Unique Anthropometric and Biomechanical Properties of the Pediatric Cervical Spine

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INTRODUCTION: Cervical Spine Trauma & Spinal Cord Injury (SCI)

Pediatric spinal trauma & SCI are prominent societal issues

- *28% pediatric mortality rate; 2.5 to 1 ratio compared to adult population*
- *Cost $7 billion annually (SCI)*
- *Motor vehicle accidents (MVA) = most common cause for SCI in pediatric population*
- *Approximately 60-80% of all vertebral injuries in the pediatric population are associated with the cervical spine*
- *Children under the age of 8 years typically exhibit upper cervical spine injuries*

NSCISC, 2005; Roche et al., 2001; Eleraky et al., 2000; Brown et al., 2001; Kokoska et al., 2001 Babcock, 1975; Bonadio, 1993; Heilman et al., 2001; Sun et al., 2000; Lo et al., 2002; Orenstein et al., 1994 Patrick et al., 2000; Nitecki et al., 1994; Hamilton et al., 1992; DeVivo, 1997

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INTRODUCTION: Pediatric Cervical Spine Trauma

Vertebral synchondroses (cartilaginous growth regions) are the site of typical injuries in the pediatric population *(Adams, 1992; Clasper et al., 1995; Keller et al., 1990; Seimon et al., 1977; Bhattacharyya et al., 1974; Ewald et al., 1971; Schatzker et al., 1971; Smith et al., 1993)*

Upper cervical spine injuries to synchondroses include fractures or displacements

- *Atlas (C1) vertebra* *(Thakar et al., 2005; Mikawa et al., 1987)*
- *Axis vertebra (C2)* *(Schippers et al., 1996; Shaw et al., 1999; Sanderson et al., 2002; Blauth et al., 1996; Odent et al., 1999; Lui et al., 1996; Heilman et al., 2001)*

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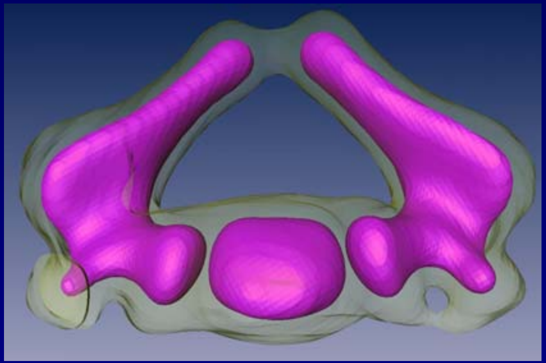
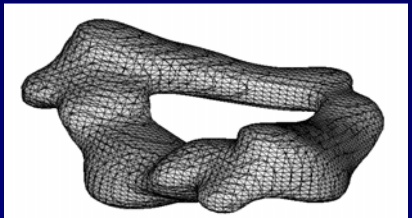
INTRODUCTION: Pediatric Cartilaginous Failures Observed in PMHS Testing Environment

LCS Injuries (C45 & C67)

- *End-plate failures*
  - *Both inferior or superior*





1 Day – C4
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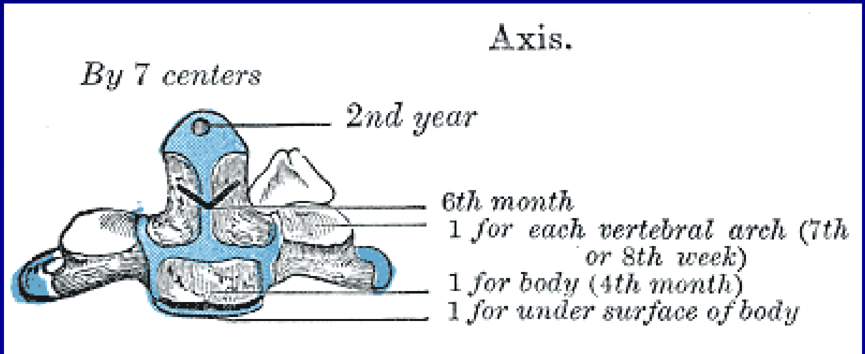
UCS Injuries (OC2)

- *Associated with C2*
  - *Synchodrosis fractures*
  - *C2 centrum fractures*



Gray's Anatomy

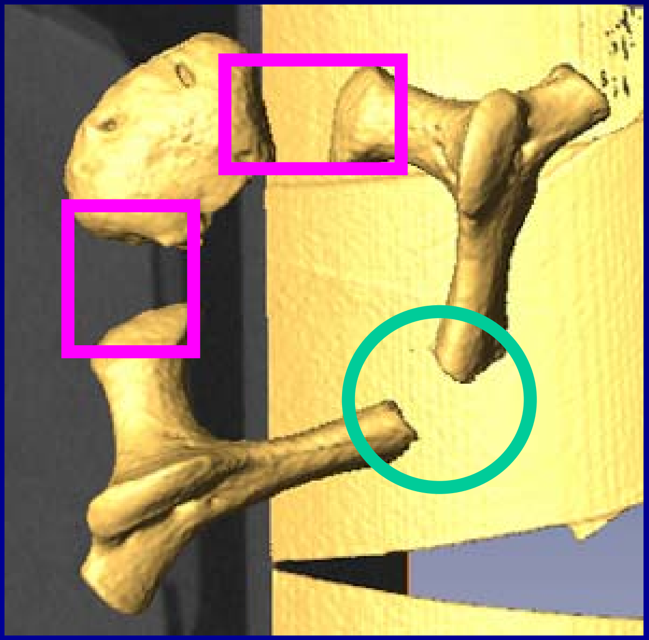
Luck et al., 2006

INTRODUCTION: Pediatric Lower Cervical Spine Anatomy

Pediatric cervical spine requires a mechanism and anatomy for growth

Growth regions => synchondroses

- *C3 - C7 = 3 synchondroses*
- *Posterior synchondrosis (1)*
- *Neurocentral synchondroses (2)*



Thoracic vertebra
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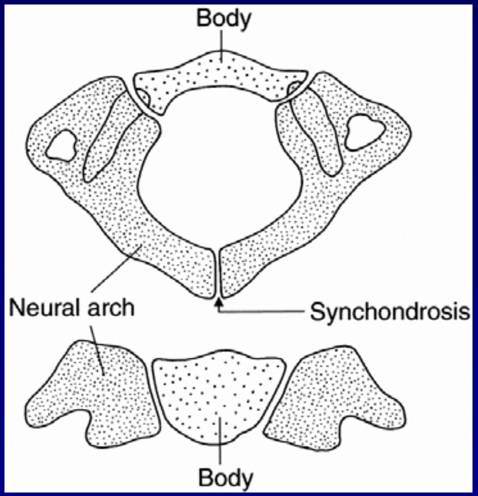
INTRODUCTION: Pediatric Upper Cervical Spine Anatomy

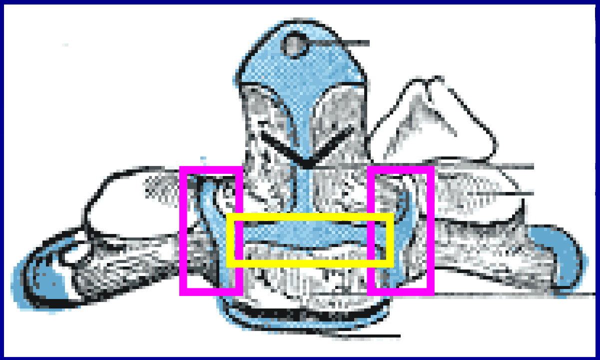
Atlas (C1)

- *2 cartilaginous regions* *(Bailey, 1952; Ogden, 1984a)*



Axis (C2)

- *4 synchondroses (Ogden, 1984b; Fesmire et al., 1989)*
- *Posterior (1)*
- *Neurocentral (2)*
- *Dentocentral (1)*



Gray's Anatomy

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INTRODUCTION: How can we help?

Improve biofidelity of future pediatric cervical spine computational models

- Provide quantitative anthropometric vertebral data of the developing cervical spine
- Determine material & failure properties of vertebral synchondroses in the developing cervical spine

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METHODS: Neck Anthropometric Measurements

Current pediatric PMHS tension testing protocol

- *Select linear measurements obtained*
- *Depending on vertebra; 4 to 5 measurements*
- *Current age range (pre-term / neonate to infant)*
- *Proposed age range (current to young adult)*

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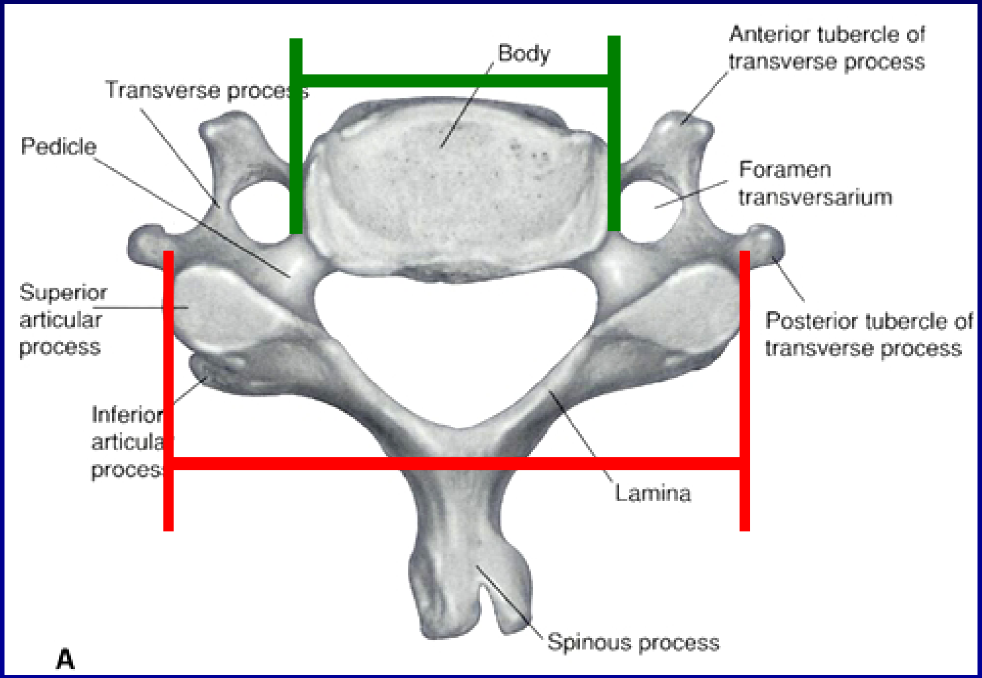
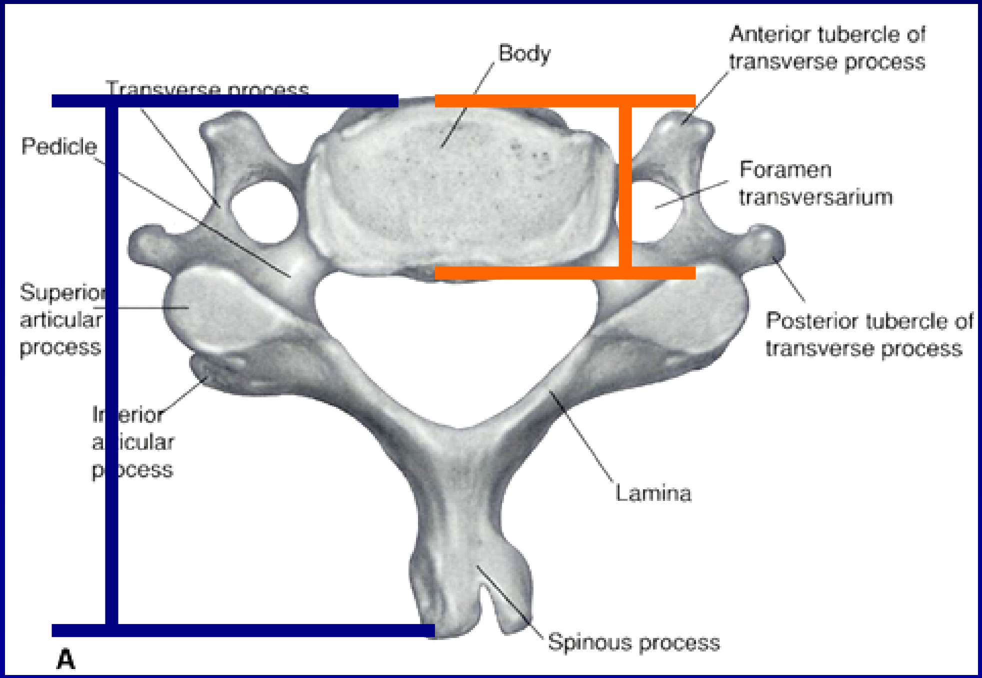
METHODS: Description of Neck Anthropometric Measurements





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METHODS: Procedure for Acquiring Measurements via CT

GE LightSpeed^{16} CT Scanner

- **Imaging & Data Acquisition**
  - **DICOM Format**

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TGS Amira 3D 3.0

- **Reconstruction & Visualization**

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Objective threshold methodology needed

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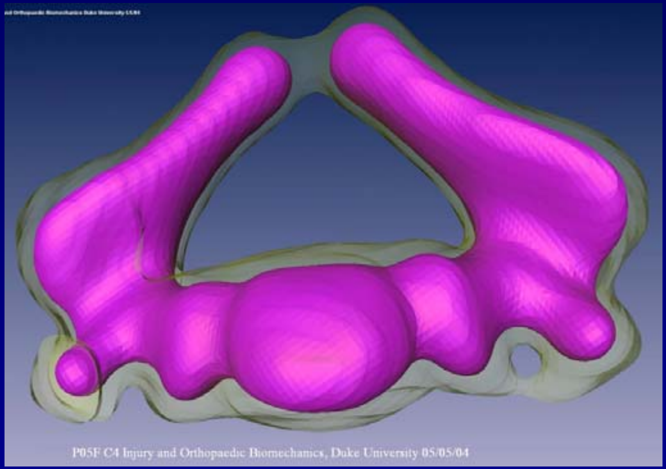
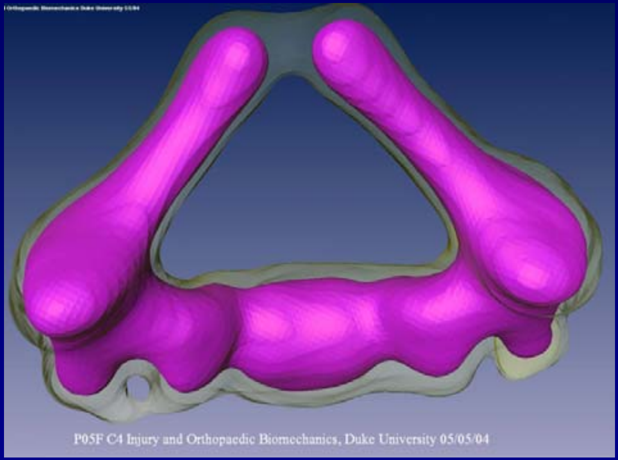
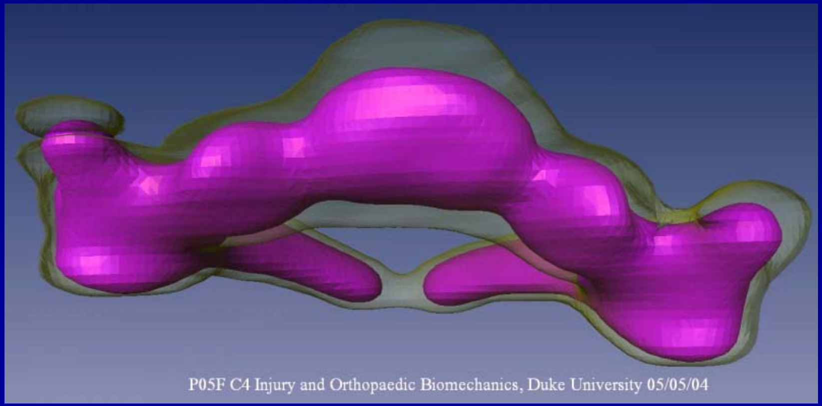
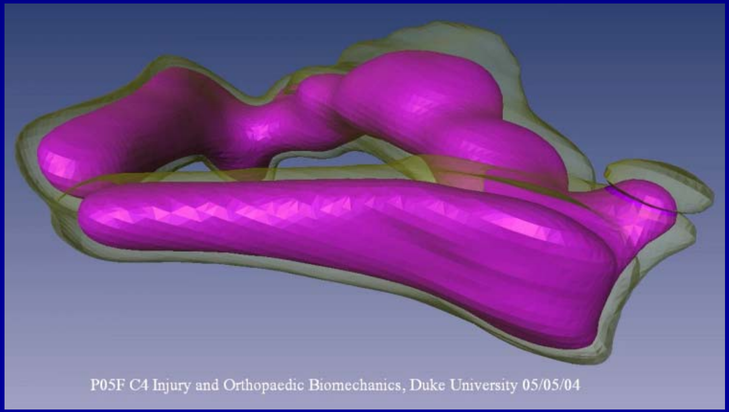
METHODS: Threshold Variation Leads to Geometry Variation









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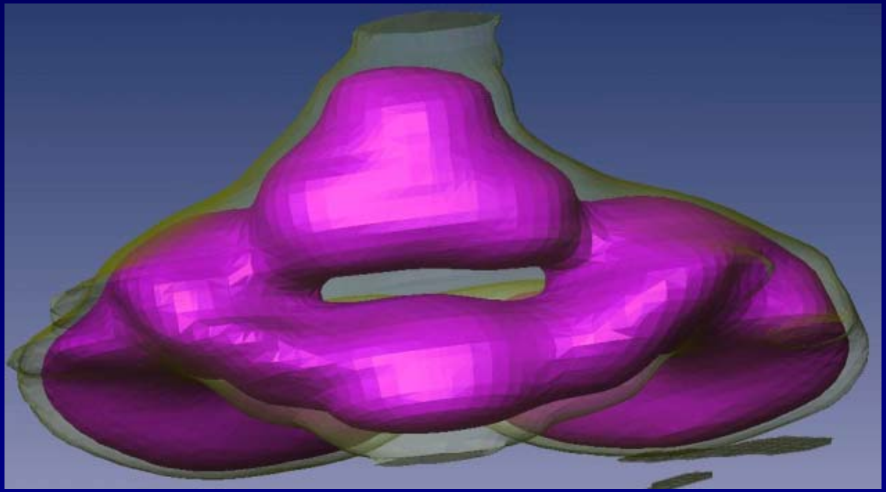
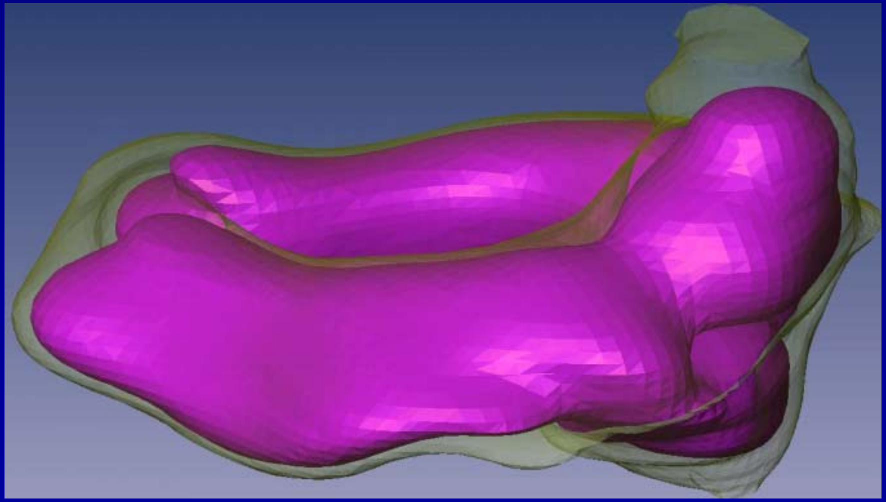
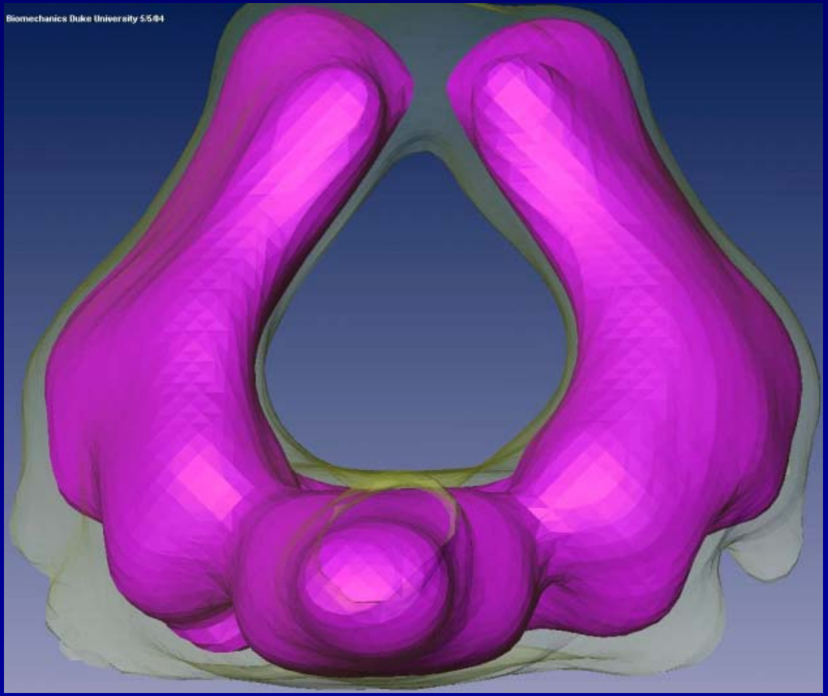
METHODS: Threshold Variation Leads to Geometry Variation







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METHODS: Determining an Appropriate Threshold

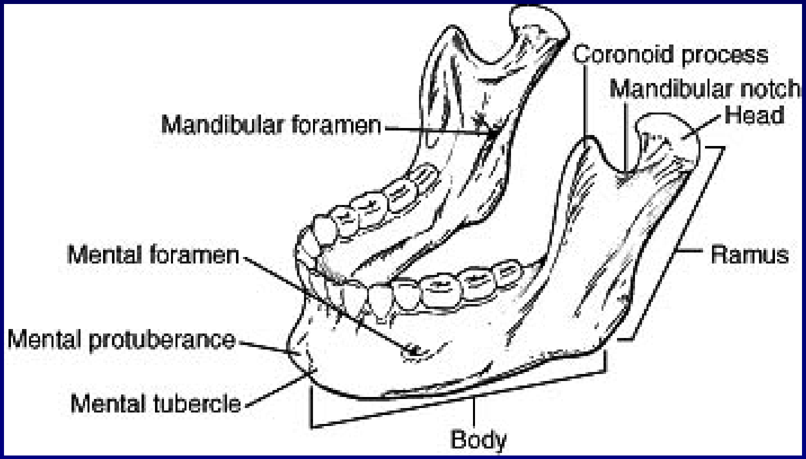
Mandible removed

5 Anatomical mandible measurements

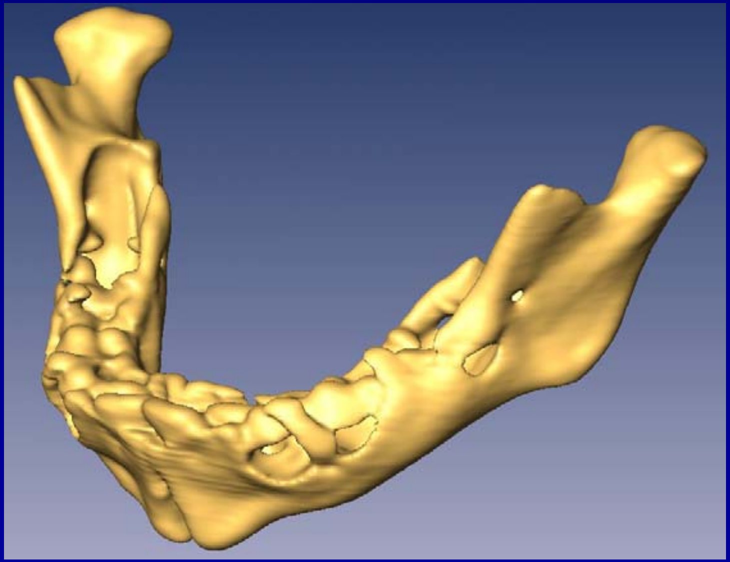
Isosurfaces (Amira 3.1)

Anatomical measurements (from isosurface)

Average absolute error



www.emedicine.com



1 day - mandible

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Loyd et al., 2004

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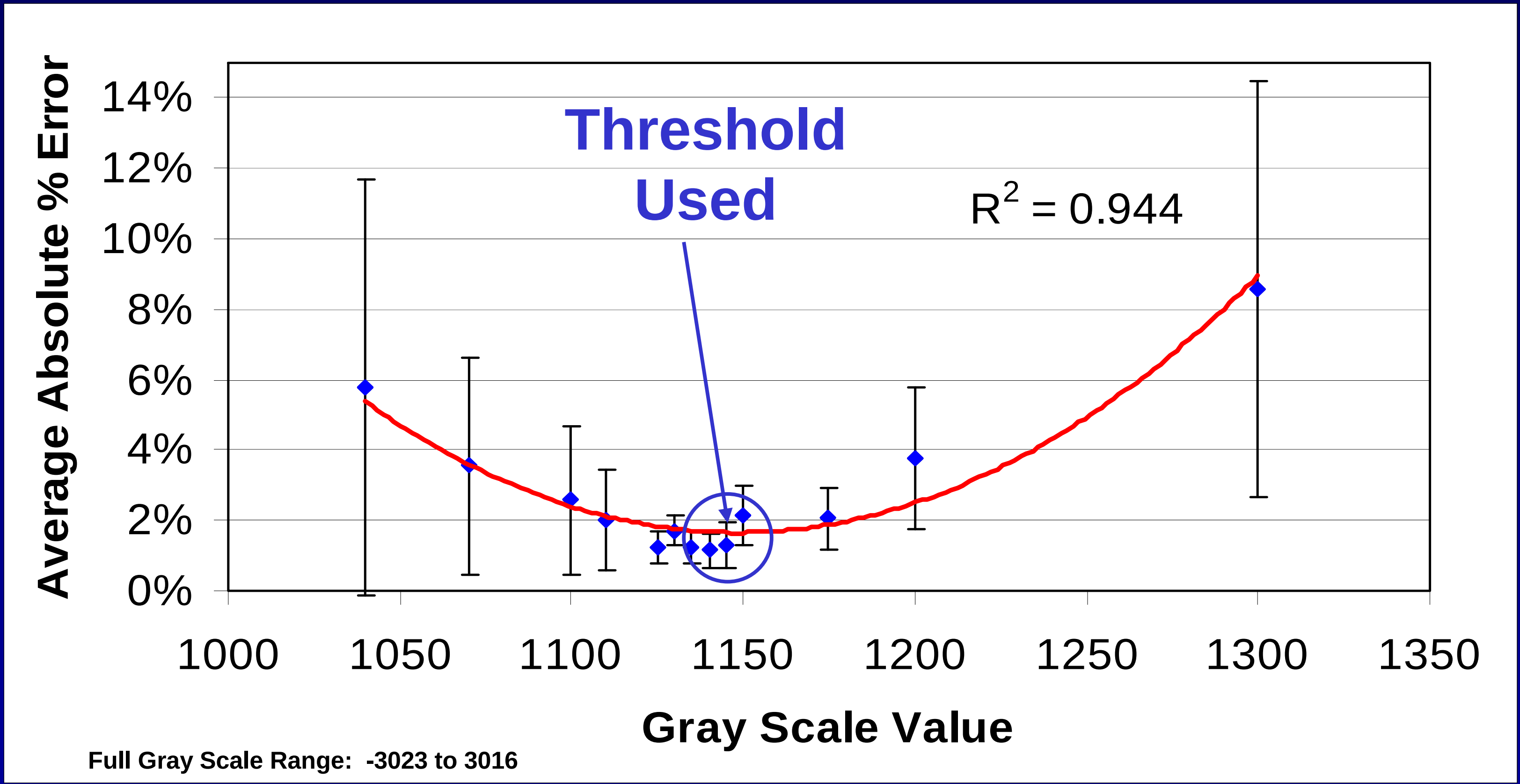
METHODS: Determining an Appropriate Threshold



Threshold obtained from mandible analysis used for vertebral measurements

Loyd et al., 2004

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RESULTS: Pediatric Anthropometric Vertebral Data

	One Day Old			
	C6	C6H	Difference	% Error
A: Vertebral height (Body)	0.3997	0.4650	-0.0653	-14.043
B: Superior Articular (Facet) Process	2.5170	2.5700	-0.0530	-2.062
C: Inner Radii of Foramen Transverium	1.4770	1.4000	0.0770	5.500
D: AP Whole Vertebra	1.7374	1.9100	-0.1726	-9.037
E: AP Vertebral Body	0.6405	0.6700	-0.0295	-4.403

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DISCUSSION: Neck Anthropometric Data Summary

1 Day, 11 Day, 33 week (gest)

- *C3 – C7 measurements*

33, 35, 37.5 week (gest), 16 day, 5 week (preme), 5 month

- *Currently tested and measurements obtained*

Future PMHS testing will provide additional data points in the older age range

Provide data for scaling to ages not present in inventory

Provide STL files for modeling use

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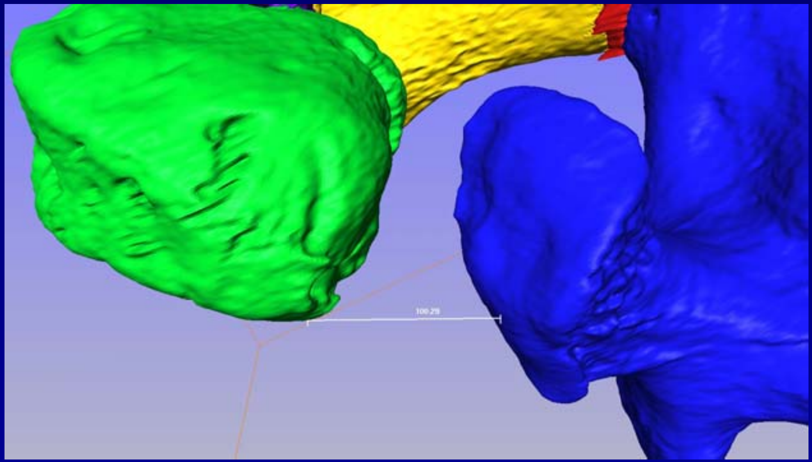
METHODS: Synchondrosis Material Properties

Obstacles to Synchondrosis Material Characterization

- *Very small (2 mm or less)*
- *Complex geometry*
- *Difficult to segment from bony elements*

Approach to overcome obstacles

- *MicroCT vs. Standard CT*
- *Inverse FEA approach*



Thoracic vertebra
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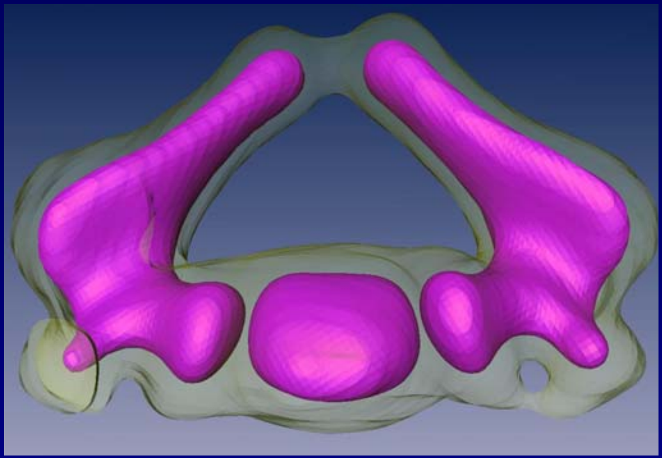
METHODS: MicroCT versus High Resolution CT

Standard High Resolution CT

- *Large changes in threshold create significant changes in geometry*

MicroCT

- *Large changes in threshold create minimal changes in geometry*
- *Allows for improved characterization of synchondrotic joint space*



Cervical vertebra
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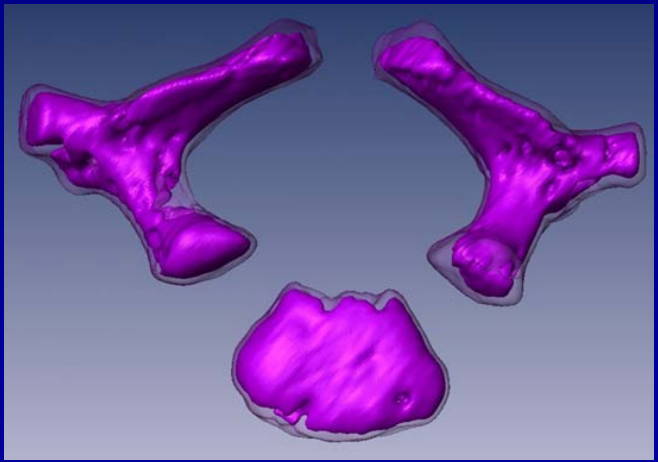

Thoracic vertebra
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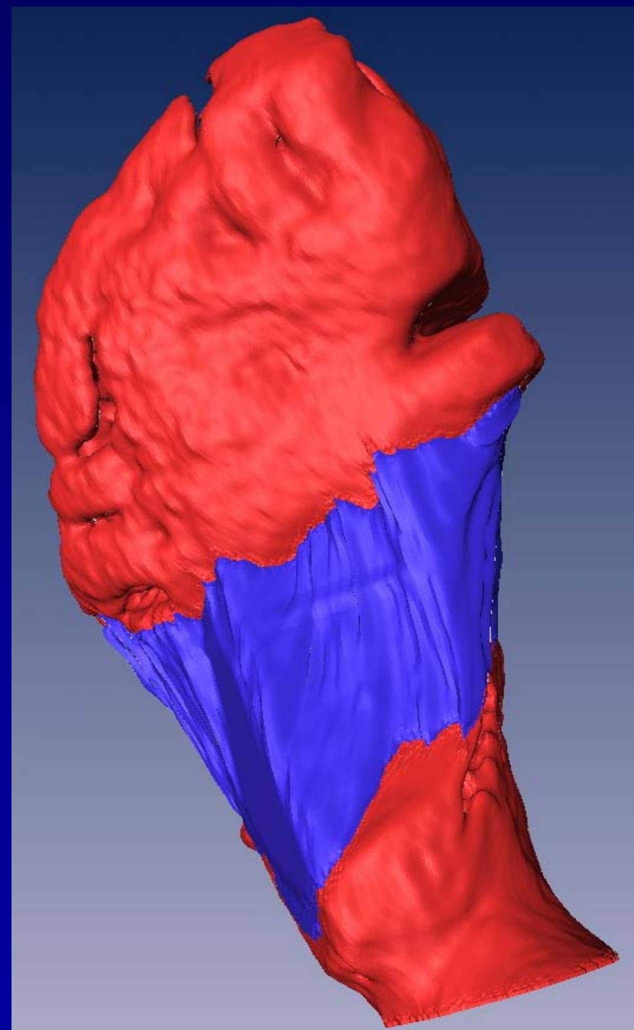
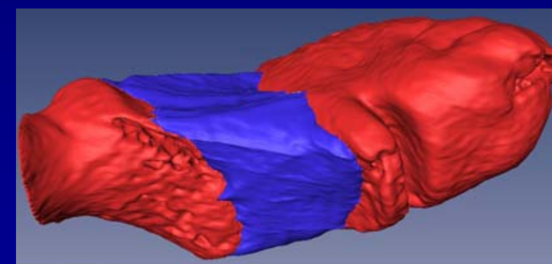
METHODS: Synchondrosis - MicroCT to FEM

MicroCT to Amira 3D
Pediatric PMHS vertebra

Bony Elements

Cartilaginous Tissue
Synchondrosis





Thoracic vertebra
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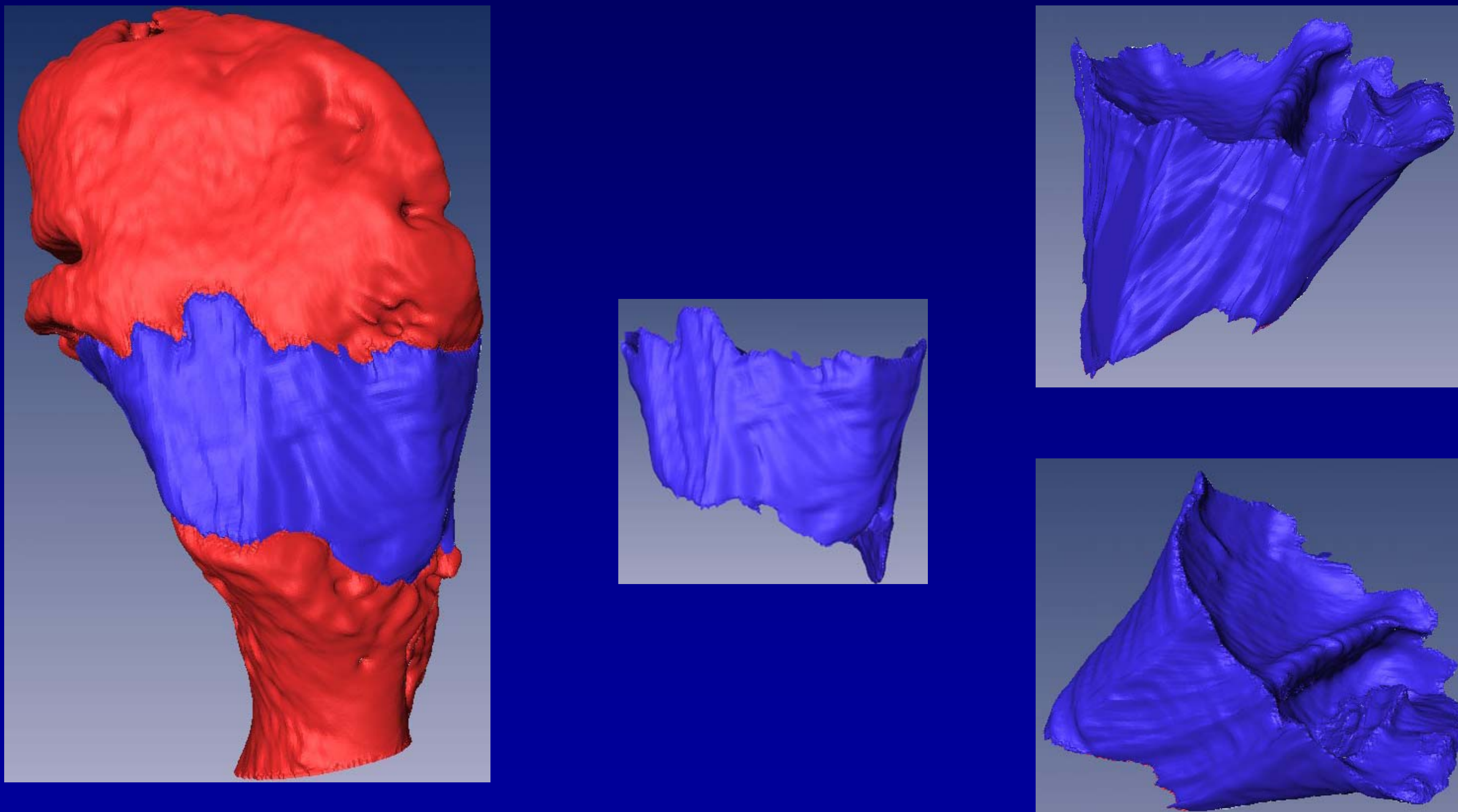
METHODS: Complex Geometry - Revealed



Thoracic vertebra

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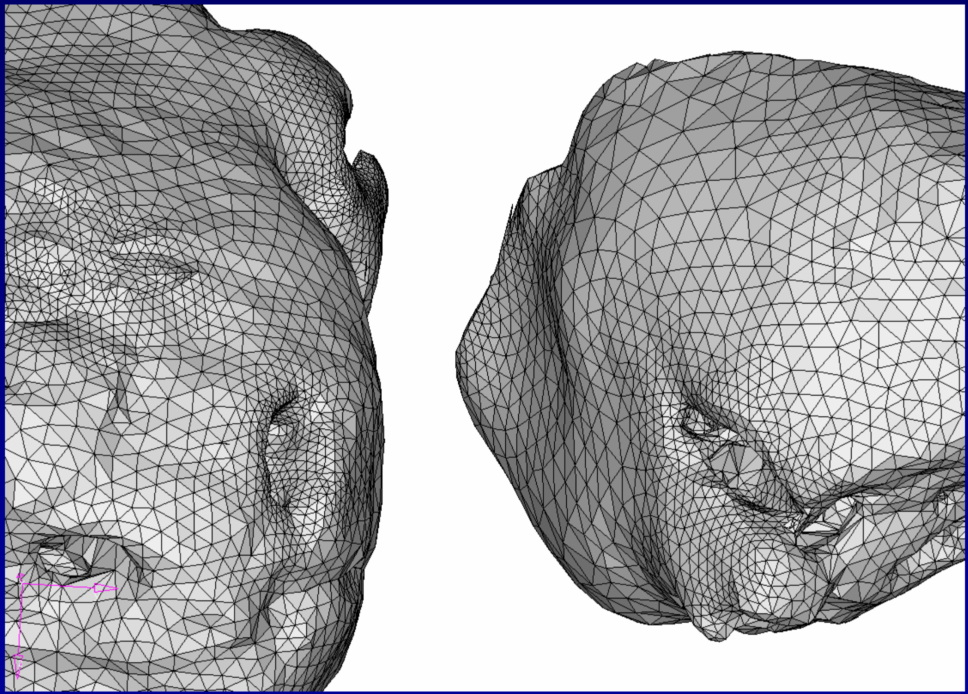
METHODS: Bone/Synchondrosis Interface - FEM

FEM creation

- *Surfaces imported to HyperMesh™ 7.0 (Altair Engineering)*
- *Solid finite element mesh is generated*



Thoracic vertebra
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METHODS: Experimental Testing of Synchondrosis

Bose Electroforce 3200 (ELF)

- *Displacement capability in sub-millimeter range*
- *Load capability in the sub-Newton range*
- *Provide platform for structural and material testing*

Bose Corporation

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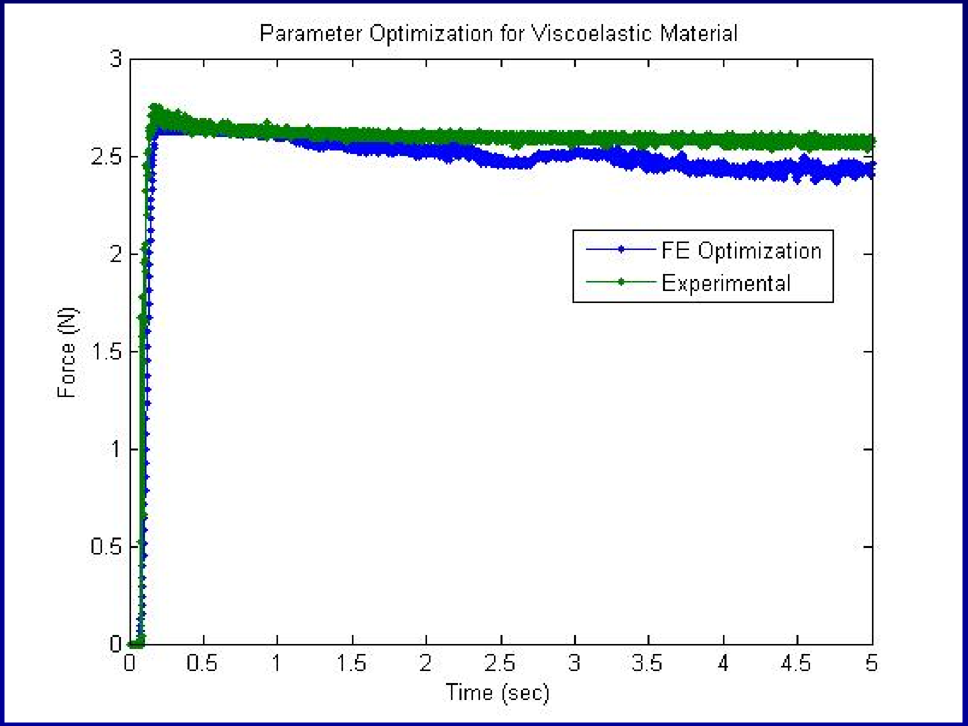
METHODS: Inverse FEA

Determination of material properties

- *Initial values defined in FE model*
- *Optimization (LS-Dyna, LS-Opt)*
- *Replicate force-displacement behavior from laboratory testing*



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DISCUSSION: Synchondrosis Summary

MicroCT provides imaging modality suitable for visualizing synchondrosis

Amira 3D provides reconstruction software suitable for segmenting synchondrosis

Hypermesh, LS-Dyna, LS-Opt

- *Provide platforms for mesh generation, model computation and material parameter estimation*

ELF 3200 platform provides testing environment appropriate for scale of tissue

Acknowledgements

Southern Consortium of Injury Biomechanics

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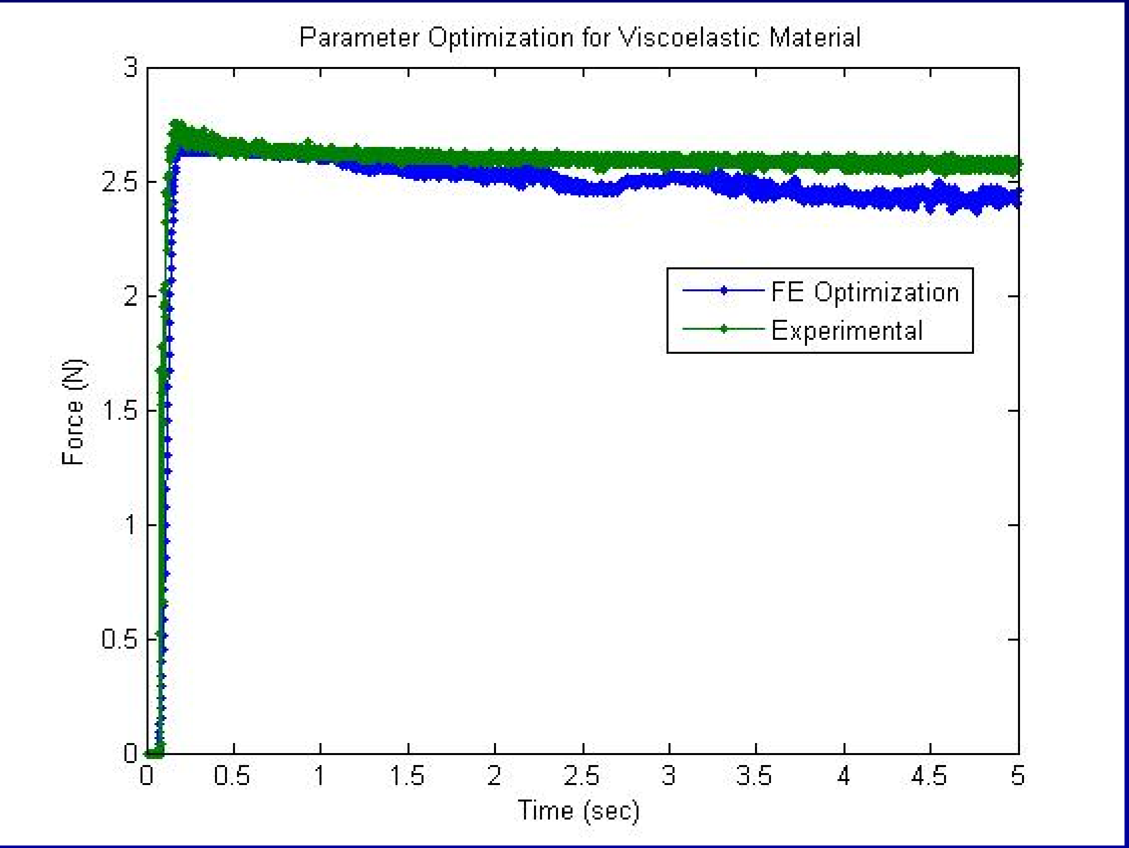
Viscoelastic Parameter Optimization

$$G(t) = G_\infty + \left(G_0 - G_\infty\right)e^{-\beta t}$$



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