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Biomechanical analysis of lumbar decompression surgery in relation to degenerative changes in the lumbar spine – Validated finite element analysis

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ABSTRACT

Background: There are no studies about the biomechanical analysis of lumbar decompression surgery in relation to degenerative changes of the lumbar spine. Therefore, the purpose of this study was to compare, by using finite element (FE) analysis, the biomechanical changes of the lumbar spine in terms of annulus stress and nucleus pressure after two different kinds of lumbar decompression surgery in relation to disc degenerative changes.
Methods: The validated intact and degenerated FE models (L2-5) were used in this study. In these two models, two different decompression surgical scenarios at L3-4, including conventional laminectomy (ConLa) and the spinous process osteotomy (SpinO), were simulated. Therefore, a total of six models were simulated. Under preloading, 7.5 Nm moments of flexion, extension, lateral bending, and torsion were imposed. In each model, the maximal von Mises stress on the annulus fibrosus and nucleus pressure at the index segment (L3-4) and adjacent segments (L2-3 and L4-5) were analyzed.
Results: The ConLa model and disc degeneration model demonstrated a larger annulus stress at the decompression level (L3-4) under all four moments than were seen in the SpinO model and healthy disc model, respectively. Therefore, the ConLa model with moderate disc degeneration showed the highest annulus stress at the decompression level (L3-4). However, the percent change of annulus stress at L3-4 from the intact model to the matched decompression model was less in the moderate disc degeneration model than in the healthy disc model.
Conclusions: Although the ConLa model with moderate disc degeneration showed the highest annulus stress, the degenerative models would be less influenced by the decompression technique.

1. Introduction

Several surgical treatments have been introduced for decompression of lumbar spinal stenosis (LSS), ranging from minimally invasive techniques to traditional laminectomy. Previous studies have shown that decompression surgery alters the biomechanical behavior of the lumbar spine [1,2]. Especially, preservation of the continuity of the posterior ligament complex (PLC) is important in alleviating instability after decompression surgery [2].

Degenerative changes of the lumbar spine also influence spine biomechanics [3–5]. Given that all patients with LSS have moderate to severe degenerative changes, the effect of this degeneration should be considered for the proper and valid prediction of biomechanical changes after decompression surgery. The removal of posterior structures for sufficient decompression might have different biomechanical implications depending on the degenerative state of the lumbar spine at the time of surgery.

Although both decompression surgery and degenerative changes can influence the biomechanics of the lumbar spine, there has been no study about a simultaneous biomechanical effect of decompression surgery and degenerative changes. Therefore, we hypothesized that biomechanical effect of decompression surgery would be different in relation with

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degenerative changes. The information about this would be clinically relevant because this may help the surgeon decide surgical method for degenerative spinal disease. Therefore, this study aimed to assess and compare, by using finite element (FE) analysis, the biomechanical changes of the lumbar spine for annulus stress and nucleus pressure after two different kinds of lumbar decompression surgery in relation to degenerative changes of the lumbar spine. Two different surgical decompression techniques were compared: the spinous process osteotomy (SpinO) technique, which preserves the PLC but involves the cutting of the base of the posterior spinous processes, and conventional laminectomy (ConLa), which involves the removal of both the PLC and the spinous processes.

2. Materials and methods

2.1. FE model of the intact lumbar spine (L2-5)

We made a three-dimensional (3D) nonlinear FE model of the lumbar spine comprising four lumbar vertebrae, three intervertebral discs, and the associated spinal ligaments. The geometric outline of the human lumbar spine (L2-L5) was obtained from high-resolution computed tomography (CT) images of a 46-year-old male subject with no spinal deformities. Although we obtained anatomical information about the lumbar spine geometry from CT images, a large part of the geography was altered for specific use in this study. With the respect to mid-sagittal plane, the geometry was modified to be symmetric. In addition, because it was difficult to distinguish geometry of the disc nucleus from the CT image, it was modeled based on the previous literature [6,7]. Similarly, cortical and cancellous bone were also modeled on the basis of the method from the previous studies [6,7]. Furthermore, because the present research used existing data and the subjects could not be identified, our institutional review board approved an exemption for obtaining informed consent in this study. Digital CT data were imported to a software program (Mimics; Materialise Inc., Leuven, Belgium) that was used to generate the 3D geometric surface of the lumbar spine. Initial Graphic Exchange Specification files exported from the Mimics software were input into Unigraphics NX 3.0 (Siemens PLM Software, Torrance, CA, USA) to form solid models for each vertebral segment. The solid model was then imported into Hypermesh 8.0 (Altair Engineering Inc., Troy, MI, USA) to generate FE meshes. In the current FE model, a hexa mesh was generated over the entire area. The FE model was analyzed with commercially available software (ABAQUS 6.11–1; Hibbitt, Karlsson and Sorenson Inc., Providence, RI, USA).

Three-dimensional solid elements with homogenous and transversely isotropic character were used to model the cortical and cancellous cores and the posterior bony parts of the vertebrae. The nucleus pulposus (NP) and the ground substance of the annulus fibrosus (AF) were modeled by using solid elements. The anterior longitudinal ligament, posterior longitudinal ligament, intertransverse ligament, ligamentum flavum, capsular ligament, interspinous ligament, and supraspinous ligament were modeled by using tension-only truss elements (Fig. 1).

2.2. Material properties

The material properties were derived from various literature sources (Table 1) [8–11]. The cortical and cancellous regions of the vertebrae were modeled independently. Because the cortical and trabecular bones in the posterior region were difficult to differentiate from each other, the posterior elements were all assigned a single set of material properties.

The AF was modeled as a composite of a solid matrix with embedded fibers (by using the REBAR parameter) in concentric rings surrounding an NP, which was considered to be an incompressible solid. Element members with a hybrid formulation (C3D8H) combined with a low elastic modulus and large Poisson ratio definitions were applied to simulate the NP. A hybrid formulation (C3D8H) was also applied for simulation of ground substance of AF. Eight-node brick elements were used to model the matrix of the ground substance. Each of the four concentric rings of the ground substance contained two evenly spaced

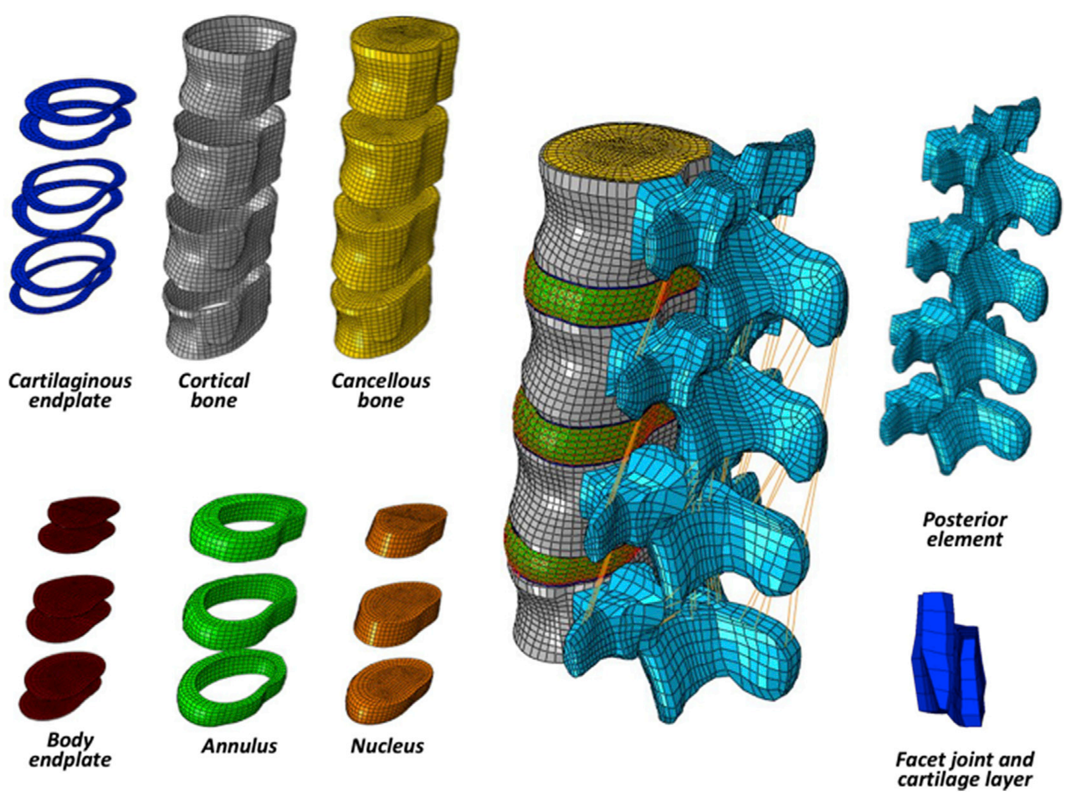

Fig. 1. The present intact finite element model.