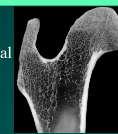
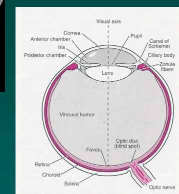
“Modeling Biomechanical Behavior of Tissues”

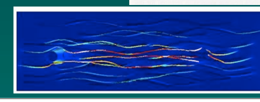
Rich Hart
Department of Biomedical Engineering
April 4, 2008

Computational Tissue Mechanics Research Interests

- Bone Adaptation
  - The ability of living bone to change material properties and geometry in response to mechanical loading. (NIH, past)
- Ocular Mechanics
  - Understanding the cascade of mechanical events leading to the progressive loss of vision due to glaucoma. (NIH)
- (New) Multiphysics modeling
  - Modeling motion of cells in gel/cell/fiber composites (NSF pending)
  - Modeling motion of cells in flowing blood?

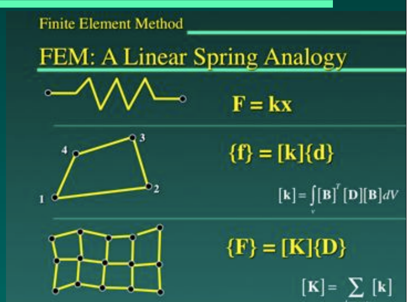




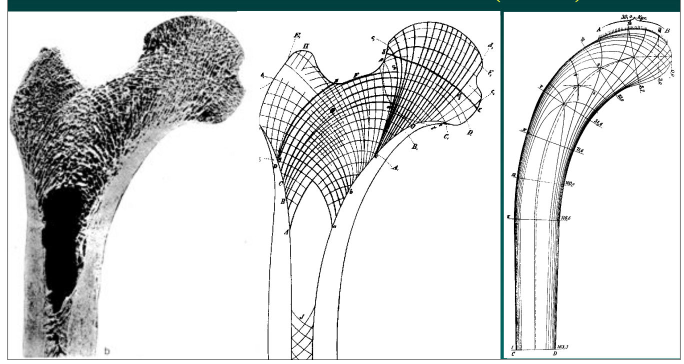


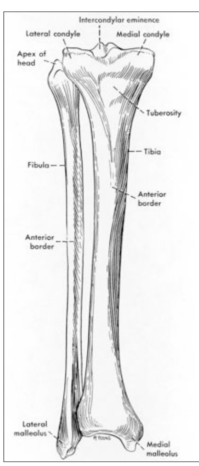
Software

- Finite Element Packages
  - ABAQUS (CalculiX)
  - COMSOL*
  - RFEM3D (self written)
- Pre-and Post Postprocessing
  - Patran*
  - Cubit (Sandia)
- Other
  - MATLAB/Simulink



Wolff’s Section and Schematic; Culman’s Calculated Stresses (1892)





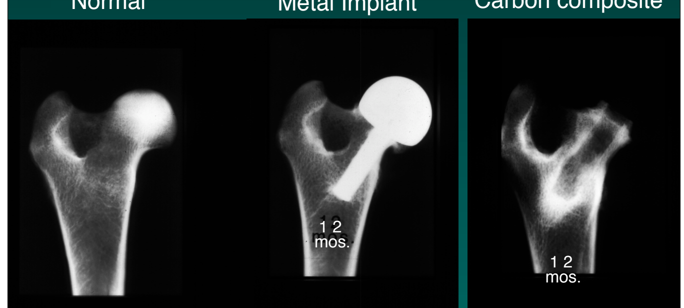
Roux’s Specimen

A natural “osteotomy experiment”

Cortical shape adaptation: “Modeling”

1 Year Post-op

Normal | Metal Implant | Carbon composite



Courtesy, Ronald C. Anderson

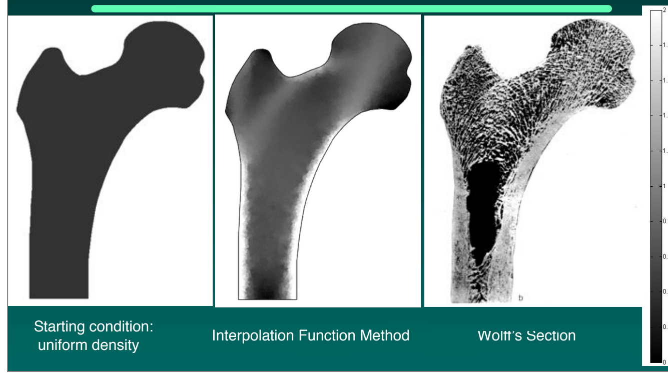
‘Wolff’s Law’ (1892)

‘Bone Form Follows Bone Function’

- Trabecular Bone
  - Trabeculae align with the principal stress trajectories (trajectorial theory)
  - Density is related to magnitude of the load
- Cortical Bone
  - Shape depends upon loading

Can adaptation be modeled, predicted, and manipulated?

Evolution of Apparent Density: Form and Function

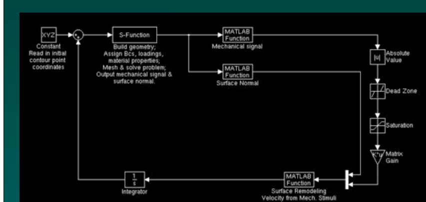


Starting condition: uniform density

Interpolation Function Method

Wolff’s Section

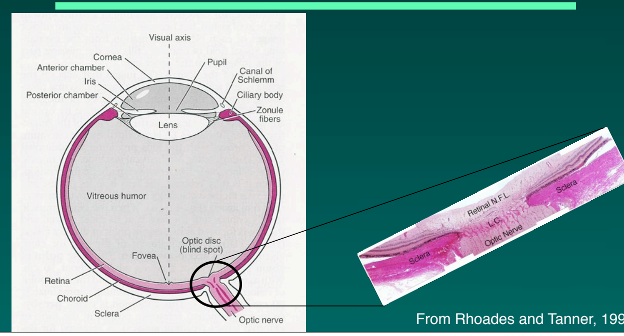
Example Application V: Human femur; Daily history



Coupled adaptation in both shape and material properties

Bone Shape Evolution

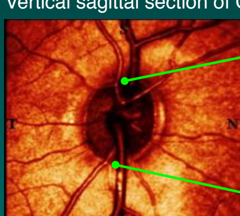
Eye Anatomy



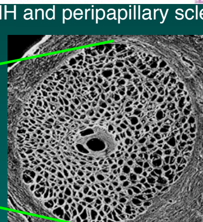
From Rhoades and Tanner, 1995

Optic Nerve Head

Vertical sagittal section of ONH and peripapillary sclera



Transverse view of ONH



SEM of a cross section of the lamina cribrosa network of connective tissues, after all the neural tissues have been removed (trypsin digest).

From Minckler, 1989

Ocular Mechanics Research: Long Term Goals

Given:

- Eye Geometry (Optic Nerve Head, ONH)
- Eye Material Properties
- Initial Conditions: Normal pressure
- Altered conditions: Increased pressure

Predict:

- Progression of damage to supporting tissues of the Optic Nerve Head due to increased pressure
- Loss of support of neural tissues and loss of vision

Methods – ONH Imaging Apparatus

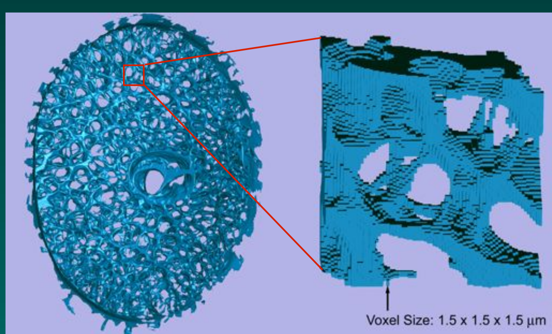
- Designed to obtain serial, transverse images of the stained surface of the embedded tissue within the paraffin block
- Camera magnification is adjusted so that each pixel represents 2.5x2.5 µm of tissue (1.5 x 1.5 µm)
- Tissue specimen is mounted on a microtome for 3 µm serial sectioning (1.5 µm)

3-D Segmentation

- Use 3-D trabecular structure direction to improve the detection and classification of laminar voxels into connective tissue or neural tissue
- Perform Coherence Enhancing Diffusion filtering using the Structure Tensor
- Perform Expectation Maximization incorporating an Anisotropic Markov Random Field
- Within the E-M algorithm, correct for intra- and inter-image illumination differences
- End result is a segmentation of the lamina with remarkable 3-D structural coherence, which is essential for modeling

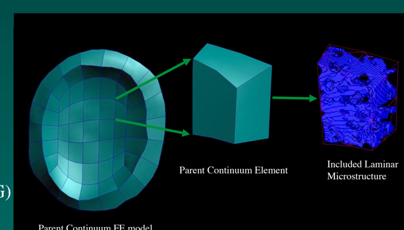
Grau, Downs, *et al.*, IEEE Medical Imaging, 2006

Laminar Microstructure Varies Regionally



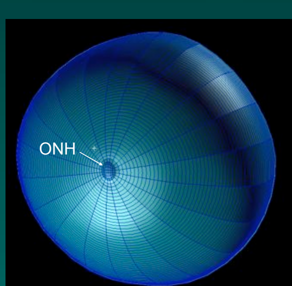
Modeling Approach

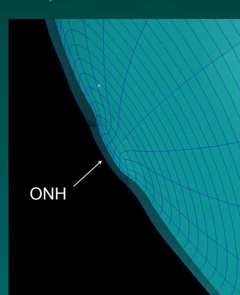
1. Generate finite element geometries of the posterior hemisphere, apply IOP loading
2. Generate ONH elements large enough to incorporate 5 or more lamina cribrosa beams)
3. Query 3-D image database to find the volume fraction and fabric tensor for each finite element.
4. Assume that the material properties of an individual beam of the lamina cribrosa are the same as that of the sclera (which can be tested).
5. Compare the deformation from experimentally induced pressure increases (20 mmHG) to that calculated for Normal and Glaucomatous eyes.



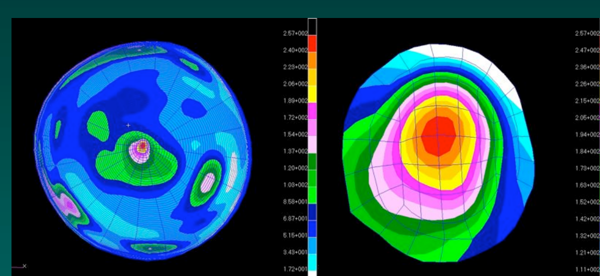
Individual-specific Model

- Model of individual monkey lamina and peripapillary sclera inserted into a generic scleral shell (anatomic shape and thickness)



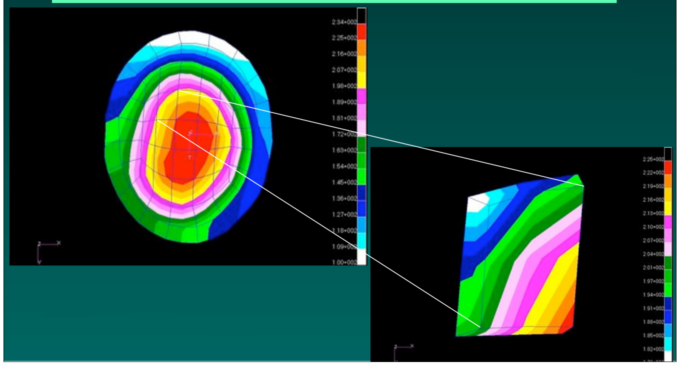


Results - Displacement (μm)

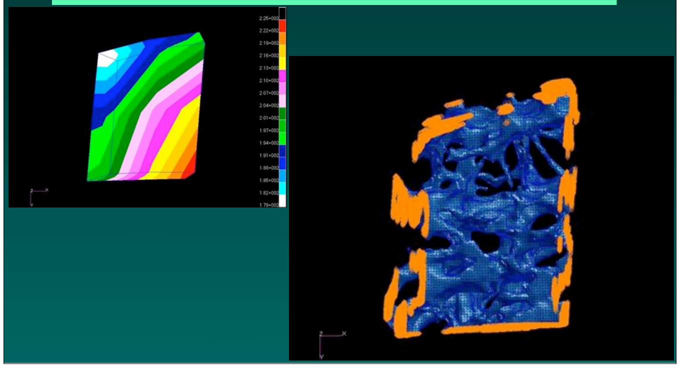


Contour plot showing the magnitude of displacement in an EG eye model

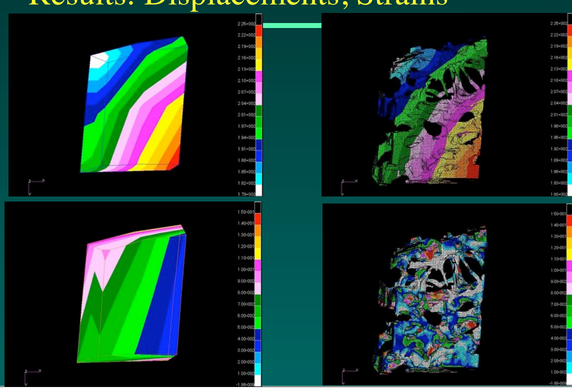
Results: Continuum Displacements

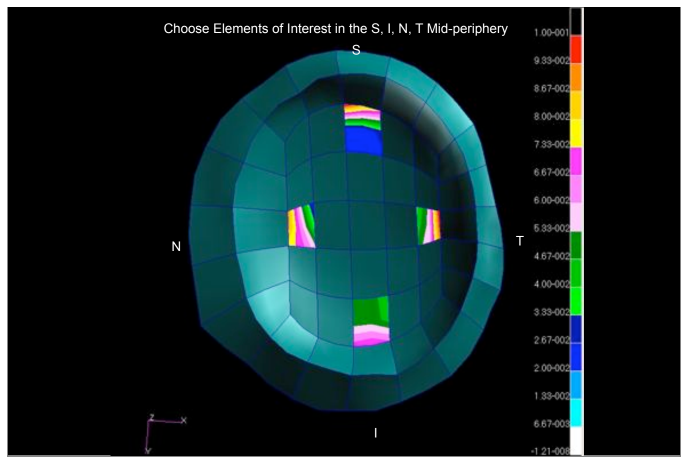


Results: Continuum Displacements as Boundary Conditions for MicroModel



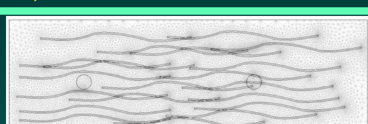
Results: Displacements, Strains



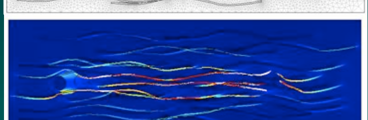


FEM: Gels, Fibers and and Cells

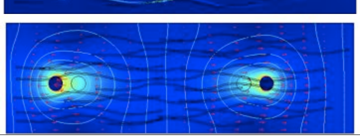
Finite Element Mesh



von Mises stress carried by fibers



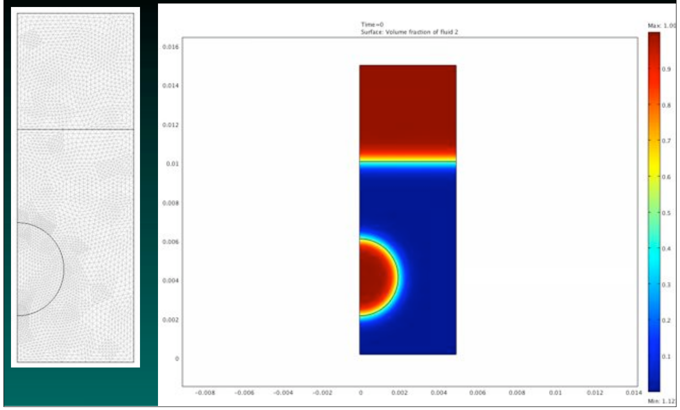
No fibers (properties same as gel); displacement contours shown

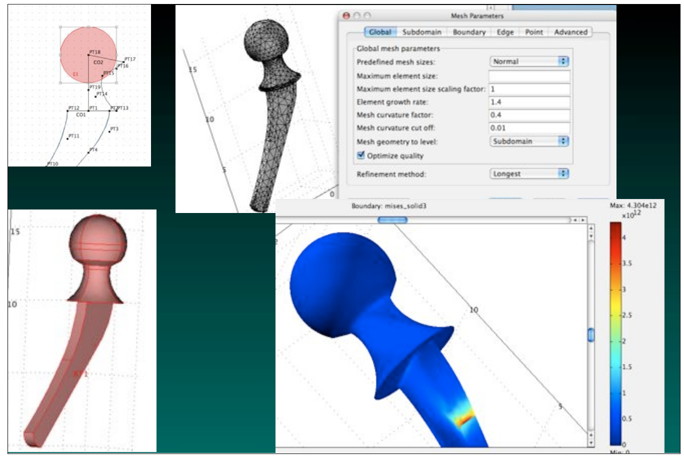


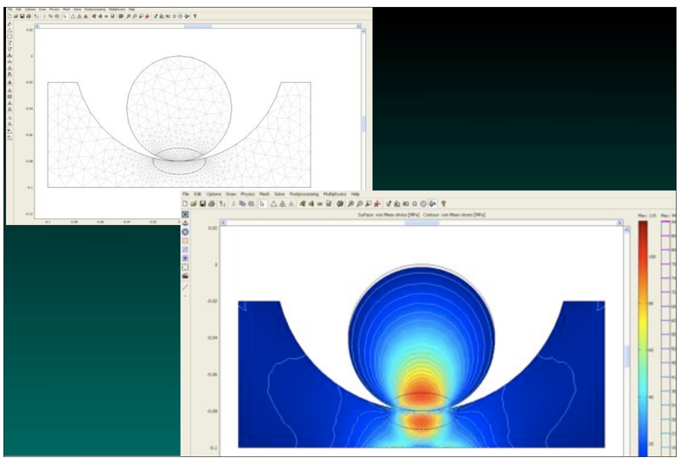
Educational Use

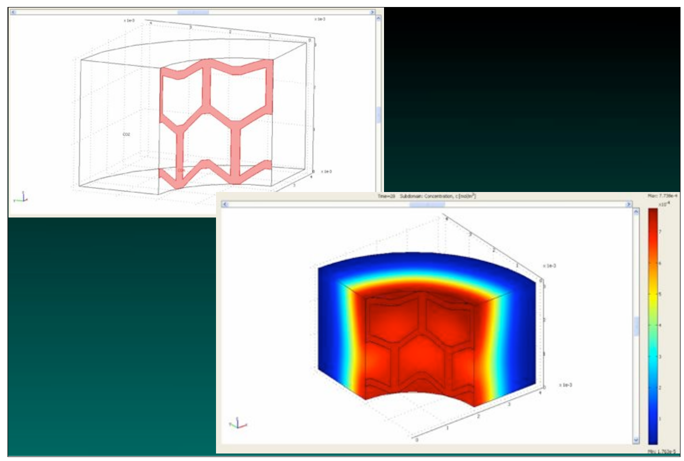
- BME 694 Finite Element Applications in Biomedical Engineering
  - Multiphysics applications
    - Structural
    - Thermal
    - Fluids
    - Diffusion

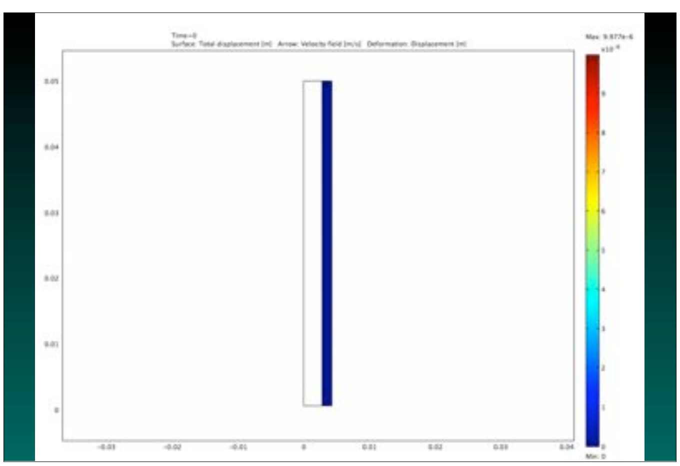
COMSOL: Level Set Tutorial











Acknowledgements

- Dr. Dwight T. Davy
- Dr. Susannah P. Fritton
- Dr. Z. Maria Oden
- Dr. John C. Coleman
- Dr. Michael D. Roberts
- Dr. Claude F. Burgoyne
- Dr. J. Crawford Downs
- Dr. Anthony Bellezza
- Dr. Xia Liu
- Xiaoyue Ma
- Becky Jansen

Thanks for the opportunity
to present this today!

Questions?