Constitutive Modeling of Cortical and Trabecular Bone Applied to Compression Loading and Failure of a Lower Cervical Spine Segment Model

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Introduction

- Automotive collisions are the most common etiology for cervical spine injuries, with approximately 44% being traumatic injuries (AIS 3+) [Myers,1995; Carter,2002].
- The lower cervical spine, particularly at the C5-C6 level, was the most commonly involved region [Yoganandan,1989].
- At the lower cervical spine, the most common mechanism of injury was presumed to be flexion-compression, resulting in wedge fractures and burst fractures [Argenson,1997].

Motivation of Study

- Human body models currently utilize isotropic symmetric elastic-plastic material models to predict hard tissue response and failure.
- Cortical and trabecular bone materials exhibit asymmetric, anisotropic and rate dependent mechanical properties. Trabecular bone is often characterize as a foam material exhibiting progressive crushing leading to consolidation under compression loading.

Objective

- To investigate constitutive models to predict hard tissue response and failure in human body models (HBM) and simulate compression loading of a lower cervical spine functional spinal unit,C5-C6-C7.

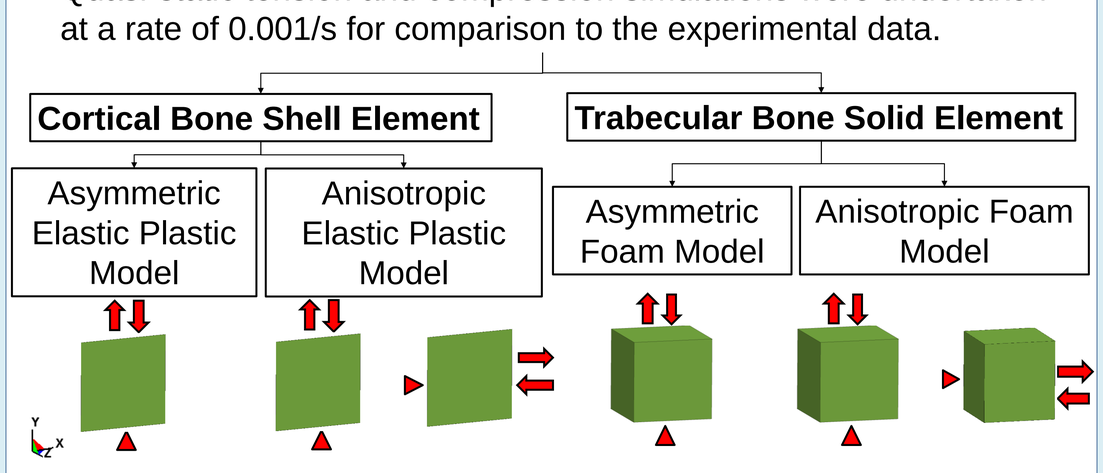
Methods

1) Experimental Data

- Quasi-static stress-strain curves for cortical and trabecular bones were digitized from experimental studies [Hansen, 2008; Liu,2013].
- The material properties were from relatively young individuals. Cortical bone: diaphysis of femur, 51 year old male [Hansen,2008]; Trabecular bone: Cervical spine with high apparent bone density of 0.9247g/cc) [Liu,2013].
- Axial compression experimental failure values and displacements of the cervical spine segments were used to assess the model response [Carter,2002].

2) Single Element Simulation

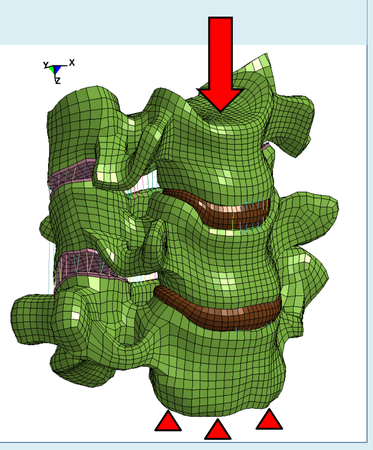
- A 1mm^2 area shell element and a 1mm^3 solid element were created to verify the cortical and trabecular bone models, respectively.
- Quasi-static tension and compression simulations were undertaken at a rate of 0.001/s for comparison to the experimental data.



3) Axial Compression Simulation

Boundary Conditions

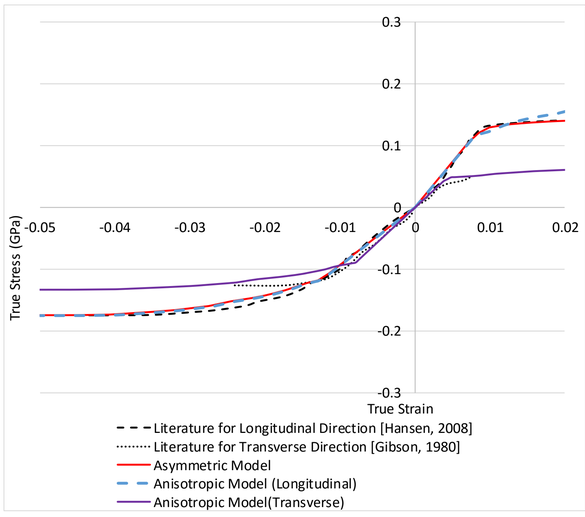
- The C6 inferior endplate was fixed as in the experiment.
- A 40N axial preload was applied as reported in the experimental tests.
- The C4 superior endplate was assigned an axial displacement with a Haversine velocity profile (peak velocity of 1.493mm/ms and a pulse width of 18ms).



Results and Discussion

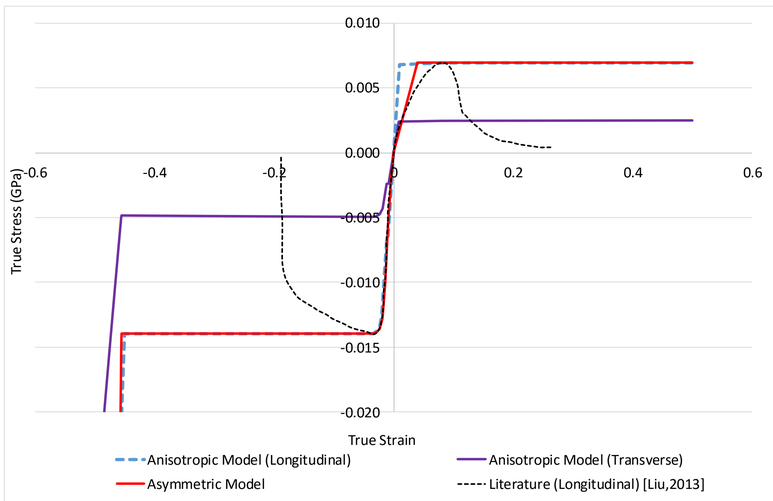
Single Element Simulation

Cortical Bone Shell Element



- The asymmetric model (red curve) provided tension and compression responses that were in agreement with the longitudinal direction (osteon orientation) data [Hansen, 2008].
- The anisotropic model (dotted blue: longitudinal direction; purple: transverse direction) predicted the anisotropic response but did not incorporate asymmetry in tension and compression.

Trabecular Bone Solid Element



- Compression responses [Liu,2013] were extended to include the crush plateau and densification region.
- Anisotropic model in transverse direction was based on anisotropic ratios from the literature [Augat, 1998; Sanyal,2012; Mosekilde,1985].
- Asymmetric and anisotropic models predicted longitudinal moduli and ultimate stresses well in both tension and compression. The anisotropic model under-predicted the ultimate strain in tension.

Lower Cervical Spine Segment C5-C6-C7 Compression Simulation

Fracture Patterns

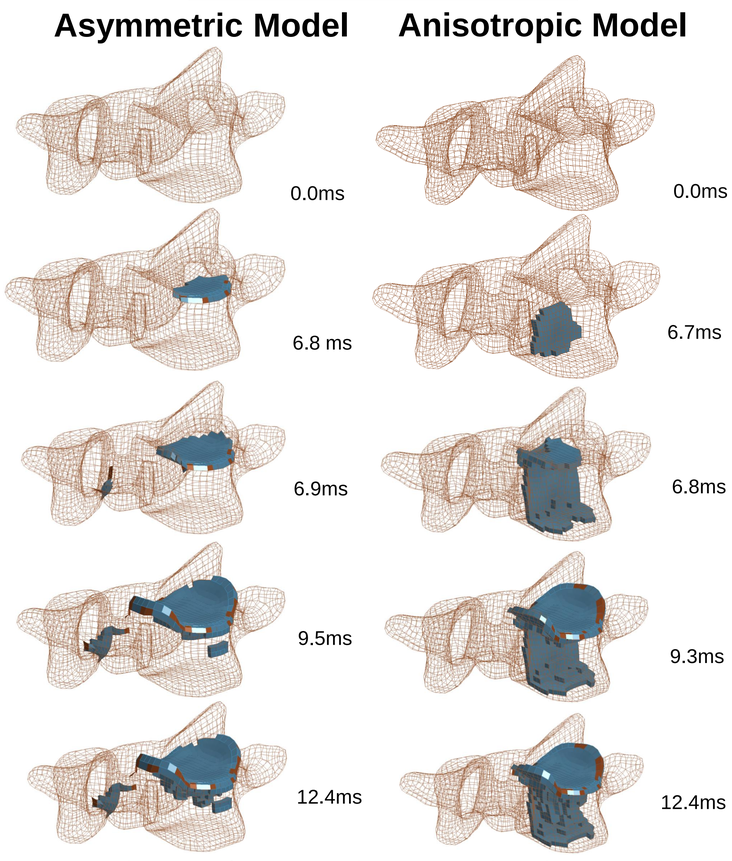


Figure 1: Element Erosion Progression of C5 Segment(Brown: Eroded Cortical; Blue: Eroded Trabecular)

Kinematic Response

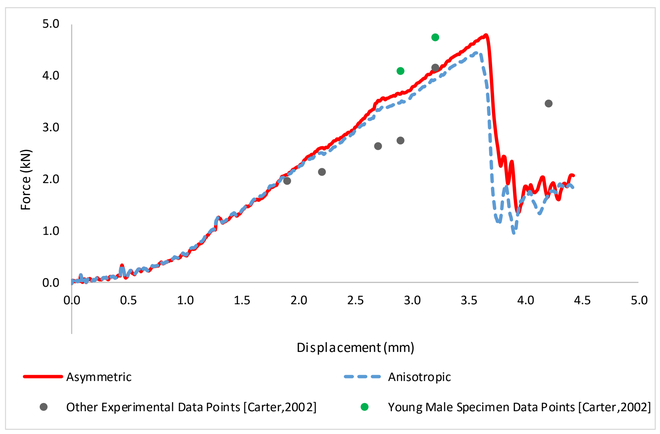


Figure 2: Kinematic Responses (Asymmetric: Max Force =4.78kN, Max Displacement= 3.66mm; Anisotropic: Max Force= 4.47kN, Max Displacement= 3.59mm)

- Asymmetric model (solid red curve) and anisotropic model (dotted blue curve) are in reasonably good agreement with failure forces of young specimens (green circles) but with higher failure displacements (~0.5mm).
- Both models fall within the range of failure displacements for all test samples (grey circles).

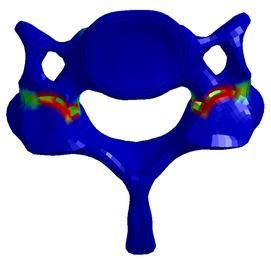


Figure 3: 1st principal strain plot showing fracture at base of pedicles in asymmetric model

- The asymmetric model fracture was predicted to initiate at the superior region of the C5 vertebral body and progressed towards C6. The anisotropic model initiated failure within the vertebral body.
- Studies have shown that damage is dominated by trabecular bone and the tissues that have a higher risk of failing are located near the endplates as opposed to the mid transverse region [Eswaran, 2007].
- Fracture at the base of the pedicles (predicted by the asymmetric model) (Figure 3) has been reported [Hongo,1999; Wilcox 2004] attributed to high tensile stresses during compression loading.

Conclusions

- Both asymmetric and anisotropic material properties in the segment model demonstrated good comparison to the kinematic response from the experimental test specimens. Both models predicted failure forces in agreement with younger specimen values, but over-predicted failure displacements by approximately 0.5mm.
- The fracture in the anisotropic model was predicted to initiate within the vertebral body. The asymmetric model fracture initiated at the superior region of the vertebral body and was comparable to fractures observed in experiments.

Acknowledgements

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