

BIOMECHANICAL RESPONSE OF ENTIRE LUMBAR SPINE TO LARGE COMPRESSION –A FINITE ELEMENT MODEL STUDY

Tim Brown¹, Raghu N. Natarajan² and Gunnar B.J. Andersson²

¹Bioengineering Department, University of Illinois at Chicago, Chicago, IL, USA

²Department of Orthopedic Surgery, Rush University Medical Center, Chicago, IL, USA

E-mail: Raghu_Natarajan@Rush.edu

Web: www.ortho.rush.edu/CADlab/

INTRODUCTION

During normal daily activities and in the workplace, the lumbar spine is exposed to very large and complex loading conditions. The mechanisms by which the lumbar spine supports standing postures with and without external loads are complex and not well understood. In vivo studies give insight into the loading conditions prevalent during normal and intense activities, but they are still limited in scope and detail in describing the total biomechanical response to the postural loading the lumbar spine is subject to. A compressive “follower” load (1200 N) has been successfully applied in-vitro (1) to the whole lumbar spine to mimic the mechanical behavior of the musculature. Finite element models have tried to mimic the mechanics of the musculature by using optimal stabilizing moments at each motion segment level, pelvic rotation, or a variation of the follower load technique (2). These studies provide few details of the biomechanical behavior of each segment under the large compressive load. The current study with the help of a validated 3-D, non-linear, finite element model created from CT images will address this issue. The “follower” load technique was used to apply large, axial compressive loading of 2000 N to the model and ensured that the compressive load vector was perpendicular to the midplane of each intervertebral disc, mimicking the mechanical behavior of the musculature and minimizing motion artifacts that are inherent when applying a large, axial compressive load.

The goal of this study was to investigate the complete biomechanical response of the intervertebral discs and the facet joints to large compressive loads. The findings of this study will help better understand the effect of large compressive loading of the lumbar spine and its potential consequences in terms of location of lumbar disc component failure.

METHODS

The finite element representation of L1-S1 included six vertebrae with posterior elements, five discs, 6 ligaments per level and pairs of facet joints at each level. The cortical bone, cancellous bone, posterior elements, endplates, facet cartilage, annulus and nucleus were modeled as 8-node, three-dimensional, isoparametric elements. The left and right superior and inferior articulating surfaces of the facet cartilage were modeled by 4-node, quadrilateral, moving frictionless contact surfaces. The annular fibers of the intervertebral discs were assembled in a criss-cross fashion at an angle of approximately 30°. The ligaments and annular fibers were modeled as 2-node, non-linear truss elements with cross-sectional area and reacted to axial tension only. Excellent agreement was found between the finite element validation results and the in vitro study (3) at all motion segment levels for all loading modes. “Follower” rods and guides through which the vertebra move were then developed bilaterally that followed the lordotic curve of the lumbar spine in the sagittal plane such

that when the compressive load was applied, its vector was perpendicular to the mid-plane of each disc.

RESULTS AND DISCUSSION

Successful application of the “follower” load should result in a minimization of the segmental rotations at each level. In the frontal and transverse planes, the current finite element model with the “follower” rod and guide system produced rotations at each level that were less than one degree for the compressive load of 2000 N.

The force-disc compression response was nonlinear at all levels. The model predicted a total axial compression of 10.6 mm, with 2.0 mm at L1-L2, 2.6 mm at L2-L3 mm, 3.0 mm at L3-L4, 2.7 mm at L4-L5, and 3.1 mm at L5-S1. Berkson et al. (4) measured the compression in single motion segments from L1-L2 to L5-S1 in vitro and reported an average value of 0.51 mm of disc compression for a 400 N axial compressive load. The finite element model values at 400 N of axial compression was in agreement with these values.

The results from the finite element study suggest that failure would occur in the endplates at all levels. Maximum von Mises stress varied from 8 MPa to 13 MPa in the endplates. The location of the failure was on the periphery of the endplate at the trabecular interface at each level.

The response of the annular fibers to applied load exhibited nonlinear behavior at all levels. The outer and middle layers at all levels had an average maximum von Mises stress below 5 MPa. For the inner layer, all levels were at or above 10 MPa with L1-L2 having the highest value of 28 MPa. Overall, the current finite element model showed that the annular fiber failure occurs near the inner surface of the annulus, which compares well with the published results.

The highest value of annular matrix von Mises stress of 10 MPa occurred at L1-L2 and the lowest value of 6 MPa occurred at L4-L5. The values of the maximum average von Mises stress occurred in the posterior quadrant at L1-L2 and at the inner posterior quadrant at L2-L3 to L5-S1. The maximum average von Mises stress in the nucleus ranged from 5.5 MPa at L1-L2 to 8.0 MPa at L5-S1.

At all of the segment levels, facet forces exhibited non-linear behavior with load. The right lateral facets showed the highest contact forces at the L1-L2 to L3-L4 levels and the left lateral facets showed the highest contact forces at the L4-L5 to L5-S1 levels. The maximum contact force generated from the 2000 N compressive load was at L4-L5 (613 N) and the smallest was at L5-S1 (184 N).

SUMMARY

A 3-D finite element model of the entire lumbar spine was developed and using the “follower” load concept was able to apply large compressive loads that are seen in vivo and reported in the literature. Detailed biomechanical behavior of the whole lumbar spine under large compressive load is presented here. Current model predictions of disc compression values, locations of both endplate failure and annular fiber failure and the load supported by facet joints all agree with those reported in literature.

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