Hard Tissue Failure of an Aged Lower Cervical Spine Segment Model in Compression Loading with Anterior-Posterior Eccentricity

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Introduction

- There is a high possibility of the cervical spine being subjected to axial compression loading in rollover accidents [Raddin et al., 2009; Foster, 2016]. A large portion (86%) [Wigglesworth, 1991] of vehicle-related spinal cord injuries are associated with rollovers [O'Connor, 2002].
- Detailed finite element human body models (HBM) can help us understand response to impact and the potential for injury.
- Material properties and failure criteria are critical for HBM to predict hard tissue response and failure.

Motivation of Study

- Linear isotropic and symmetric material models are frequently utilized in the trabecular and cortical bones in HBMs [Erbulut et al., 2010; Hong-Wan et al., 2006].
- Trabecular and cortical bones demonstrate orthotropic properties that vary with age which are needed to assess hard tissue fracture.

Objective

- To identify a set of orthotropic material properties for cortical and trabecular bone and assess them in a C57 segment model (GHBMC M50) under dynamic compression loading.

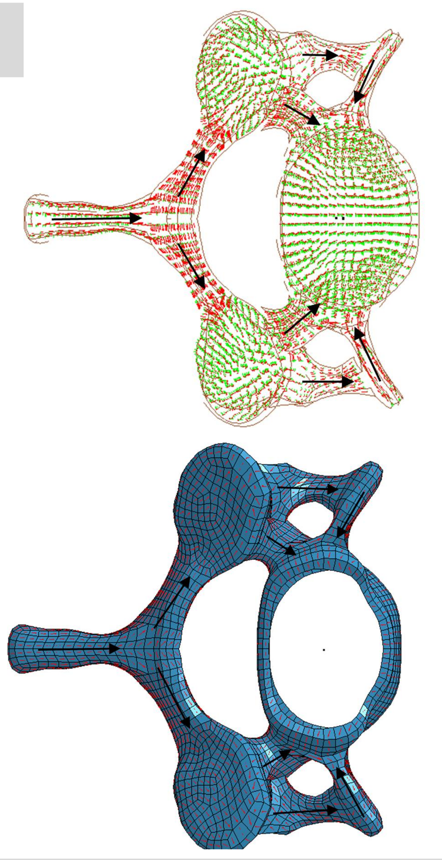
Methods

1) Experimental Data

- Mechanical properties of cortical and trabecular bones were retrieved from experimental studies [Reilly and Burstein, 1975; Tang et al., 2015; Liu, 2013; Yang, 1999]. Age effects were included for the "young" (<50 years old) and "aged' (>50 years old) [Reilly and Burstein, 1975; Mosekilde et al., 1987; Hayes and Carter, 1976].
- Centric compression, anterior eccentricity and posterior eccentric load cases were used for model assessment [Carter, 2002].
- Model results were assessed based on kinetics, kinematics, and hard tissue fracture pattern.

2) Constitutive Model Implementation

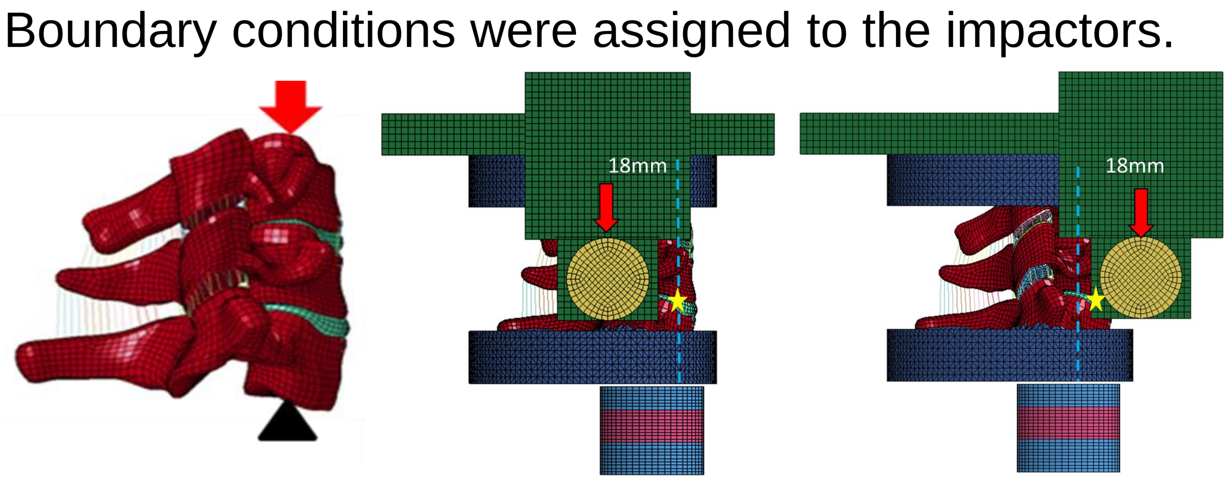
- Orthotropic models for cortical (MAT108: MAT_ORTHO_ELASTIC_PLASTIC) and trabecular (MAT142:MAT_TRANSVERSELY_ISOTROPIC_CRUSHABLE_FOAM) bone were implemented with mechanical properties from a literature review.
- Single element simulations were performed for constitutive model verification.
- Material directions were defined in both cortical bone shell elements and trabecular bone solid elements in the C6 vertebra to ensure they were oriented with the direction of the trabeculae or osteons [Smit et al., 1977].



3) Axial Compression Simulation

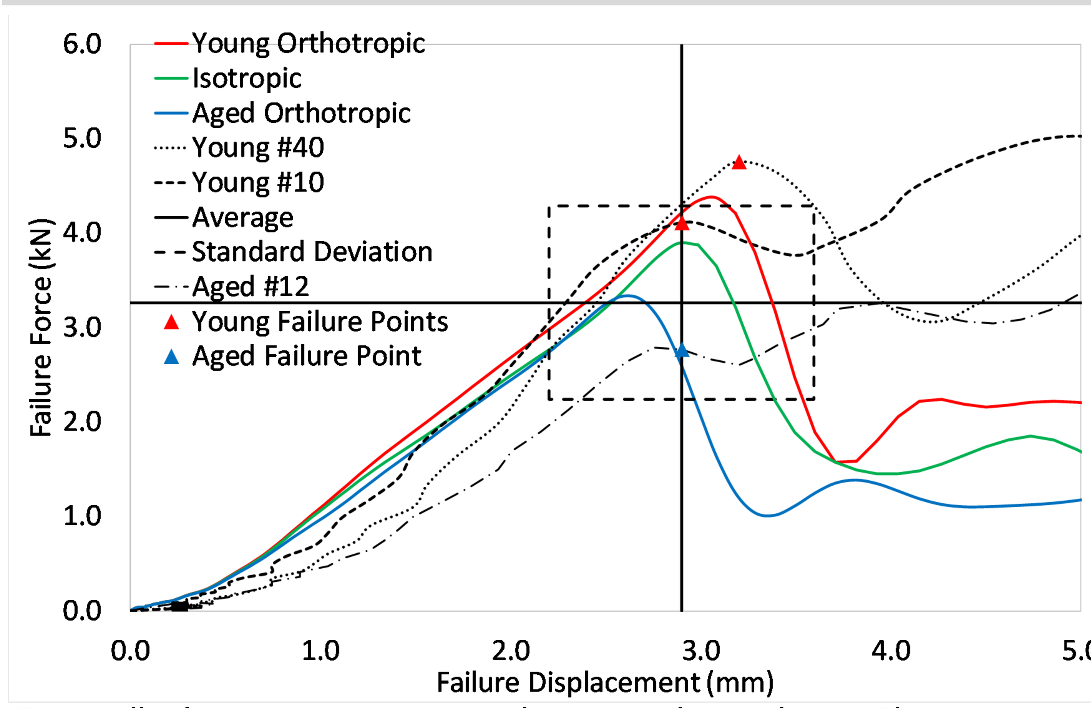
Boundary Conditions

- Centric compression: The superior C5 endplate was assigned an axial displacement using an experimental velocity profile.
- Anterior-posterior eccentricity: The complete test fixture was modeled with 18mm anterior-posterior eccentricity from the CG of the C67 IVD. Boundary conditions were assigned to the impactors.



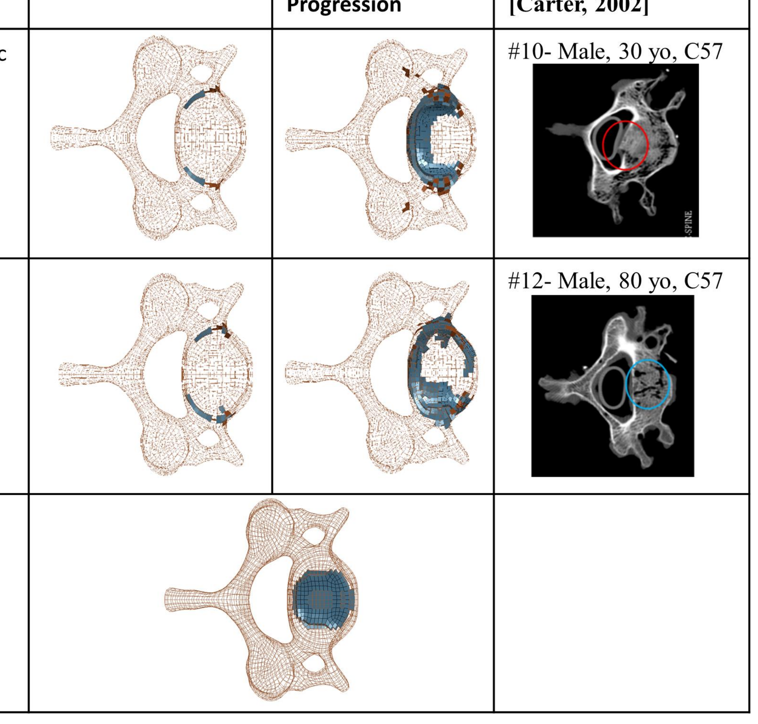
Results and Discussion

Centric Compression Simulation



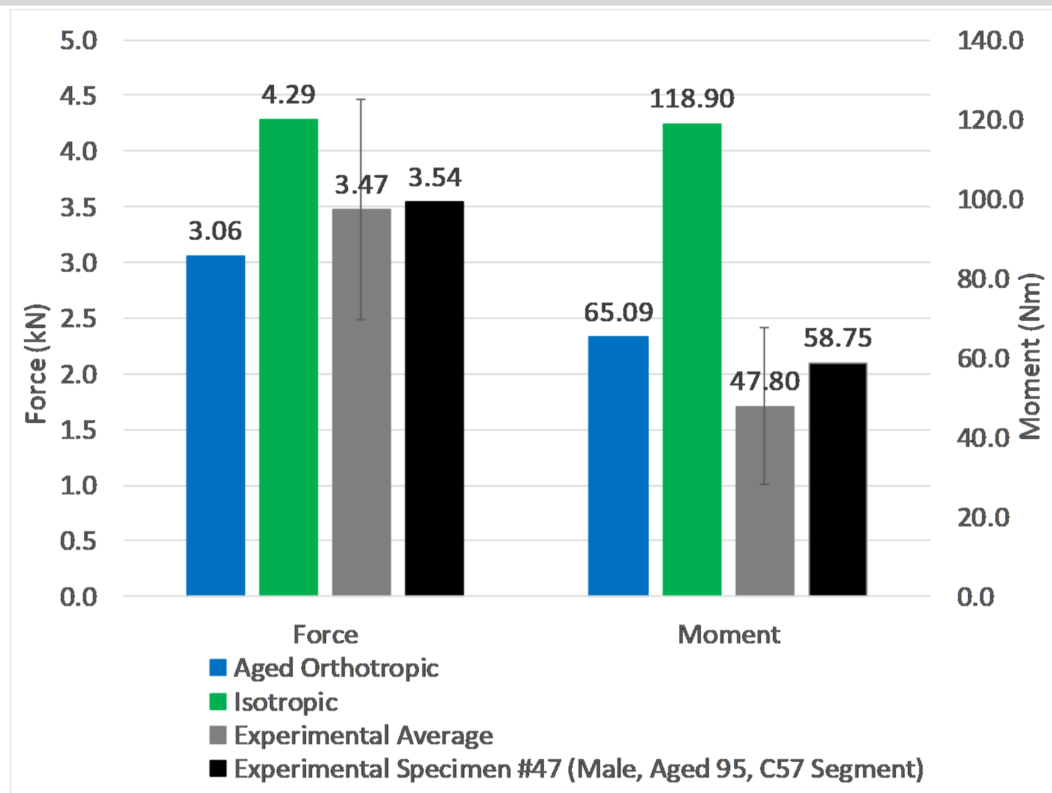
Force-displacement responses (young orthotropic: 4.37kN, 3.08mm; aged orthotropic:3.33kN,2.59mm; isotropic: 3.89kN,2.88mm)

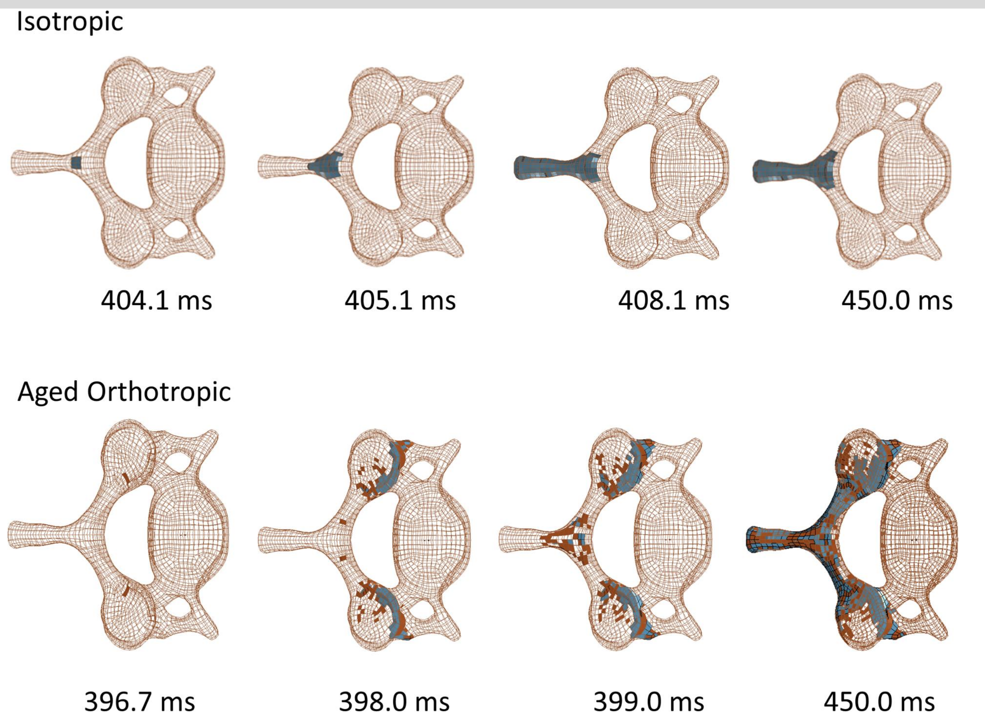
Loading Method	Fracture Initiation	Fracture Progression	Experimental X-ray [Carter, 2002]
Young Orthotropic			#10- Male, 30 yo, C57
Aged Orthotropic			#12- Male, 80 yo, C57
Isotropic			



- Isotropic model under-predicted young experimental failure force (12.2%) and displacement (34.9%) and over-predicted aged experimental failure force (40.6%).
- Young orthotropic model accurately predicted young experimental data.
- Aged orthotropic model over-predicted aged failure force by ~20% and under-predicted failure displacement by ~ 10%.
- Fractures predicted in the vertebral body were in agreement with the experimental data.

Posterior Eccentricity Compression Simulation



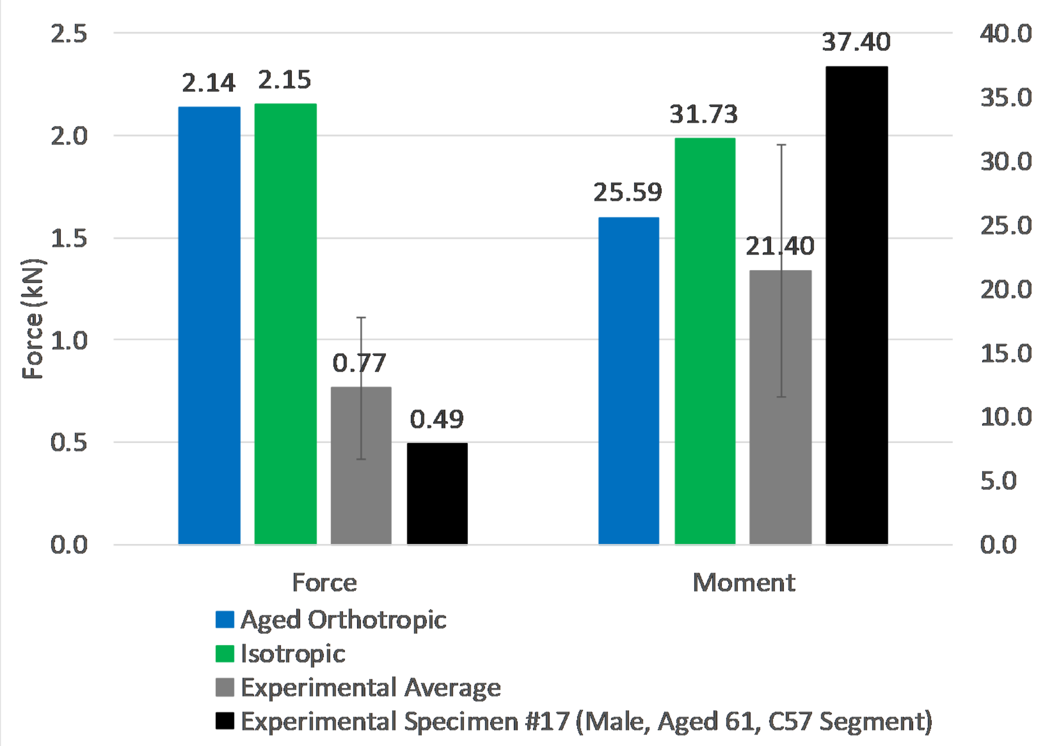


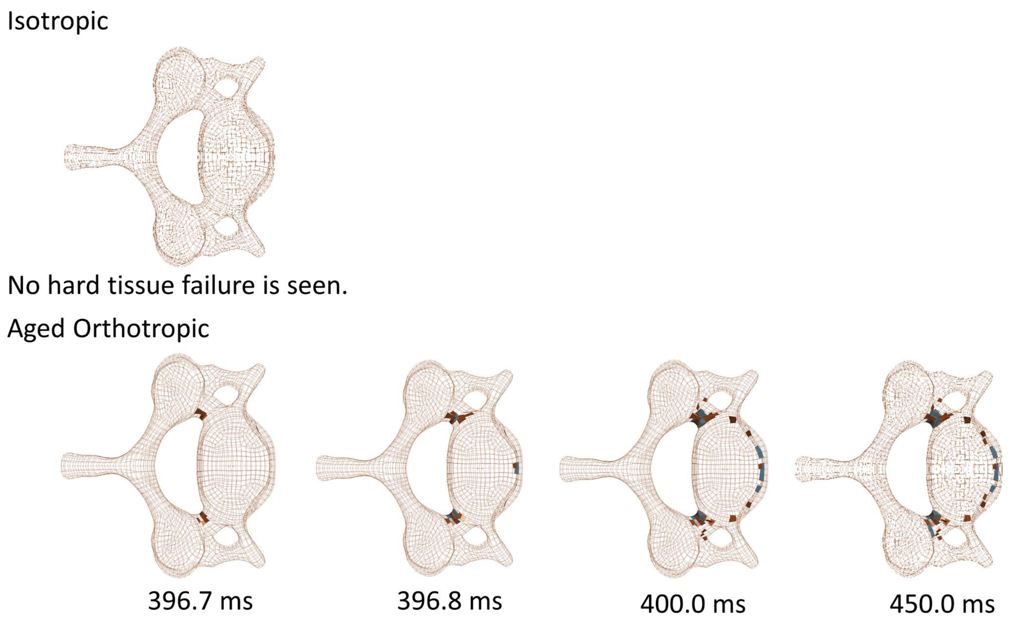
Posterior Eccentricity	Hard Tissue					
Spec # (Gender, Age, Segment level)	AVB	PVB	PED	AP	LAM	SP
14 (F,55,C6-T1)						
29 (M,88,C2-4)						
39 (F,76,C6-T1)						
41 (M,91,C3-5)						
43 (F,87,C5-7)						
45 (F,88,C5-7)						
47 (M,94,C5-7)						
49 (F,86,C4-6)						
Isotropic						
Aged Orthotropic						

Anterior Vertebral Body (AVB), Posterior Vertebral Body (PVB), Pedicles (PED), Articular Process (AP), Lamina (LAM), Spinous Process (SP).

- Aged orthotropic model agreed well with aged experimental data.
- Isotropic model over-predicted the average moment by 149%.
- Fracture predominantly occurred in spinous process, as seen in the experimental data.

Anterior Eccentricity Compression Simulation





Anterior Eccentricity	Hard Tissue					
Spec # (Gender, Age, Segment level)	AVB	PVB	PED	AP	LAM	SP
3 (F,70,C5-7)						
5 (F,90,C5-7)						
7 (F,53,C5-7)						
8 (F,34,C5-7)						
15 (M,50,C5-7)						
17 (M,61,C5-7)						
27 (F,77,C5-7)						
48 (F,72,C5-7)						
Isotropic						
Aged Orthotropic						

- Failure forces by both models were over-predicted (more than +1SD).
- Failure moment were within 1SD of average data.
- Fracture patterns for both models agreed with experimental data (no hard tissue failure or failure in the vertebral body).
- Higher number of female specimens in experimental data could cause lower failure forces due to geometrical and mechanical property differences.

Conclusions

- Both isotropic and orthotropic models predicted fracture patterns in good agreement with experimental data.
- Orthotropic model with age effect better predicted the centric and posterior eccentricity cases by 32%.
- It is important to include the effect of age on material properties. Limitations of this study were the small number of experimental test samples (C57) and the models did not include gender and rate effects.
- This study highlights the importance of simulation studies in providing additional insight on fracture initiation and progression that may be challenging to measure in dynamic experiments.

Acknowledgements

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