Introduction: Surgical treatments for adolescent spine deformity are successful but invasive. Potential new treatments are based on altering growth by mechanically redistributing stresses across the growth plates. Preclinical studies have shown that some of these methods cause curvatures in normal spines. Changes in the structure of the growth plate indicate that a staple-like implant created a compression gradient in disc and growth plates. Preliminary studies have reported biomechanical changes due to insertion of this implant in vivo and in vitro.

Finite element (FE) models have long been used to understand the biomechanical behavior of the normal and pathological spine, including in design of spinal implants. These models generally do not consider the range of motion (ROM), where the stiffness matrix approaches zero. Preliminary experimental studies have indicated that the major effect of the staple-like implant on axial compression is to decrease the range of motion and increase the linearity of the load-displacement curve, rather than increasing the tangent stiffness. The implant was also shown to decrease peak compressive stresses in the annulus. The purpose of this study was to determine the ability of a FE model to predict load-displacement curves in compression and compressive stresses bilaterally in the disc annulus before and after insertion of a staple-like implant.

Methods: A three-dimensional FE model was developed from a CT scan of a porcine T7-T8 motion segment and imported to Abaqus (v6.9, Dassault Systèmes, Providence, RI). The STL file obtained from the CT scan (3D Slicer, BWH, Boston, MA) was processed (Hypermesh v10.0, Altair HyperWorks) to obtain the discretized model (Fig. 1) which included cortical, cancellous, and end plates of the vertebral body. The disc was separately modeled using hexagonal elements using a continuum model of the annulus fibrosus. To add the implant, a CAD model was constructed. Contacts were defined between endplates and disc and between implant and bone using rigid body elements. Geometric validation was performed by comparing the model dimensions to experimentally measured anthropometric measures.

Material properties for the model were adopted from Eberlein. Cortical and cancellous bone were considered to be orthotropic, and the endplates were isotropic. The annulus fibrosus (AF) was modeled as an incompressible anisotropic hyperelastic constitutive material with decomposition of the AF into ground substance and fibers with corresponding neo-Hookean material and exponential strain energy function. The nucleus was modeled as an incompressible fluid inside a cavity. The bottom nodes of the T8 endplates were constrained, while displacements were applied to the top nodes of the superior vertebra.

The analysis was performed with and without the implant, which was modeled as a unilateral constraint on intervertebral displacements under the assumption that the implant insertion process itself did not induce disc stress or displacement. Load-displacement curves in axial compression were determined from the nonlinear analysis performed with and without the unilateral constraint. They were compared with previously reported load-displacement behavior by adding the measured ROM into the region of maximum compressive mechanical behavior. For the implant insertion did not cause a disc displacement gradient.

Discussion: Finite element analysis of a porcine motion segment before and after insertion of a unilateral constraint predicted some aspects of compressive mechanical behavior well, particularly the nonlinear stiffness of the normal motion segment. Limitations include the general inability of FEA to model the ROM, and the specific assumption that implant insertion did not cause a disc displacement gradient.

Results: For the intact segment, the model and experiments agreed well in the tangent stiffness region of the L-D curve (Fig. 2). The addition of the implant in this model overestimated the stiffness increase compared to experiments. Predicted disc stresses were within measurement error (Fig. 3). The model showed stress-shielding of the disc, as measured, and a side-to-side peak stress difference of 0.3 MPa that has not yet been experimentally verified.

Figure 1: FE model of porcine T7-T8 motion segment. (a) Normal intact motion segment, coronal view. (b) Motion segment with implant modeled as unilateral constraint, oblique view.

Figure 2: Compressive load-displacement curves with and without implant, comparing FEM and previous experiment. Red brackets indicate experimentally determined decreased ROM after stapling.

Figure 3: Longitudinal stresses in AF during compression (a) Comparison of bilateral longitudinal stresses in the mid-annulus region during compression of 0.56 mm of applied displacements (b) Stress plot showing axial compressive stresses without implant; (c) with implant.