Finite Element Analysis of Compressive Properties and Disc Stresses Before and After Spinal Hemiepiphysiodesis

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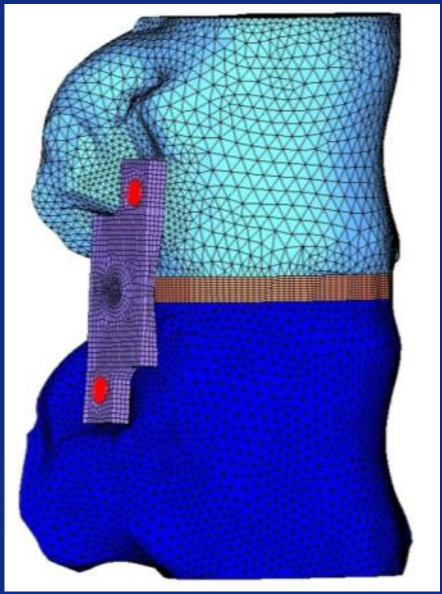

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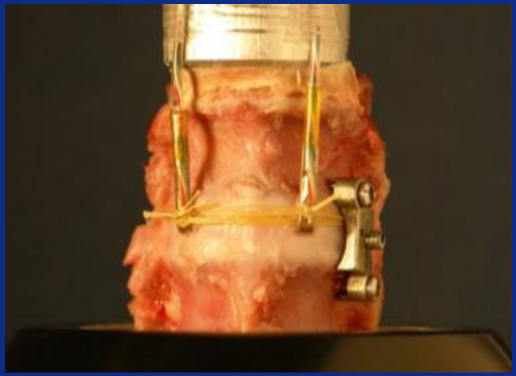
Background and Significance

- Growth modification methods redistribute intervertebral forces. *In vivo* studies have shown that some methods cause curvatures in normal spines [1]
- Change in the growth is presumed to be due to a compression gradient on disc and growth plates [2]
- Initial biomechanical changes due to staple implantation have been reported [3]
- Various computational models including finite element (FE) analyses have been developed to investigate effects of implants [4]. Some models have incorporated simulated growth [6,7,8,9]
- A nonlinear anisotropic continuum model of the annulus [5] has been reported to predict anisotropic stress response

Spine staples (stainless steel, and later, titanium) induced curvatures [1]



In vitro, biomechanical properties changes after SS staple insertion [2]

Purpose

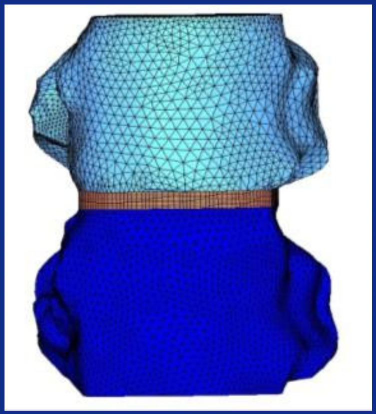
Determine whether a continuum finite element model of a single motion segment predicts

- **Compressive structural properties**
- **Disc stresses**
  - **Before and after staple implantation**

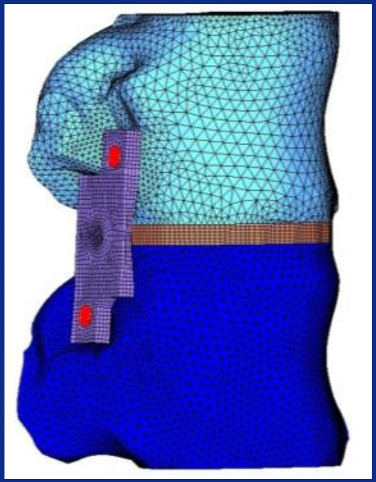
as compared to experimentally measured values

Methods – FE Model Construction

- **3D FE model developed from CT scan of porcine spine**
  - **Stereolithography (STL) file obtained from processing of CT scan in 3D Slicer**
  - **STL file processed using Matlab code and Hypermesh v10 to segregate a single motion segment and remove noise and irregularities**
  - **Smooth surface was created on top and bottom of bone segment for uniform distribution of force during analysis**
  - **Different regions of bone created: cortical, cancellous, endplates**
  - **Annulus fibrosus modeled separately**
  - **Geometric data verified with available experimental values**
  - **Simple implant [3] CAD model was created in Solid Works 2009, meshed using Hypermesh, and placed in spinal segment model**
  - **Screws were modeled as equivalent beam elements**
  - **Contacts defined between disc and endplates, implant and bone: Implant assumed in perfect contact with bone**



Coronal view of FE model of normal spinal segment



Oblique view of FE model of motion segment with implant

Methods – Material Properties

- Material properties were adapted from Eberlein et al [5]

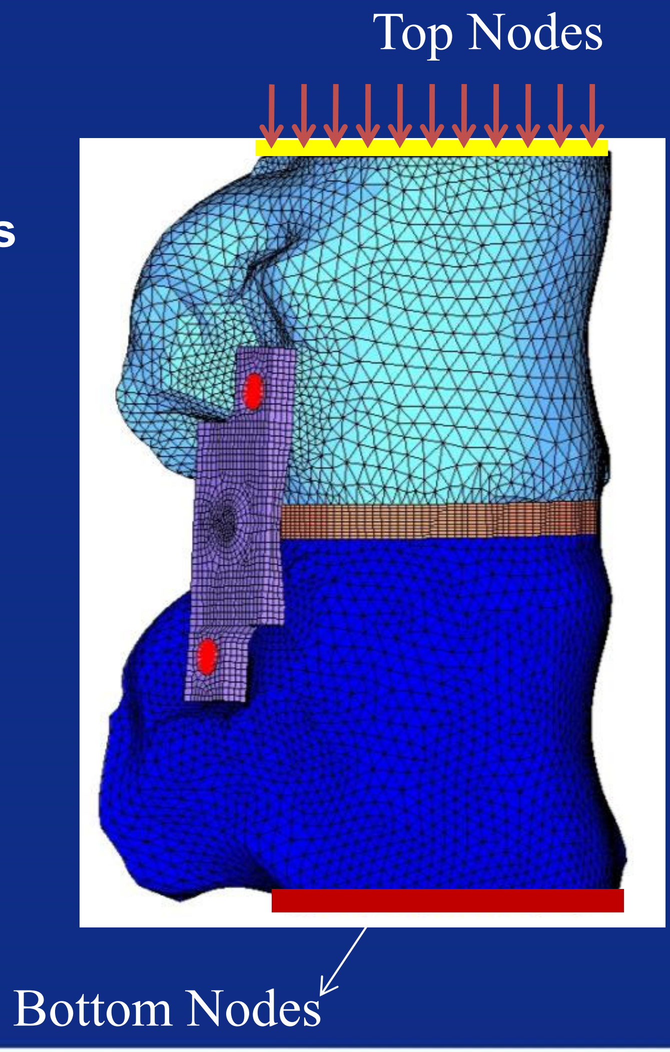
S NO	Description	Property	Values
1.	Cortical bone		E_{11} = 11300 MPa, E_{22}=22000 Mpa, E_{33} = 11300 MPa; G_{13}=3800 MPa; G_{12}=5400 MPa; G_{32}=5400 MPa; ν_{13}=0.484; ν_{12}=0.203; ν_{32}=0.203;
2.	Cancellous bone	Orthotropic	E_{11} = 140 MPa, E_{22}=200 Mpa, E_{33} = 140 MPa; G_{13}=48.3 MPa; G_{12}=48.3 MPa; G_{32}=48.3 MPa; ν_{13}=0.45; ν_{12}=0.315; ν_{32}=0.315;
3.	Endplates	Isotropic	E=23.8 MPa; ν=0.4
4.	Nucleus	Incompressible Fluid	
5.	Annulus fibrosus	Anisotropic Hyperelastic	K_1=2 MPa ; K_2=190; μ=0.5(outer) K_1=5 MPa ; K_2=10; μ=0.5(inner)
6.	Implant	Isotropic	E=210 GPa ; ν=0.3

Methods – Boundary Conditions

- All bottom nodes constrained in longitudinal direction
- A few nodes constrained in other directions to remove rigid body motion
- Displacements applied in longitudinal direction to simulate experimental boundary conditions

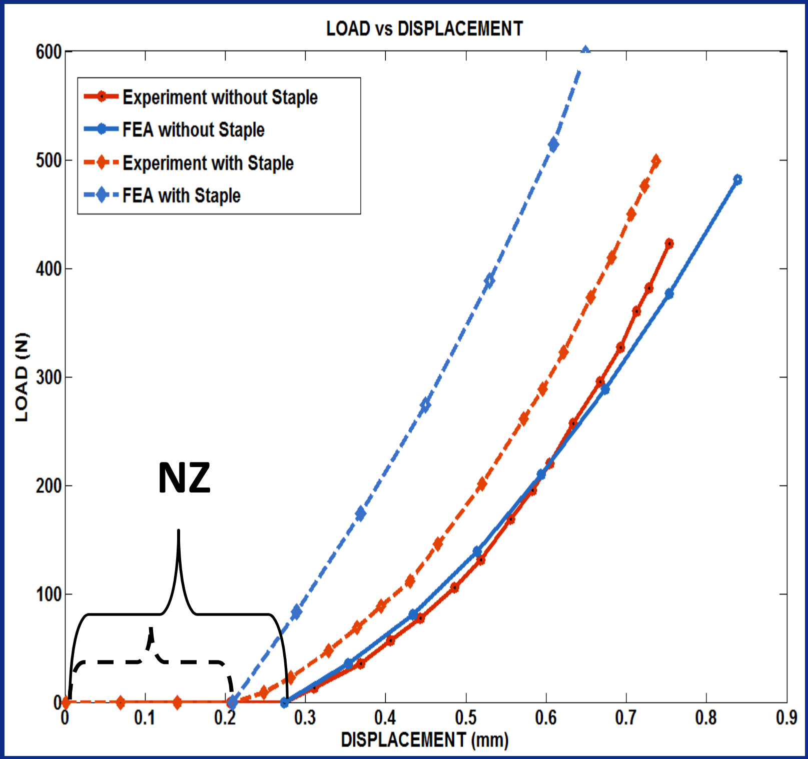
Solution Method

- FE model created in Hypermesh was imported to input file format Abaqus and solved using Abaqus v6.8-2
- Nonlinear large deformation static analysis performed



Results – Load vs Displacement Curves

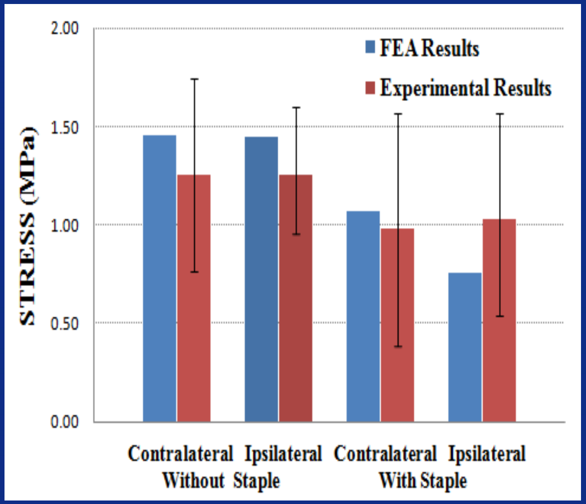
- Load vs displacement plotted by
  - Sum of reaction forces at constrained nodes
  - Adding measured neutral zone (NZ) displacement
- FEA results of normal spine segment (no staple) agreed well with experimental results
- FEA results of spinal segment with implant overestimated the stiffness when compared with experimental results



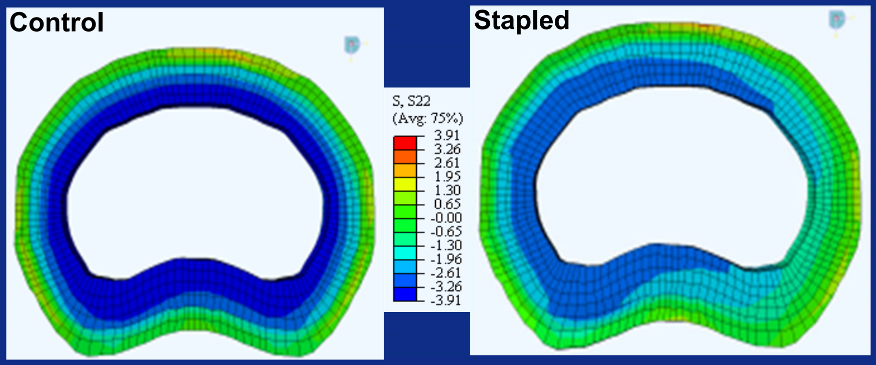
With Staple
Without Staple

Results – Longitudinal Stress Distribution

- Longitudinal peak stress at mid-annulus obtained by averaging stress in elements in that region
- Longitudinal stress corresponding to measured peak load of ~400 N compared with experimental results



Comparison between FEA and experiments: Stapled model showed lower peak annular stresses and a side-to-side peak stress difference



Longitudinal stress (MPa) distribution in mid-annulus
Negative indicates compressive

- Peak stresses
  - Control values
    - Symmetric
  - Stapled
    - Stress-shielded
    - Coronal plane gradient

Conclusions

- Computational (FE) model of spinal motion segment with and without unilateral implant
  - Control: Normal motion segment structural behavior was <u>well correlated</u> with experimental results
  - With staple: FEA <u>over-estimated</u> stiffness compared to measured values
  - FE longitudinal peak stresses at mid-annulus were within experimental error of measured values from spine segments both with and without staple
    - FE model predicted bilateral difference in stress-shielding of 0.3 MPa which, though hypothesized, has not yet been verified by experimental results
- FE models, if and only if carefully and critically developed with experiment for validation, may augment and extend experimental results and help guide implant design changes with limits

Limitations

- **Material properties**
  - **No viscoelastic or growth effects**
- **Initial conditions**
  - **Stresses / strains induced by staple implantation itself were not considered in current model**
  - **Simulation of immediate post-op condition only**
- **Neutral zone**
  - **FEA cannot model the NZ, an important component of biomechanical structural behavior**
    - **NZ indicates rigid body motion and/or mass transfer**
    - **In *in vitro* studies, compressive loads decreased neutral zone and tangent stiffness under loads from slight tension to 400 N compression**

Discussion

- A finite element model predicted well the nonlinear stiffness region of biomechanical structural properties of the normal porcine thoracic spinal motion segment, and overestimated the stiffness of the stapled motion segment
- Limitations of FE include
  - General inability of the method to model the neutral zone
  - Particular assumptions regarding, for example,
    - Initial conditions imposed on motion segment by implant insertion itself
    - Contact conditions between bone and other construct components
- FE can be a useful adjunct to experiment when carefully applied and interpreted, with an understanding of both the basic limitations of the method in biomechanical modeling, and the specific limitations of the particular model

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