work of the medical team of the Centro Hospitalar de Vila Nova de Gaia, Vila Nova de Gaia, Portugal.

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