STRESS ANALYSIS OF THE HUMAN LIGAMENTOUS LUMBAR SPINE-FROM COMPUTER-ASSISTED TOMOGRAPHY TO FINITE ELEMENT ANALYSIS

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Abstract Detailed investigation on biomechanics of a complex structure such as the human lumbar spine requires the use of advanced computer-based technique for both the geometrical reconstruction and the stress analysis. In the present study, the computer-assisted tomography (CAT) and finite element method (FEM) are merged to perform detailed three dimensional nonlinear analysis of the human ligamentous lumbar spine. The details of the development of a three dimensional model of the lumbar spine using CAT images are initially described. Then the predicted nonlinear response of the system subjected to axial compression force is presented. The stress analysis is performed using a finite element code developed by Shirazi-Adl.

Key Words Spinal Column, Stress Analysis, Geometrical Reconstruction, Finite Elements, Stability

چکیده تحقیقات اساسی در بیومکانیک ستون فقرات انسان احتیاج به روشهای کامپیوتری جهت بازسازی هندسی و آنالیز مکانیکی دارد. در این تحقیقات، رادیوگرافی و روش اجزاء محدود توأماً بکار گرفته می شوند تا آنالیز سه بعدی و غیر خطی ستون فقرات انجام می گیرد. در آغاز به روش بازسازی، مدل ستون فقرات مطرح می شود. متعاقباً، نتایج آنالیز مکانیکی زیر بار نیروی فشاری عرضه می شوند.

INTRODUCTION

Low-back disorders are serious problems that affect a large proportion of the population. Despite considerable efforts in the last few decades, regarding their etiology, they remain still poorly understood and inadequately managed. Epidemiological as well as biomechanical studies have demonstrated the important role of mechanical factors in the back disorders. For example, exposure to heavy manual handling tasks and lifting particularly involving axial torsion are known to increase the risk of the low-back pain.

The lumbar region of the human spine is a very complex three dimensional structure consisting of various tissues such as discs, ligaments, vertebral bodies, and muscles. Detailed biomechanical analysis of this system requires an accurate 3-D finite element mesh. In the present study, the computer-assisted tomography images of a cadaveric lumbar spine are used to automatically reconstruct the geometry of the lumbar spine [1].

In order to perform an accurate stress analysis of such a complicated structure, the previous code used for the analysis of a single lumbar motion segment [2, 3] has substantially been modified to account for the specific features of the present multi-motion segments model [4-6]. This is then applied for the nonlinear stress analysis of the lumbar spine with different boundary conditions under axial compression force.

METHOD

The structure of the spinal column is schematically presented in Figure 1. The lumbar spine is that part of the spine located in between the thoracic and the sacrum regions and is distinguished by its sagittal curvature referred to as the lumbar lordosis. The lordotic curvature is made of wedge-shaped lumbar intervertebral discs which are thinner posteriorly. This variation in height is particularly noticeable at the lower lumbar discs. Adjacent bony vertebrae are attached to each other by an intervertebral disc and a number of ligaments. Each disc is composed of a central gelatinous fluid-like nucleus pulposus surrounded by composite annulus fibre layers.

Computer-assisted tomography images of a cadaveric ligamentous lumbar spine of a 65-year-old male subject were obtained using 2 mm thick transverse slices at 2 mm intervals. The specimen was insured to be normal with no undue degeneration or deformity. The digital images were recorded on a magnetic tape and were directly uncoded using an in-house developed software to automatically identify the geometry of various tissues in every single image. This was done using a thresholding method based on the analysis of the pixel intensity curve of CAT images and was subsequently verified and corrected by an interactive slice edition program. The 3-D triangular polygon mesh of the vertebrae including the facets was then reconstructed by a reconstruction algorithm.

Due to the poor visibility of the disc contours on the scanner images, the intervertebral discs were reconstructed using the geometry of the adjacent vertebral end-plates. A special software was developed to automatically generate the mesh for the intervertebral discs using 8-node brick elements. Articular surfaces of the facets were digitized on the IRIS work station screen employing sets of contactor points and target triangular surfaces. Attachment points of the ligaments were also identified in a

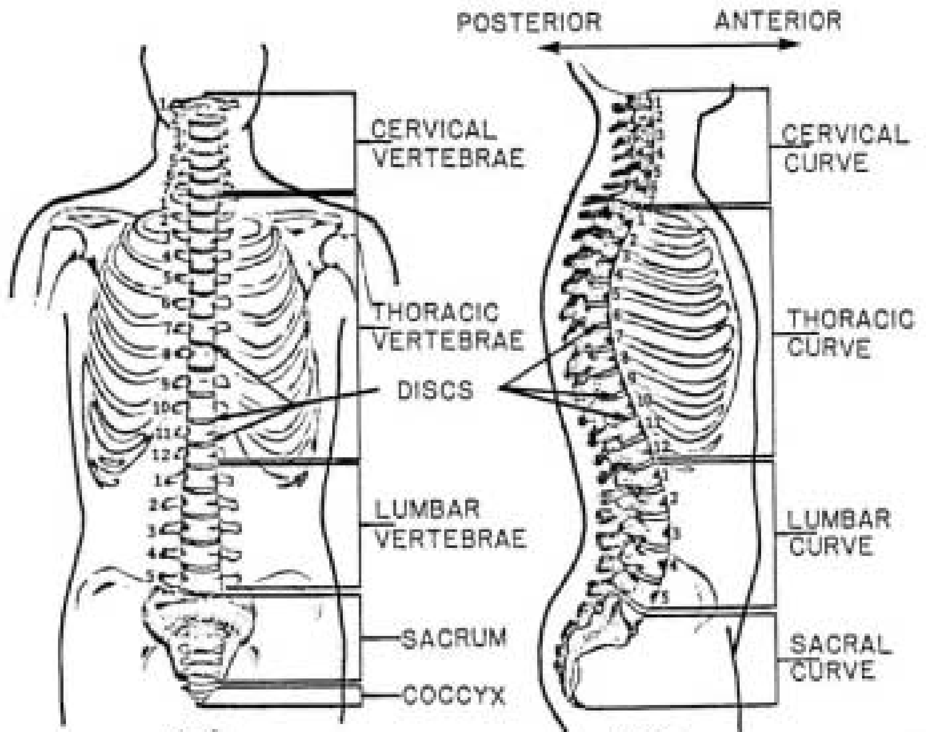

Figure 1. Human vertebral column. (a) Frontal or anterior view, (b) Sagittal or lateral view.

similar manner. The details of the reconstruction procedure are available elsewhere for reference [1].

The constructed model of the ligamentous lumbar spine includes six vertebrae (L1-S1), five discs, ten sets of superior and inferior facet articulating surfaces (two at each level), and many ligaments (supra/interspinous, ligamentum flavum, intertransverse, capsular, posterior longitudinal, anterior longitudinal, iliolumbar, and fascia).

Figure 2 shows two segments with the middle vertebra removed. The finite element mesh of the discs, facet articular surfaces, and some ligaments are visible in this figure. The model of the whole lumbar spine and the grids for typical facet joints and an intervertebral disc are shown in Figures 3 and 4. This model of the lumbar spine contains 1080 8-node solid elements (for the annulus matrix of the discs), 5760 3-node membrane elements (for the annulus collagenous layers), 315 2-node uniaxial elements (for ligaments), 180 4-node planar elements (for the vertebral end-plates), 250 contactor points (for the facet inferior articular surfaces), 662 target triangular surfaces (for the facet superior articular surfaces), 11 rigid bodies (for the vertebrae), 10 beam elements (for the vertebrae), and a total of about 2983 nodal

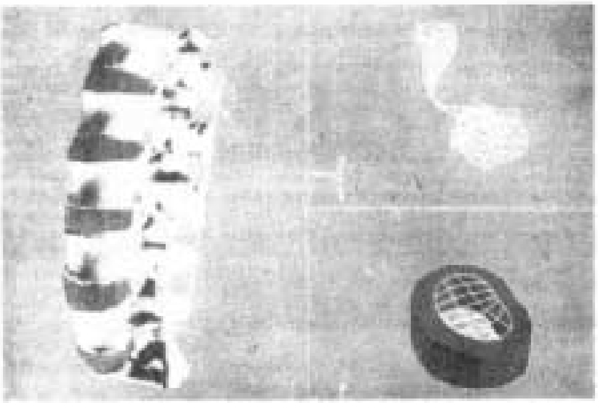

Figure 3. A view of the model and typical grids for the facet joints and intervertebral discs.

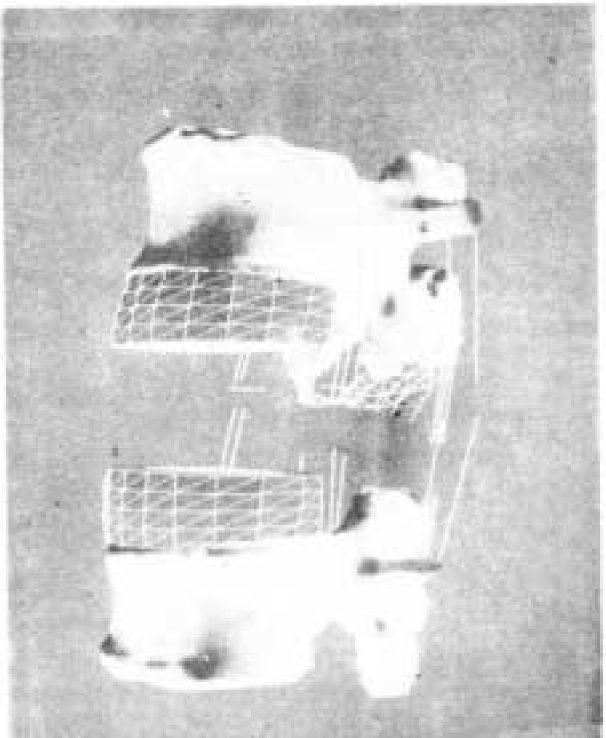

Figure 2. Representation of two motion segments with the middle vertebra removed.

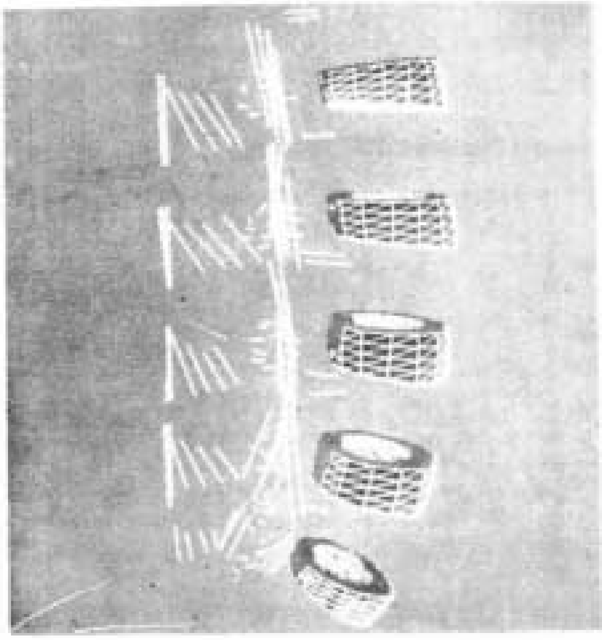

Figure 4. The entire model showing various deformable elements (rigid bony elements are not shown).

points. The generated data are then transferred to a mainframe computer to be utilized in an in-house developed 3-D nonlinear finite element program.

In order to make the analysis tractable and at the same time preserve the accuracy, each vertebral body is modeled by two rigid bodies inter-connected by two deformable spatial beam elements. This representation is based on the earlier studies on the role of the vertebral compliance on the segmental response [4, 5]. The addition of rigid bodies that can be attached to deformable elements and articulate with each other or with deformable bodies required a substantial modification to the authors' existing program [2, 3]. Moreover, the nonlinear treatment of a fluid-filled cavities inside solid structures [2] needed to be reformulated to allow for the presence of more than one fluid cavity in the media [6].

The material properties are based on earlier studies [2, 3] as well as extensive survey of recent data in the literature. The loading is applied at the L1 anterior vertebral body (see Figure 1) and consists of an axial compression which incrementally reaches its maximum value of 700 N for the case in which the L1 is restrained in horizontal translations and of 200 N for the cases with either a restraint in the sagittal translation at the L1 or no restraints at all. The distal end of the model at the S1 (i.e., sacrum) is fixed in all cases analyzed. The applied axial load is in the global Z direction which is set to be perpendicular to the mid-plane of the L3-L4 intervertebral disc. The global X and Y directions are in the horizontal plane oriented in the sagittal (towards the posterior side in Figure 1b) and lateral (towards the left side in Figure 1a) directions respectively.

RESULTS AND DISCUSSION

Sagittal displacement (X) at different levels for the case with unconstrained L1 is shown in Figure 5. Very large sagittal translations and rotations with softening behaviours are computed in this case. Restraint on the sagittal translation at the L1 stiffens the lumbar spine and results in instability (i.e., large displacements or hypermobility) in the frontal plane, as depicted in Figure 6. The model with the L restrained in the horizontal translations is found to be the stiffest of all with minimal displacement under axial compression loads up to 700 N. The predicted axial translations (Z) for this case are shown in Figure 7. The variation of the intradiscal pressure

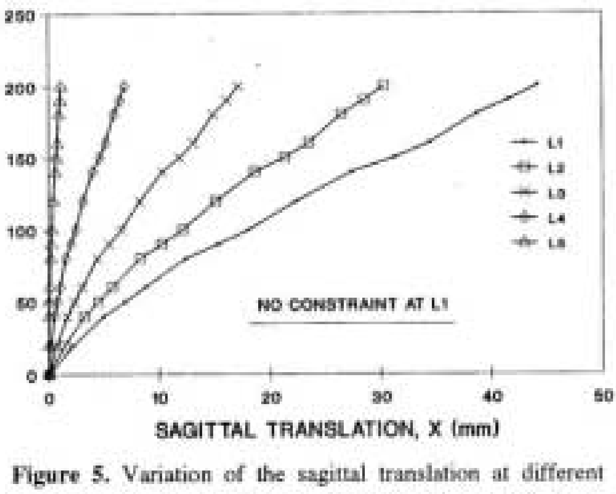

Figure 5. Variation of the sagittal translation at different vertebrae with the axial force for the case with no constraint at the L1.

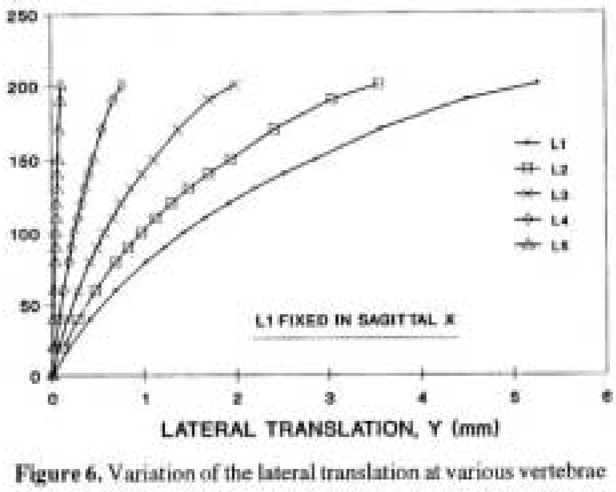

Figure 6. Variation of the lateral translation at various vertebrae with axial force for the case with the L1 constrained in the sagittal direction.

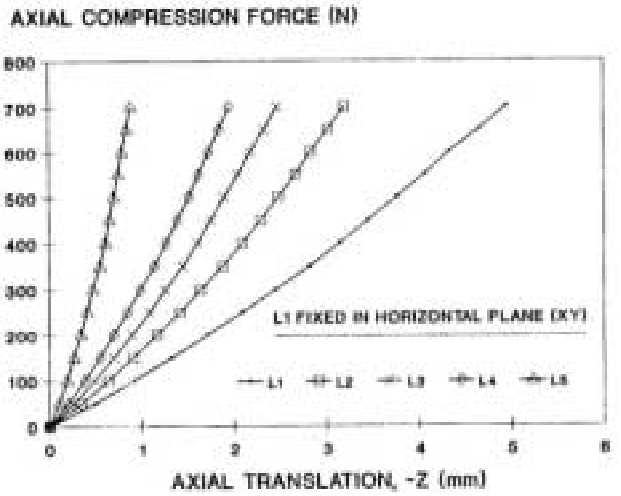

Figure 7. Variation of the axial translation at various vertebrae with axial force for the case with the L1 constrained in horizontal directions.

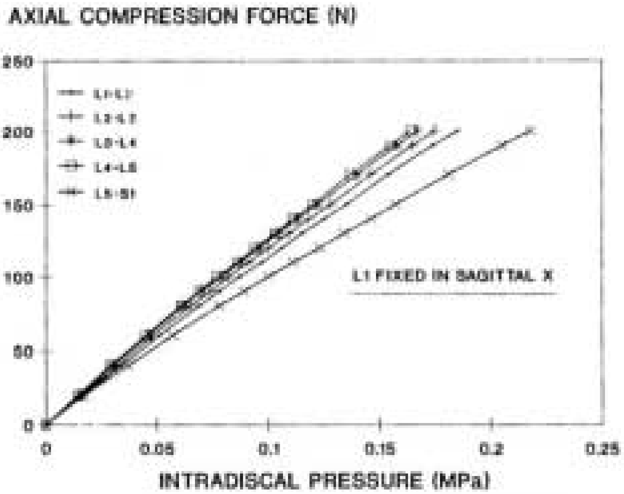

Figure 8. Variation of the disc pressure at differet levels with axial force for the case with the L1 constrained in the sagittal direction.

(i.e., nucleus pressure) at different segmental levels with the applied load for the case with the L1 restrained in the sagittal translation is shown in Figure 8. It is noted that the disc pressure varies depending on the segmental level considered.

Acknowledging a few other multi-motion segment models [7], the present model is likely the most complex and accurate one of all lumbar spine reported so far. This work was performed to elucidate the load-carrying capacity of the ligamentous lumbosacral spine in compression. It was found that the lumbar spine is a nonlinear system with imprefection-sensitive character. Due to its curvature in the sagittal plane (lordosis), in compression, the lumbar spine is the least stiff in the sagittal plane. The reported buckling load of 88 N for the lumbar spine in the frontal plane [8] appears not to be supported by the current results shown in Figure 5. The likely mechanisms that could enhance the compression load-carrying capacity of the spine beyond the levels present in physiological activites and their interactions with the active muscular system are examined and discussed elsewhere in details [9, 10].

In conclusion, the developed procedure of merging computer-assisted tomography and finite element modeling does not require manual digitization of the images. This is advantageous in both preserving the accuracy and saving the pre-processing preparation time. Moreover, the mesh generation routine allows for a number of user defined parameters such as the number of elements to be used along the circumference, through the radial thickness, and along the height of the disc annulus.

The developed interactive system is also of great importance a diagnostic point of view. It permits a wide range of interactions (rotations, precise measurements, sections, zoom in, etc.) with the structure seen on the screen. Finally, the above procedure can be parameterized in order to easily generate the finite element mesh of the lumbar spine of any live subject by only inputting a number of individual anatomic key values into the existing model. In this manner, the modified personalized model represents the actual geometry as accurately as possible and can directly be employed in a biomechanical analysis.

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