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Using COMSOL Multiphysics for Modeling of Musculoskeletal Biomechanics

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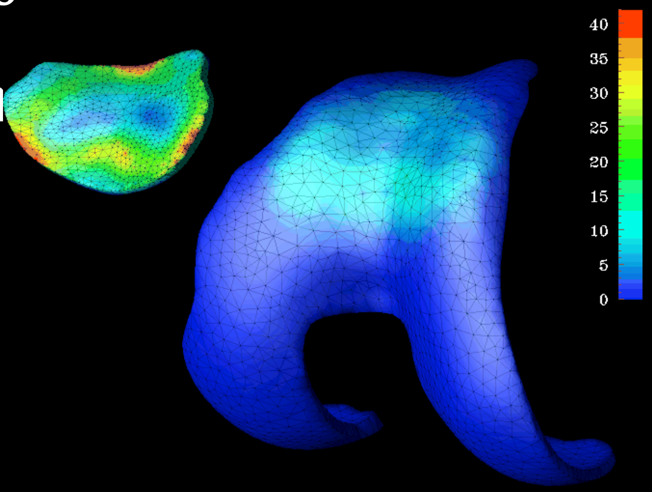
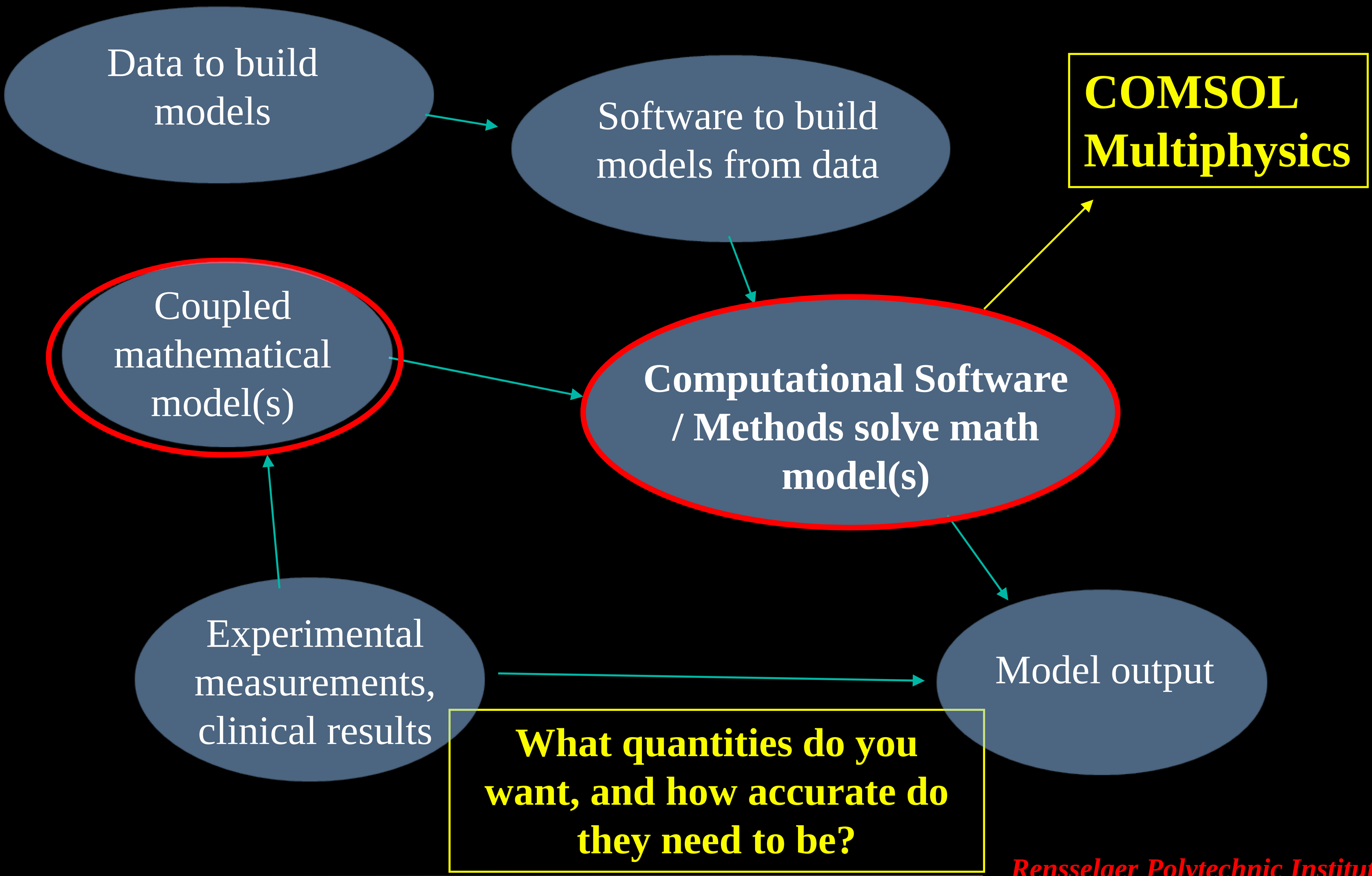
Overview

- Why is COMSOL particularly powerful for modeling physiology?
- Modeling soft tissues like cartilage
- Optimization to determine soft tissue properties
- Modeling of moving loads in the TMJ
- Robust 3D models from imaging data
- Model of primary lymphatic system
- Final comments

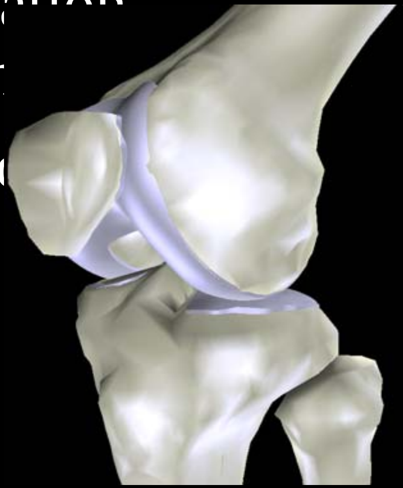


Computer Simulation of Physiology



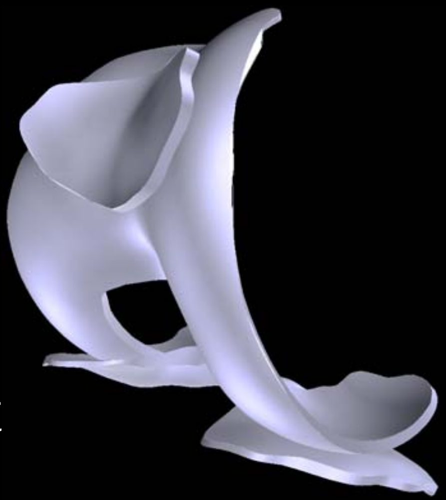
Biomechanics of Soft Physiological Tissues

- Soft physiological tissues throughout physiology (cartilage, tendon, ligament, meniscus , TMJ … cornea, organ walls ….)
- Biomechanical behavior is nonlinear and anisotropic (large loads, fibrous materials)
- Biomechanical behavior is time - dependent (e.g., like a viscoelastic material)
- Tissues have coupled multiphysics (solid deforma
fluid flow, biochemical reactions, bioelectric sig
- Multi-scale in space (gait, joint loads, tissue resp
cell response)
- Multi-scale in time (tissue growth vs running)



Example 1: Engineering a Scaffold for Tissue Growth (S. Maher, Hosp for Special Surg)

- Cell seeded, soft porous scaffold for cartilage replacement
- Subjected to cyclic compressive loads
- Cells stimulated by biophysical factors (stress, strain, transport)
- Model material as biphasic - two intrinsically incompressible phases:
  - solid (collagen, proteoglygan)
  - interstitial fluid (inviscid)
- Matches experimental measures
  - creep, stress-relaxation
  - transport
  - load sharing between phases
- Biomechanics community is primary user
- In linear form, equivalent to Biot poroelasticit



Biphasic Implementation in COMSOL

- Earth Science Module for fluid phase (steady state Darcy pressure analysis)
- Structural Mechanics Module for solid phase (static solid mechanics)
- Add coupling terms
- Define GUI-based coefficients to produce desired PDEs
- Attention to stress definitions
- Attention to traction BCs

Biphasic Implementation in COMSOL

- Biphasic fluid phase / COMSOL Darcy component:

$$\text{(Biphasic)} \quad \left(v_i^s - \kappa p_{,i}\right)_{,i} = 0$$

$$\text{(COMSOL)} \quad \left(-\delta_K \frac{\kappa}{\eta}\left(p + \rho_f gD\right)_{,i}\right)_{,i} = \delta_Q Q_S$$

- Couple through Q_s, and define (GUI) coefficients

$$Q_S = -v_{i,i}^s = -\left(\frac{\partial u_i^s}{\partial t}\right)_{,i} \quad \text{and} \quad \delta_Q = 1$$

$$\kappa = permeability(m^4 / Ns)$$

$$\delta_K = \eta = \phi^f$$

$$\rho_f = 0$$

Biphasic Implementation in COMSOL

- Biphasic solid phase / COMSOL solid component:

$$\text{(Biphasic)} \quad \left(C_{ijkl}u^{s}_{(k,l)} - \delta_{ij}p_{,i}\right)_{,j} = 0$$

$$\text{(COMSOL)} \quad -\left(C_{ijkl}u_{(k,l)}\right)_{,j} = F_i$$

- Couple through F_i: $F_i = -p_{,i}$
- Define solid phase elastic constants through GUI
- Use of Solid Mechanics Module eases transition to orthotropic and nonlinear descriptions

Stresses and Tractions in COMSOL

- Solid phase stress:

$$\sigma_{ij}^{s} = C_{ijkl}^{s} u_{(k,l)}^{s} - \phi^{s} p \delta_{ij} = \sigma_{ij}^{s^E} - \phi^{s} p \delta_{ij}$$

- Fluid phase stress: $\sigma_{ij}^{f} = -\phi^{f} p \delta_{ij}$
- Total stress: $\sigma_{ij}^{Tot} = \sigma_{ij}^{s} + \sigma_{ij}^{f} = \sigma_{ij}^{s^E} - \delta_{ij} p$

- Applying traction in COMSOL Structural Mech Module gives

$$t_{i}^{COMSOL} = \sigma_{ij}^{s^E} n_{j} = \overline{t}_{i}^{Tot} + \delta_{ij} p n_{j}$$

Unconfined Compression of Cylindrical Plug

- Compress cylindrical disc (cells/scaffold) between two perfectly lubricated, rigid, impermeable platens
- Ramp displacement (25s), followed by hold (stress relaxation) on top platen
- Behavior uniform in z, deformation and fluid flow in r
- Strong gradients in pressure, fluid flow, etc at the outer radius

Unconfined Compression -- Pressure vs time

Example 2: Using Optimization to Determine Biphasic Material Parameters

- Tissue testing needed for constitutive properties:
- Modulus, E^S, Poisson ratio, ν^S, permeability, κ
- Analytic solution of tissue test not feasible
- Use FE to simulate the test
- Solve for the measured experimental quantities
- Use optimization to control search for properties
- Find properties that give “best fit” to -- e.g.
  - normal stress at platen vs. time
  - radial displacement at outer radius vs. time

Coupling Biphasic COMSOL and Optimization Lab

Controlling Routine

- **“opt” structure**
- **Objective function pointer**
- **Bounds**
- **Initial guess**
- **Call to Opt Lab routine**

Routine that defines the objective function

Experimental results / data

FE Solution of Experiment

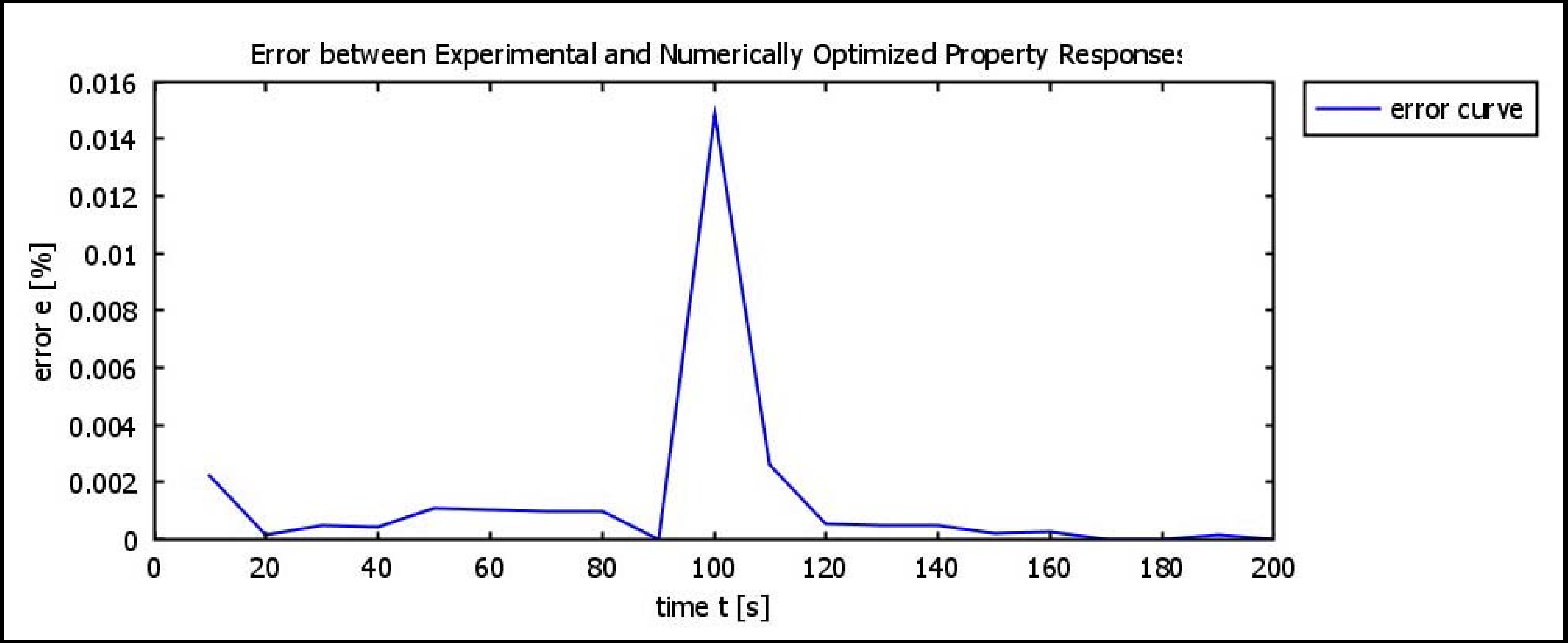
- **fem structure exported from COMSOL model**

Example -- Unconfined Compression

- Use ramp (100s) / hold unconfined compression stress relaxation experiment
- Determine E^S (0.225e6 Pa), ν^S (0.125) , κ (7.6e-15)
- Match experimentally measured radial expansion and normal stress on upper surface vs time
- Objective function = Least squares difference between experiment and FE solution at select times
- Used nonlinear optimization routine
- Initial guess E^S (1.0e6 Pa), ν^S (0.3) , κ (1.0e-15)

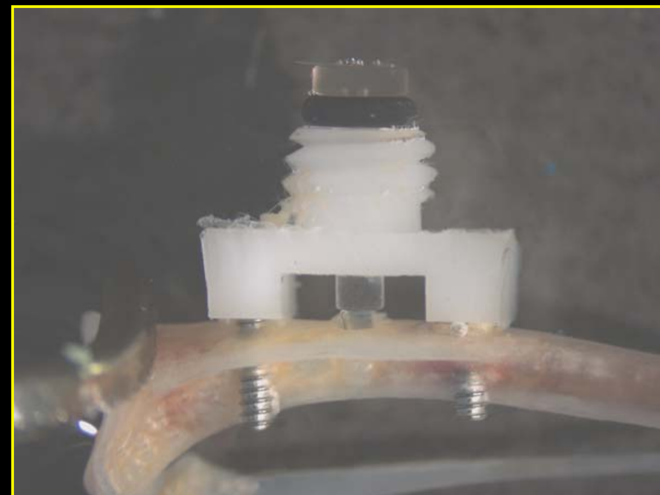
Results -- Unconfined Compression Stress

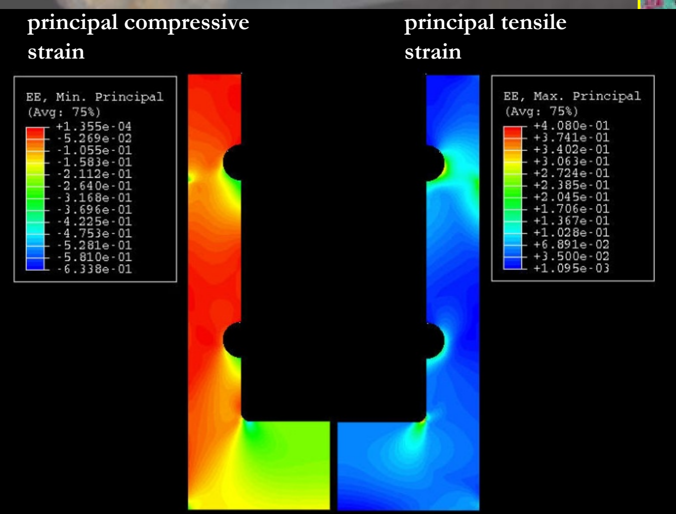
- 236 iterations, properties < 0.01% error

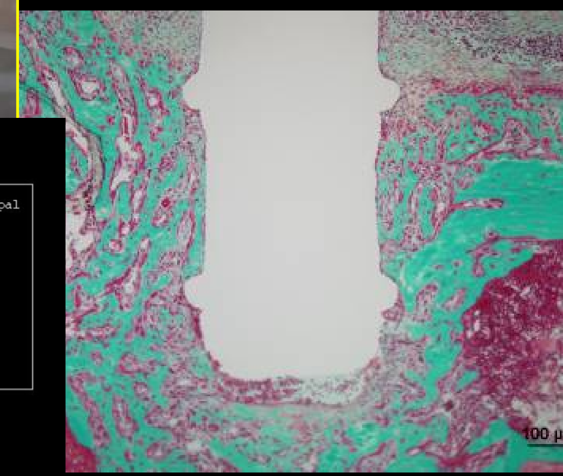


Example 3: Bone Remodeling Around Implant

- Implant in mouse tibia
- Mechanical stimulation
- Bone remodeling

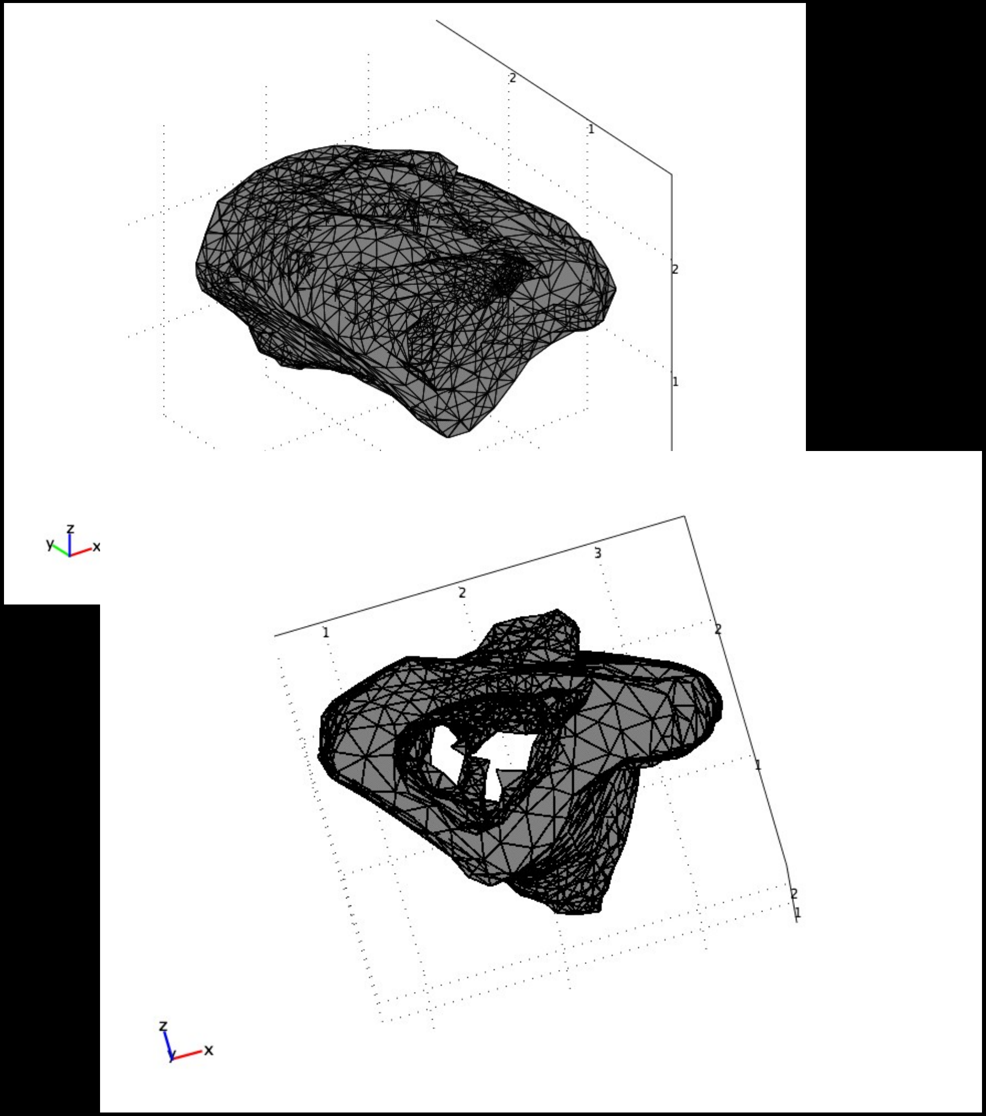






3D Model from microCT

- Import microCT of tibia
- Process dicom to get robust STL file (Mimics -- Materialize Inc)
- Insert implant (CAD model)
- Insert surrounding material
- Hypotheses -- mathematically model interface material and property changes due to cell activity and tissue growth



Example 3: Modeling Moving Contact in the TMJ (J. Nickel and L. Iwasaki, Dental School, UMKC)

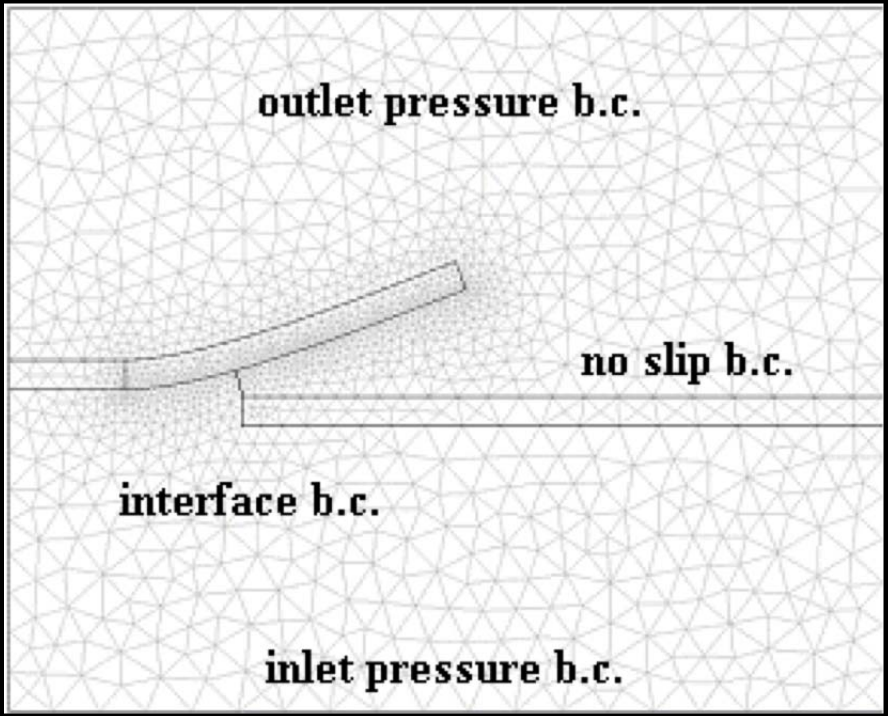
- Temporomandibular joint (TMJ)
- Hydrated soft tissue
- Few successful interventions / restorations
- Sliding Contact between mandible and jaw
- Plowing test with rigid indenter is in-vitro approximation

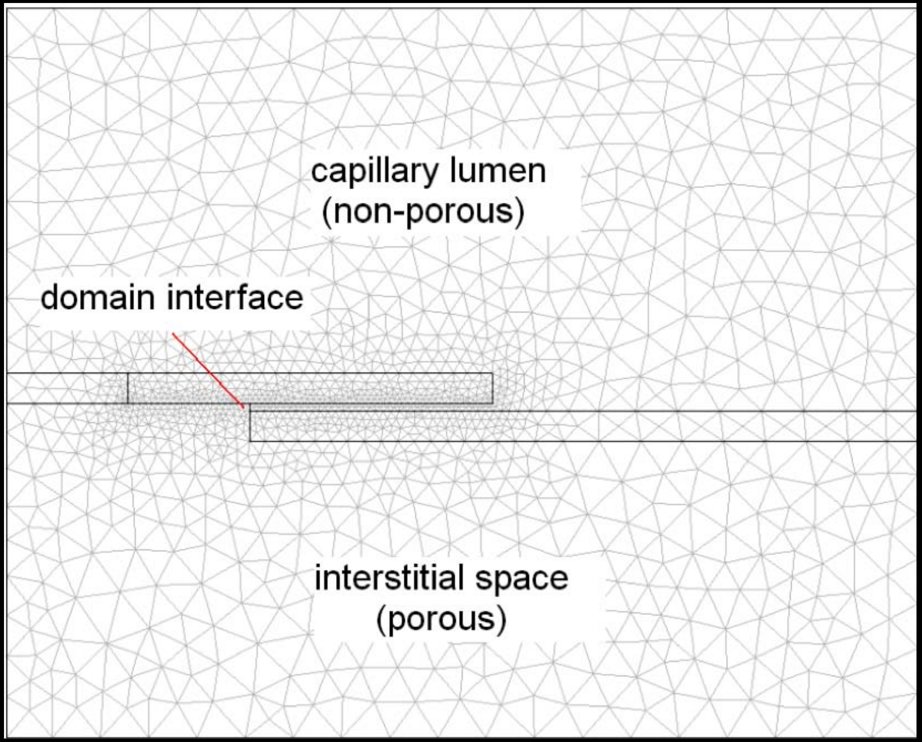
Biphasic Model Using ALE Moving Mesh

- Biphasic model of tissue
- Approximate contact with no-flow and solid phase force
- Move the indenter / BC with ALE in COMSOL
- Mesh below indenter moves with PT1 and PT2

Biphasic Model of TMJ Plowing -- Total σ_y

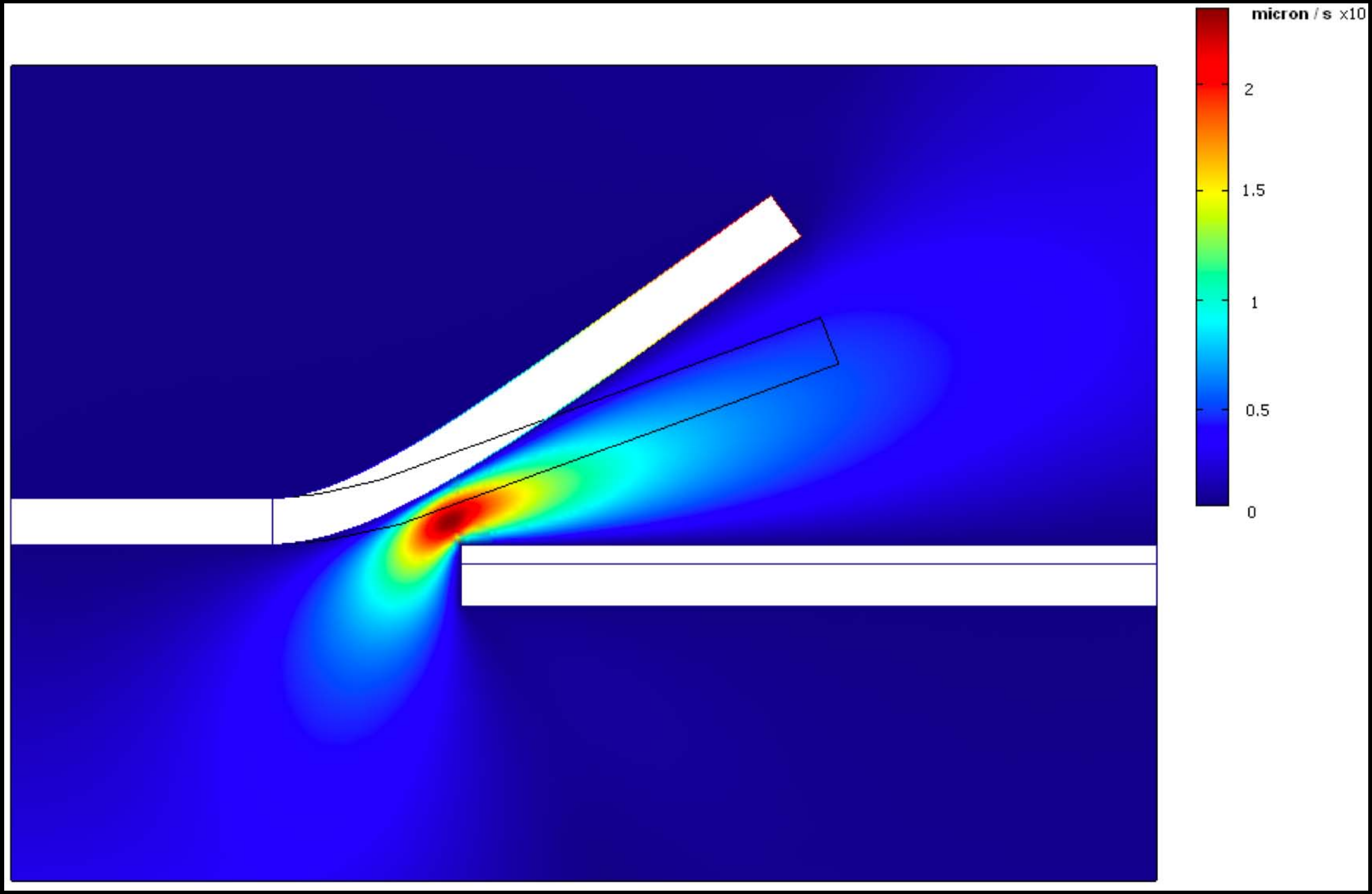
Fluid Structure Model of Primary Lymphatic System





Galie and Spilker,
J. Biomech Engng (in review)

Primary Lymph Valve -- Fluid Velocity Contour



Concluding Remarks

- Modeling human physiology for biomedical engineering is:
  - –Multiphysics
  - –Multi-scale in space and time
  - –3D
  - –Nonlinear and time dependent
  - –Engineering interacts with biology
- COMSOL gives tools for coupling, with user interface for commercial user


Thank You!
Thanks to Konrad Juethner and
support@COMSOL.com