FEBio: An Open-Source Multiphysics Finite Element Software for Biomechanics and Biophysics

Initiative for Computational Science and Engineering (iCSE) Research Day

May 12, 2021, New York, NY

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COLUMBIA | ENGINEERING

The Fu Foundation School of Engineering and Applied Science

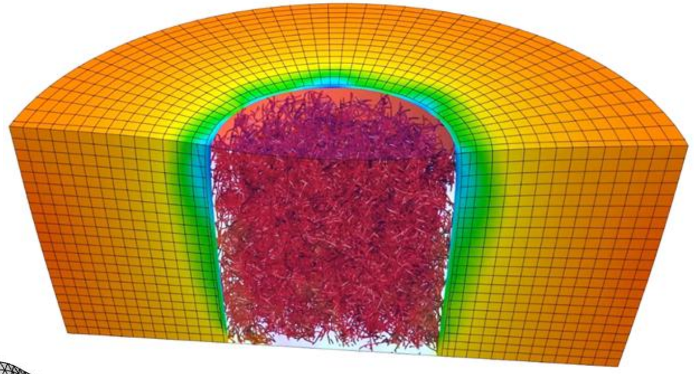
FEBio Project (febio.org)

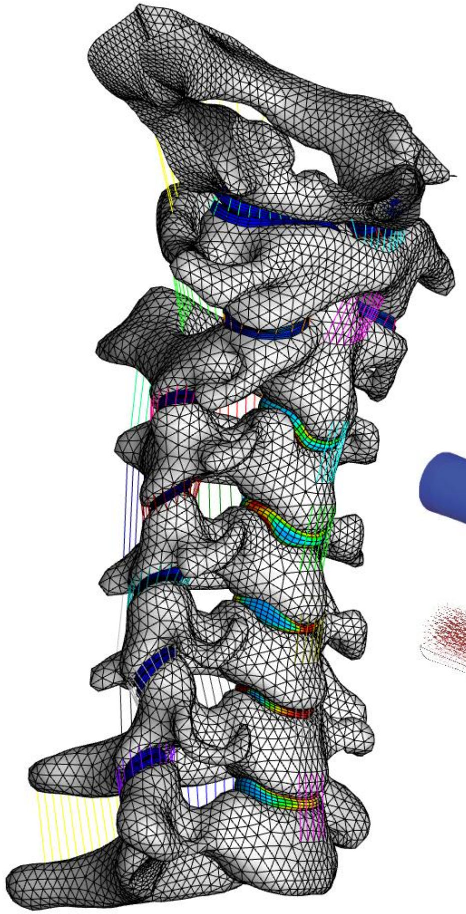
- Co-developers
  - Jeffrey A. Weiss, Ph.D.
    - Professor of Biomedical Engineering, University of Utah
  - Steve Maas, Ph.D.
    - Software Developer, University of Utah
  - Gerard A. Ateshian, Ph.D.
    - Professor of Mechanical Engineering, Columbia University

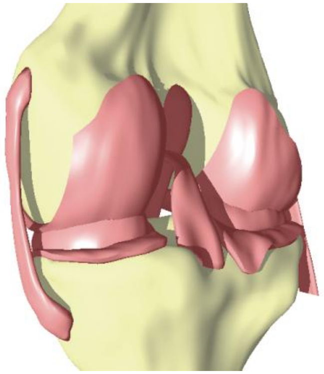
- Pillars of Project
  - Target the biomechanics community by focusing on features and simulation capabilities that are relevant to the field
  - Freely available, easy to extend
  - Thorough documentation; support and outreach to the community

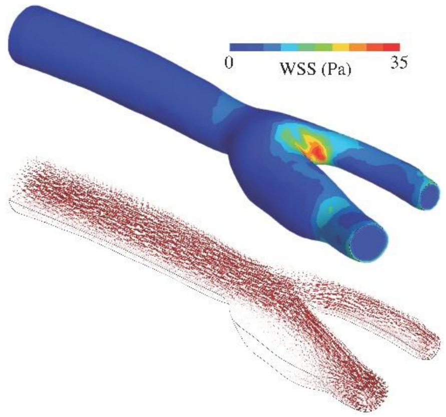
Overview of Key Features

- Physical scale from cells and subcellular structures to tissues, organs, and whole body.
- Multiphysics - mechanics of solids, fluids and mixtures with growth/remodeling, reaction/diffusion, electrokinetics.
- Constitutive models specific to biomechanics and biophysics – anisotropy, viscoelasticity, multiphasic materials, reactions, active contraction, viscous fluids, material evolution.
- Dynamic effects, residual strain, active contraction, interstitial fluid transport, fluid-solid interaction, frictional contact and sliding, interfacial mass transport and electrical conduction.





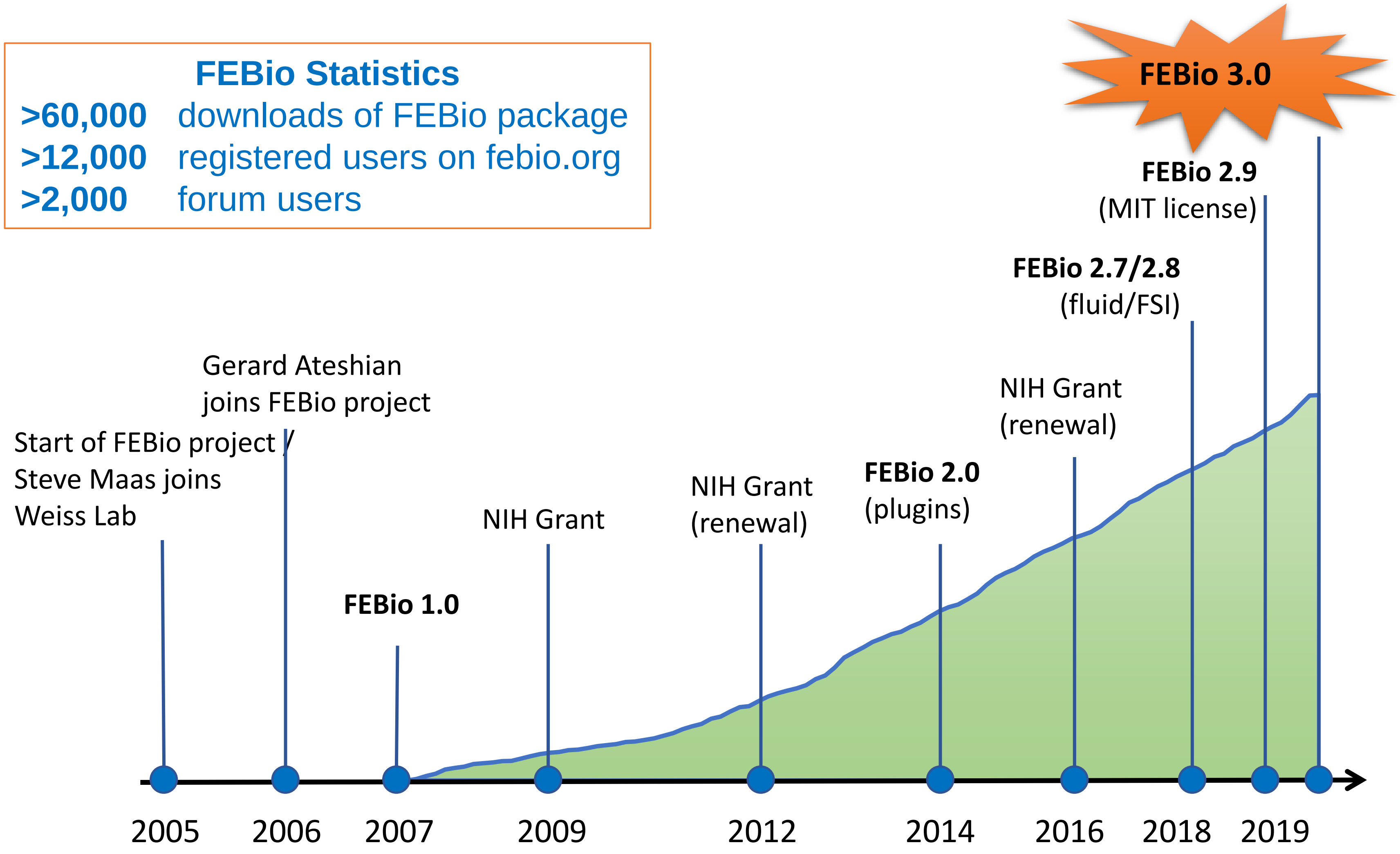




Brief History of FEBio

FEBio Statistics

>60,000 downloads of FEBio package
>12,000 registered users on febio.org
>2,000 forum users



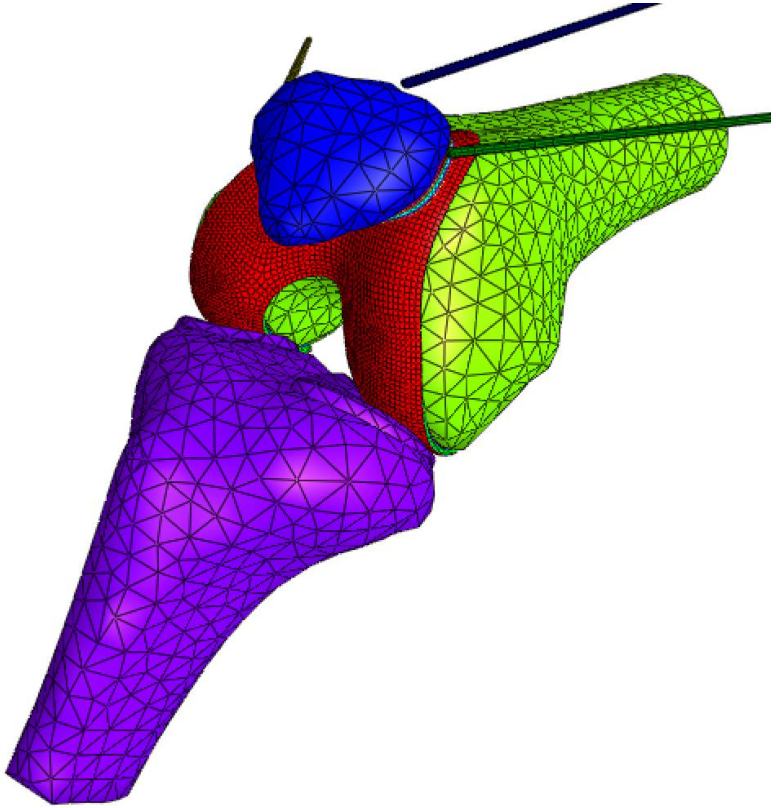
Governing Equations

- Equations are based on mixture theory. A mixture consists of any number of constituents α occupying the same elemental region. The apparent density of constituent α is denoted by ρ^α.

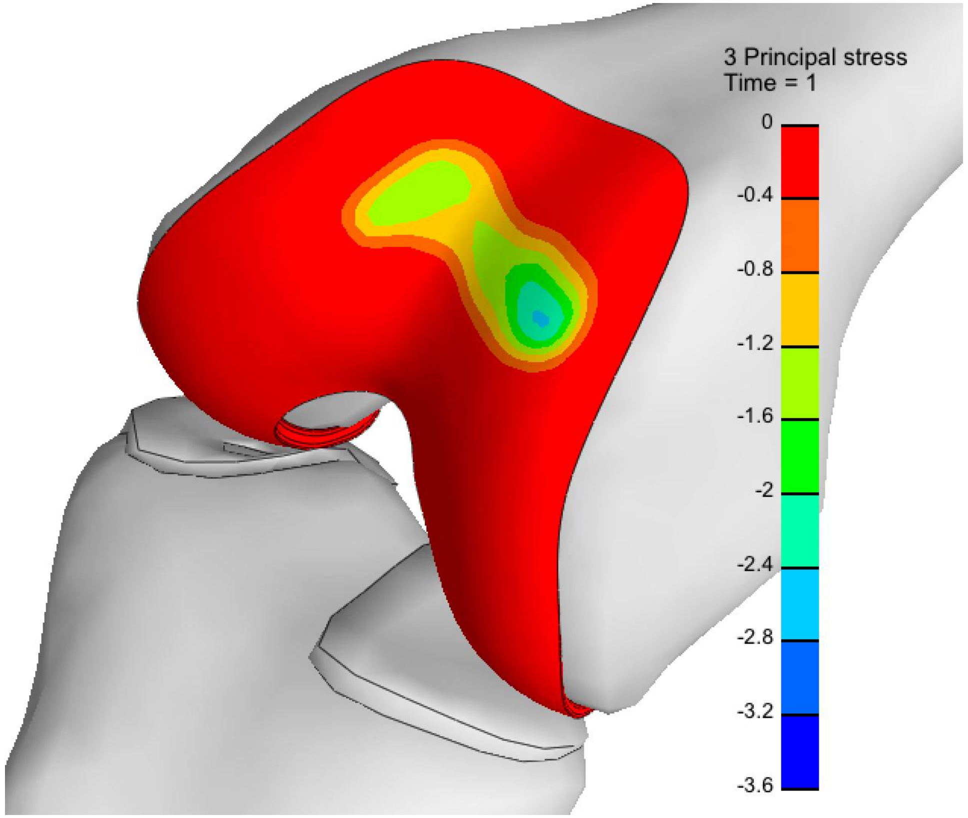
  - Mass balance $\frac{\partial \rho^\alpha}{\partial t} + \mathrm{div}(\rho^\alpha \boldsymbol{v}^\alpha) = \hat{\rho}^\alpha$
  - Linear momentum balance $\rho^\alpha \boldsymbol{a}^\alpha = \mathrm{div}\, \boldsymbol{\sigma}^\alpha + \rho^\alpha \boldsymbol{b}^\alpha + \widehat{\boldsymbol{p}}_d^\alpha$
  - Entropy inequality $\sum_\alpha -\boldsymbol{\tau}_d^\alpha : \boldsymbol{L}^\alpha + \widehat{\boldsymbol{p}}_d^\alpha \cdot \boldsymbol{u}^\alpha + \hat{\rho}^\alpha \left(\mu^\alpha + \frac{1}{2} \boldsymbol{u}^\alpha \cdot \boldsymbol{u}^\alpha\right) \leq 0$
  - Coulomb's law $\boldsymbol{b}^\alpha = -\frac{z^\alpha F_c}{M^\alpha} \mathrm{grad}\, \psi$
  - Electroneutrality $\sum_\alpha z^\alpha \frac{\rho^\alpha}{M^\alpha} = 0$

Solid-Fluid Mixtures: Biphasic Theory

- First implementation of mixture theory in FEBio (2006)
- Biphasic contact implemented in 2010



Ateshian, Maas, Weiss, J. Biomech. Eng., 2010



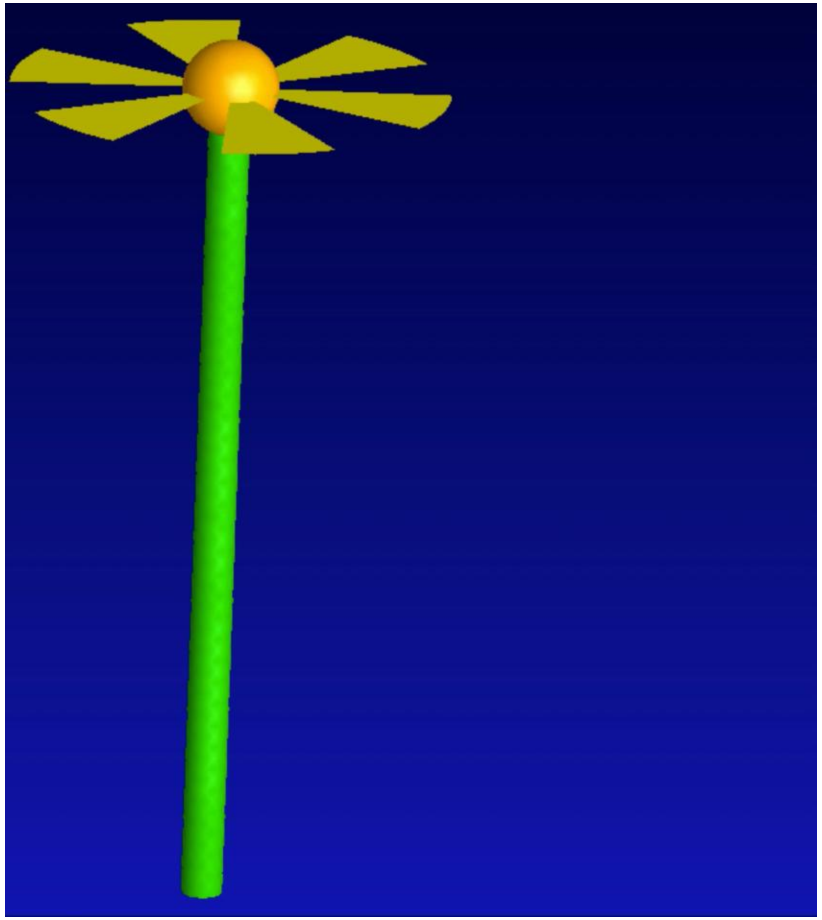
Jones, Hung, Ateshian, J. Knee Surg., 2016

Mixture of Solid, Solvent and Neutral Solute

- Mauck, Hung, Ateshian (2003)
  - Solute has negligible volume fraction
  - Friction between solute and solvent models classical Fick's law
  - Friction between solute and solid matrix models hindrance
  - Solute may be partially excluded from tissue pore space (steric effect)
  - Account for osmotic pressure
- FEBio implementations
  - Ateshian, Albro, Maas, Weiss (J. Biomech. Eng. 2011)
  - Contact interface: Ateshian, Maas, Weiss (J. Biomech. 2013)
- Solute mass balance
  - $\frac{\partial c^\alpha}{\partial t} + \operatorname{div}(c^\alpha \boldsymbol{v}^\alpha) = 0$
  - $\frac{1}{J^s} \frac{D^s\left(J^s \varphi^f \tilde{\kappa} \tilde{c}^\alpha\right)}{Dt} + \operatorname{div} \boldsymbol{j}^\alpha = 0$
  - $\boldsymbol{j}^\alpha = \varphi^f c^\alpha (\boldsymbol{v}^\alpha - \boldsymbol{v}^s)$ =solute molar flux relative to solid

Biphasic-Solute Theory

- Solute osmotic pressure



- Solute pumping
  - Due to friction between solute and solid matrix

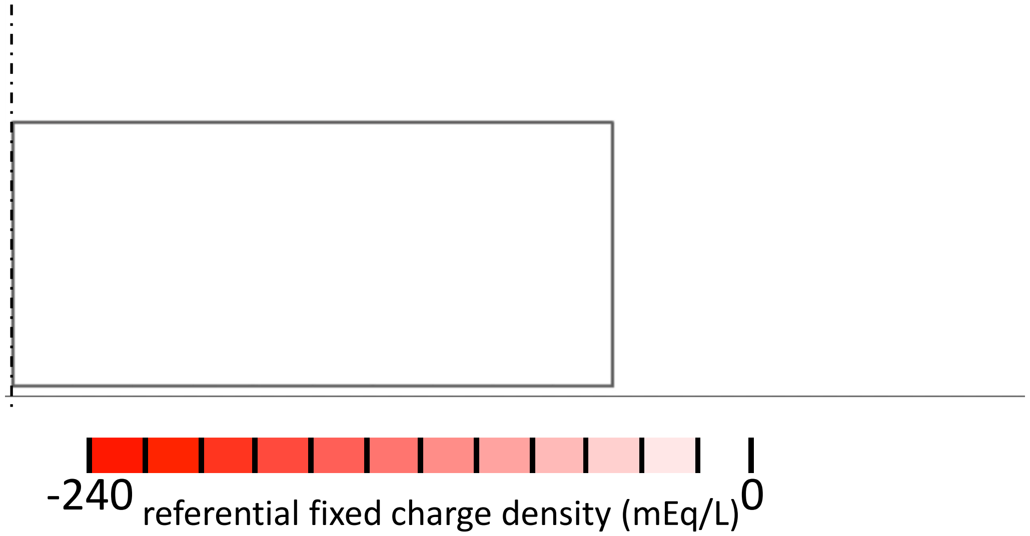
Multiphasic Theory with Reactions

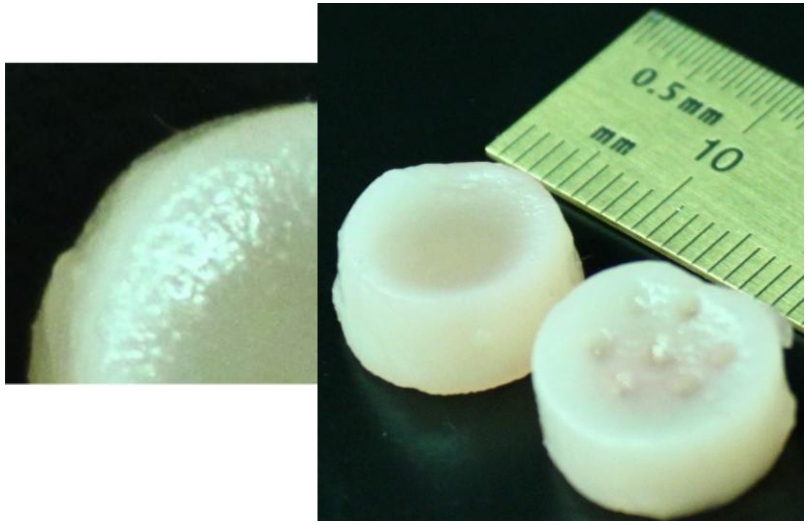
- Mixture of charged solid matrix, neutral solvent, and neutral or charged solutes (ions)
  - Triphasic theory (Lai, Hou, Mow, J. Biomech. Eng. 1991)
  - Multiphasic theory (Gu, Lai, Mow, J. Biomech. Eng. 1998)
  - Reactive mixtures (Ateshian, BMMB 2007)
- FEBio Implementations
  - Ateshian, Maas, Weiss, J. Biomech. Eng. 2013
  - Ateshian, Nims, Maas, Weiss, BMMB 2014

- Mixture momentum balance
  - $\mathrm{div}\,\boldsymbol{\sigma} = \mathbf{0}$
- Mixture mass balance
  - $\mathrm{div}(\boldsymbol{v}^s + \boldsymbol{w}) = \sum_\alpha \frac{\hat{c}^\alpha}{V^\alpha}$
  - $\hat{c}^\alpha$ =solute molar supply
  - V^α =solute molar volume
- Solute mass balance
  - $\frac{1}{J^s}\frac{D^s\left(J^s\varphi^f\tilde{\kappa}\tilde{c}^\alpha\right)}{Dt} + \mathrm{div}\,\boldsymbol{j}^\alpha = \varphi^f\,\hat{c}^\alpha$
- Reactions
  - $\sum_\alpha \nu_R^\alpha\, E^\alpha \rightarrow \sum_\alpha \nu_P^\alpha\, E^\alpha$
  - $\hat{c}^\alpha = (\nu_P^\alpha - \nu_R^\alpha)\hat{\zeta}$

Growth

- Cartilage tissue engineering (Nims et al. 2014, 2015)
    - PG synthesis, swelling and growth
    - Mixture
        - Solid
            - agarose (neo-Hookean)
            - chondroitin sulfate (CS^{2-} as SBM)
        - Fluid
            - solvent (water)
            - Glc, Na^+, Cl^-, Mg^{2+}, SO_4^{2-}
        - Reactions
            - Glucose consumption by cells for homeostasis
            - CS synthesis by cells consuming Glc and SO_4

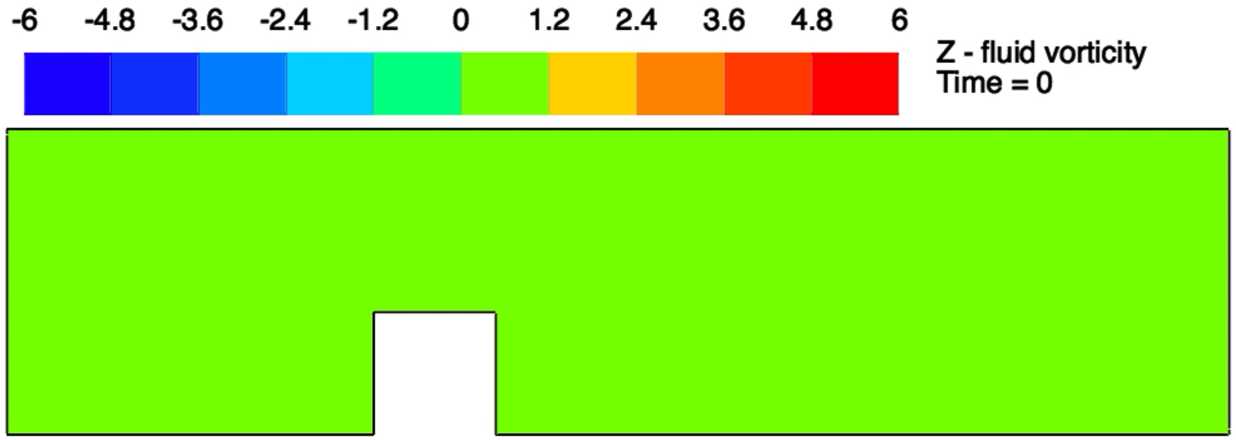




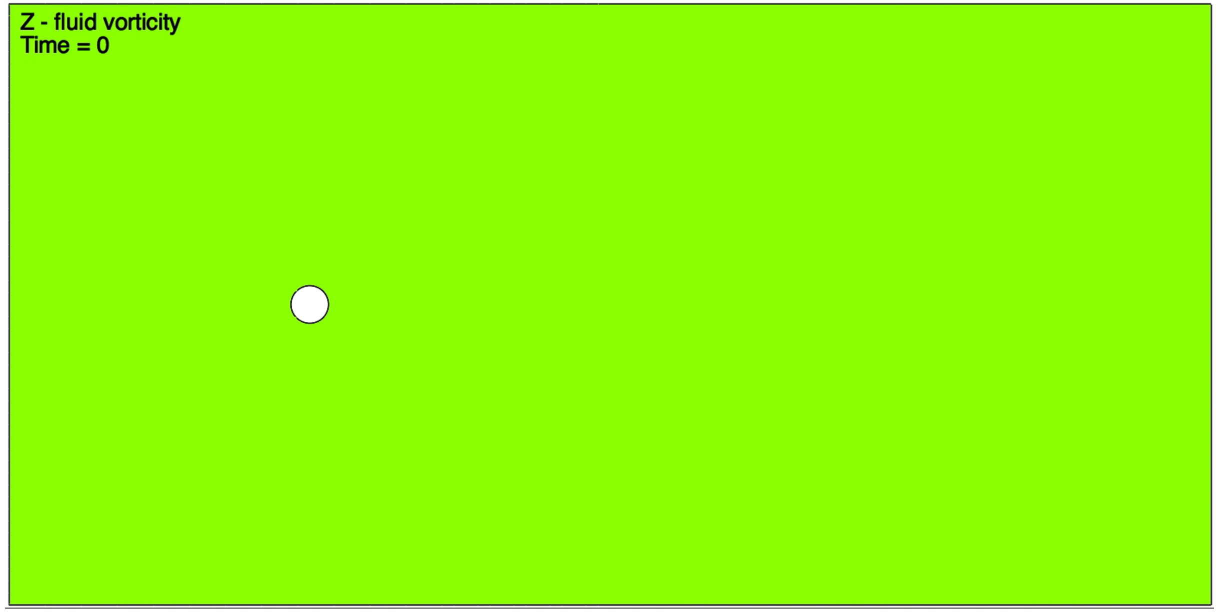
Fluid Mechanics

- Solid mechanics approach (not mixture theory)
- Momentum balance
  - $\rho^f \frac{D^f \boldsymbol{v}^f}{Dt} = -\operatorname{grad} p + \operatorname{div} \boldsymbol{\tau} + \rho \boldsymbol{b}$
  - $\boldsymbol{v}^f$ =fluid velocity, p =fluid pressure, $\boldsymbol{\tau}$ =viscous stress, $\boldsymbol{b}$ =body force
- Fluid is isothermal compressible
- Mass balance
  - $\frac{\partial \rho^f}{\partial t} + \operatorname{div}\left(\rho^f \boldsymbol{v}^f\right) = 0$
- Fluid volume ratio $J^f = \det \boldsymbol{F}^f$
  - $\boldsymbol{F}^f$ =fluid deformation gradient
  - $\dot{\boldsymbol{F}}^f = \boldsymbol{L} \cdot \boldsymbol{F}^f$ where $\boldsymbol{L} = \operatorname{grad} \boldsymbol{v}^f$
  - Solve for J^f using $\dot{J}^f = J^f \operatorname{div} \boldsymbol{v}^f$
- Constitutive relations
  - Let $p = p\left(J^f\right)$, e.g., $p = K\left(J^f - 1\right)$ where K =fluid bulk modulus
  - Let $\boldsymbol{\tau} = \boldsymbol{\tau}\left(J^f, \boldsymbol{L}\right)$
    - Model Newtonian and non-Newtonian fluids
- FEBio implementation
  - Ateshian, Shim, Maas, Weiss, J. Biomech. Eng. 2017

FEBio CFD



-6
-4.8
-3.6
-2.4
-1.2
0
1.2
2.4
3.6
4.8
6
Z - fluid vorticity
Time = 0



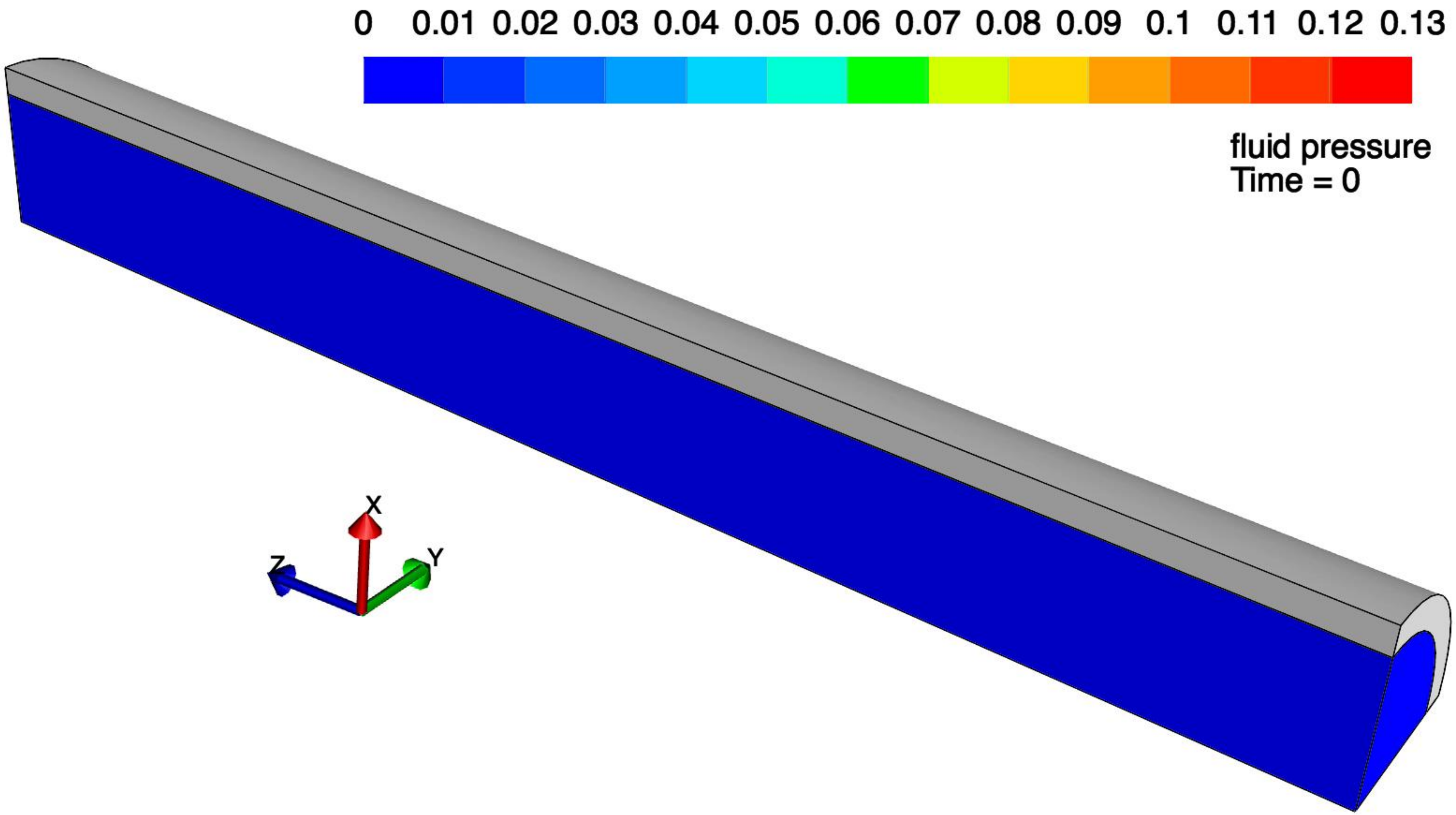
Z - fluid vorticity
Time = 0

Fluid-Structure Interactions

- Mixture approach
  - Fluid domain is a mixture of viscous fluid and specialized solid
  - Mesh is defined on solid. Solid has no mass and negligible stiffness
- Fluid momentum balance
  - $\rho^f \frac{D^f \boldsymbol{v}^f}{Dt} = -\operatorname{grad} p + \operatorname{div} \boldsymbol{\tau} + \rho \boldsymbol{b}$
- Fluid kinematic constraint
  - $\frac{D^f J^f}{Dt} = J^f \operatorname{div} \boldsymbol{v}^f$
- Solid momentum balance
  - $\operatorname{div} \boldsymbol{\sigma}^s = \mathbf{0}$
- Nodal variables
  - $\boldsymbol{w} = \boldsymbol{v}^f - \boldsymbol{v}^s, J^f, \boldsymbol{u}^s$ where $\boldsymbol{v}^s = \dot{\boldsymbol{u}}^s$
- Use material time derivative following solid mesh
  - $\frac{D^f \boldsymbol{v}^f}{Dt} = \dot{\boldsymbol{w}} + \dot{\boldsymbol{v}}^s + \left(\boldsymbol{L}^f + \boldsymbol{L}^s\right) \cdot \boldsymbol{w}$
  - $\dot{\boldsymbol{w}} = \frac{\partial \boldsymbol{w}}{\partial t} + \boldsymbol{L}^f \cdot \boldsymbol{v}^s$
  - $\dot{\boldsymbol{v}}^s = \frac{\partial \boldsymbol{v}^s}{\partial t} + \boldsymbol{L}^s \cdot \boldsymbol{v}^s$
  - $\frac{D^f J^f}{Dt} = \dot{J}^f + \operatorname{grad} J^f \cdot \boldsymbol{w}$
  - $\dot{J}^f = \frac{\partial J^f}{\partial t} + \operatorname{grad} J^f \cdot \boldsymbol{v}^s$

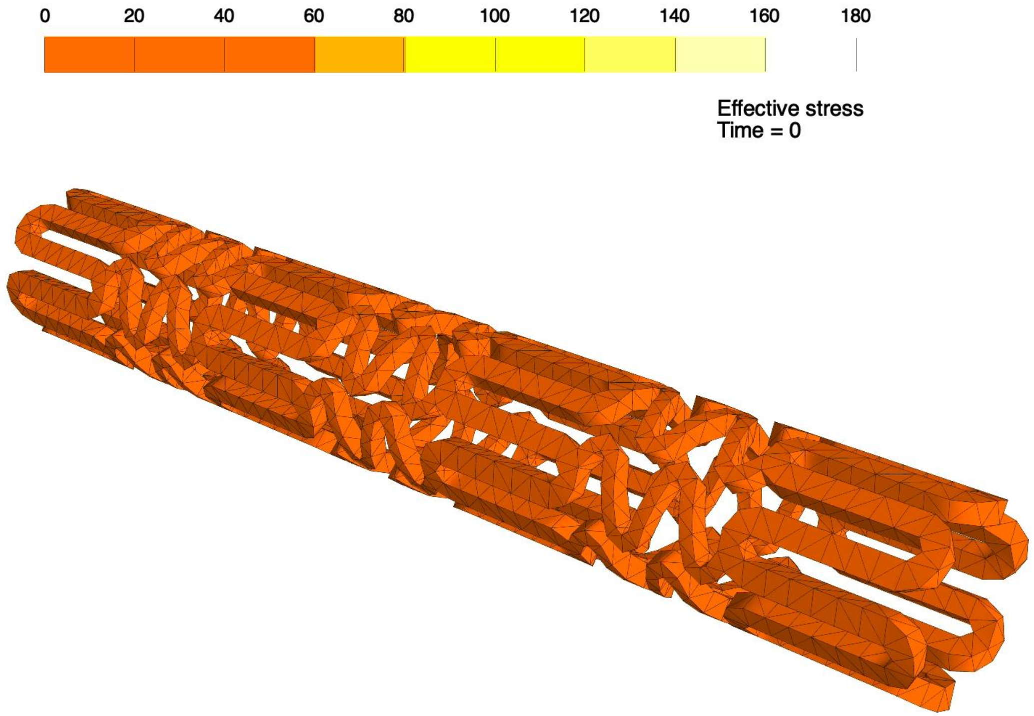
Shim, Maas, Weiss, Ateshian, J. Biomech. Eng. 2019

Fluid-Structure Interactions



Additional FEBio Mixture Models

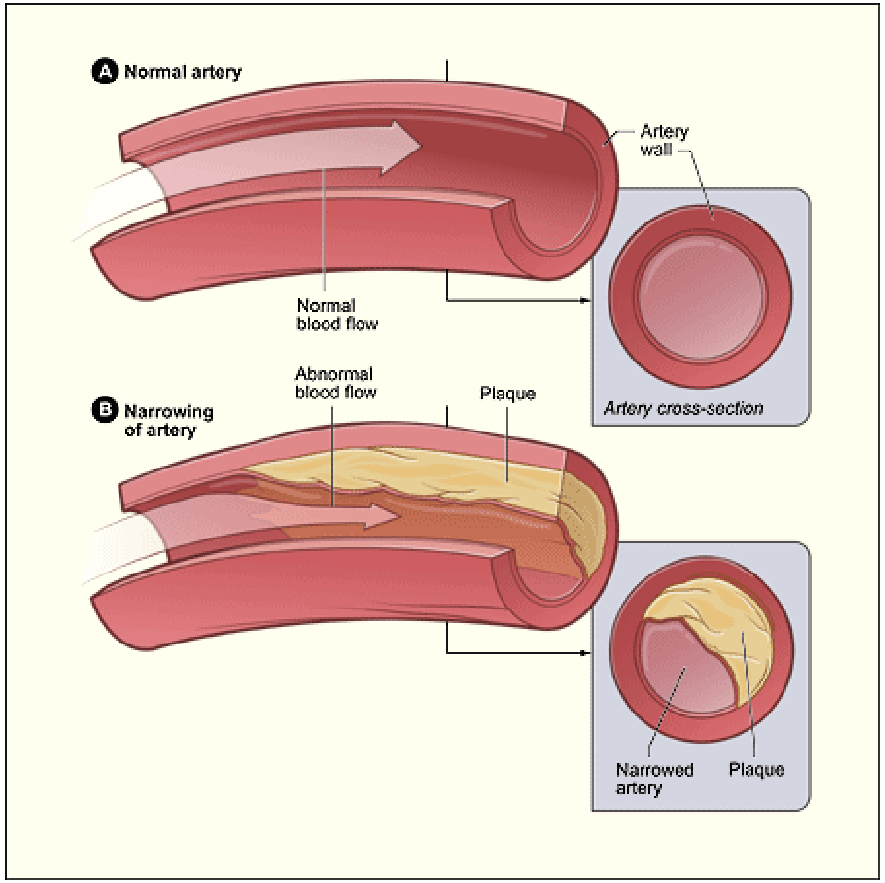
- Reactive viscoelasticity
  - Ateshian J. Biomech. 2015
- Reactive Damage
  - Nims et al. Interface Focus 2016
- Reactive Fatigue Failure
  - Zimmerman et al. WCB 2018, CMBBE 2019
- Reactive Plasticity
  - Zimmerman et al. SB3C 2019
- CFD with solutes and reactions
  - Shim et al. CMBBE 2019



Vascular stent deployment

Pulse Wave Propagation in Stenotic Arteries

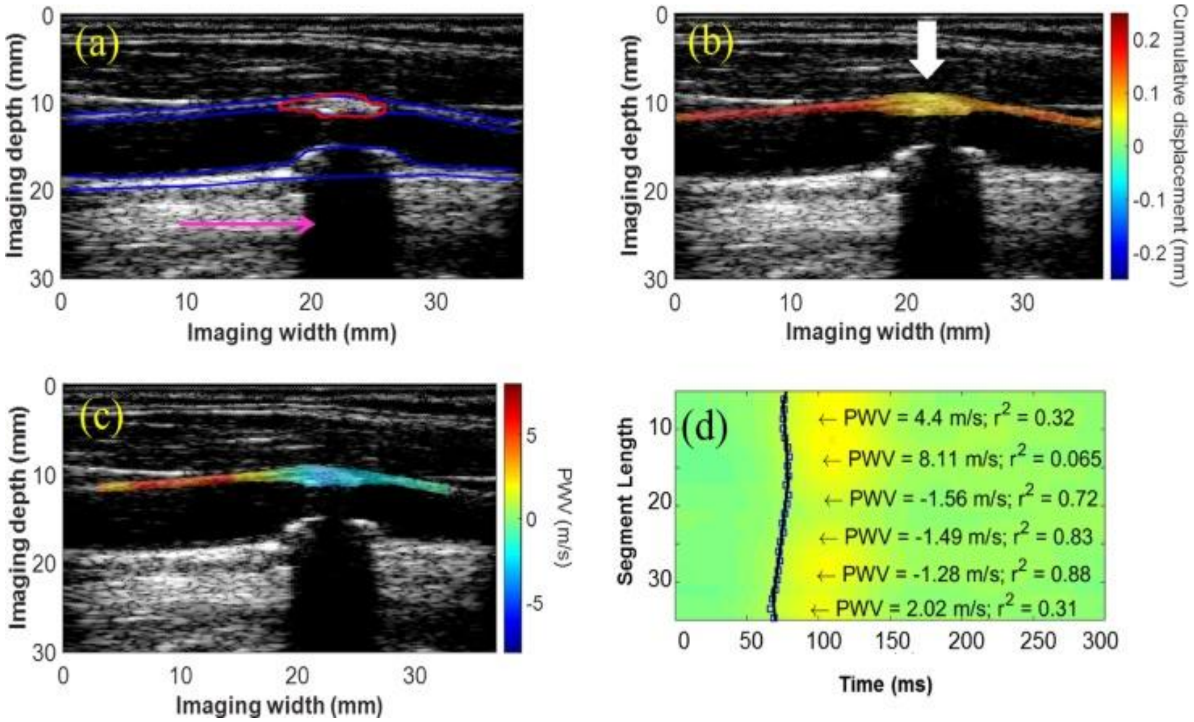
- **Atherosclerosis** is a chronic disease of the arterial wall characterized by formation of lesions and plaques
- **Rupture of vulnerable (unstable) plaques** can cause ischemic events and strokes → leading cause of death worldwide
- **Plaque characterization** is critical for diagnosis and treatment of atherosclerotic disease



Elisa E. Konofagou, Department of Biomedical Engineering, Columbia University

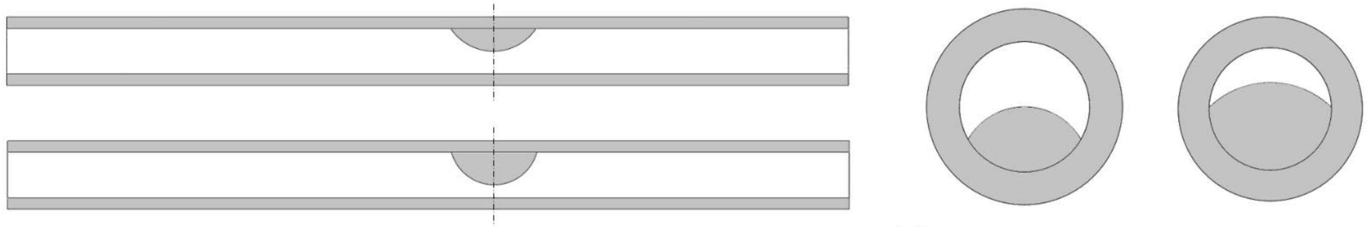
Pulse Wave Imaging for Plaque Vulnerability

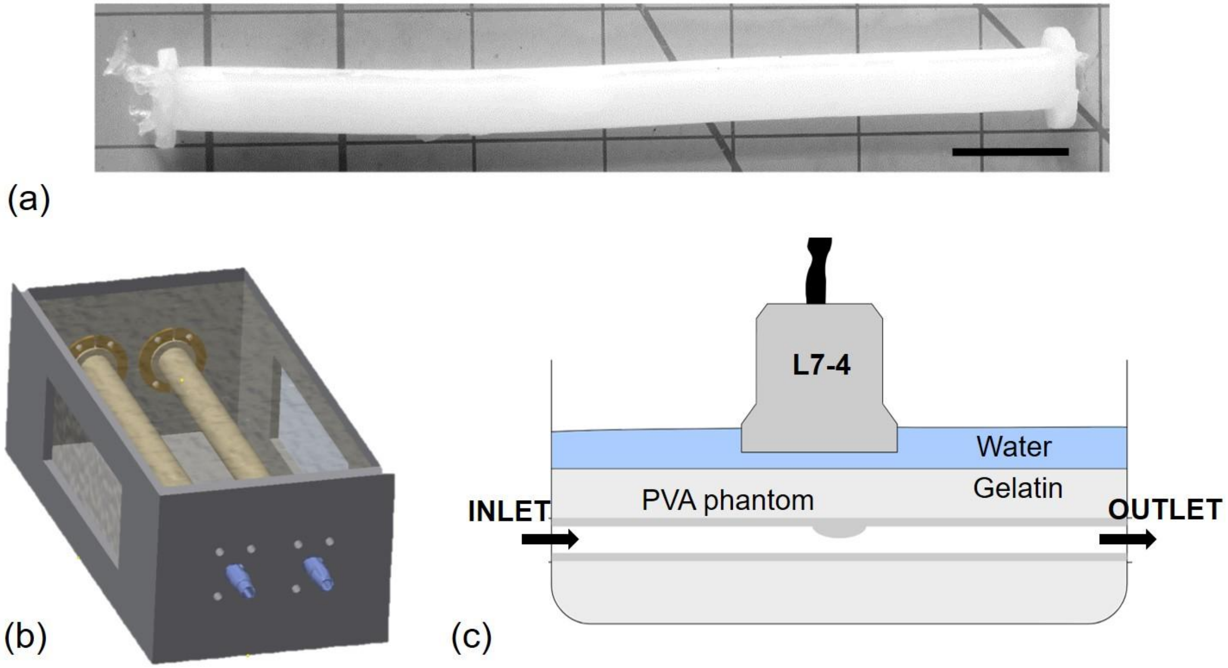
- **Pulse Wave Imaging (PWI)** is a ultrasound imaging-based technique to measure **local** pulse wave velocity (**PWV**) and **mechanical properties** of arterial walls
- **PWI + strain imaging** can help to differentiate plaques of varying stiffness, location and composition (**stable** vs **vulnerable plaques**)

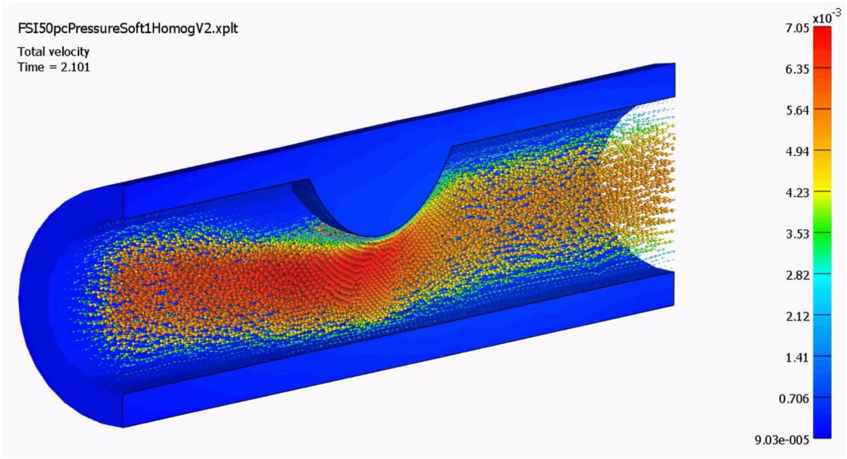


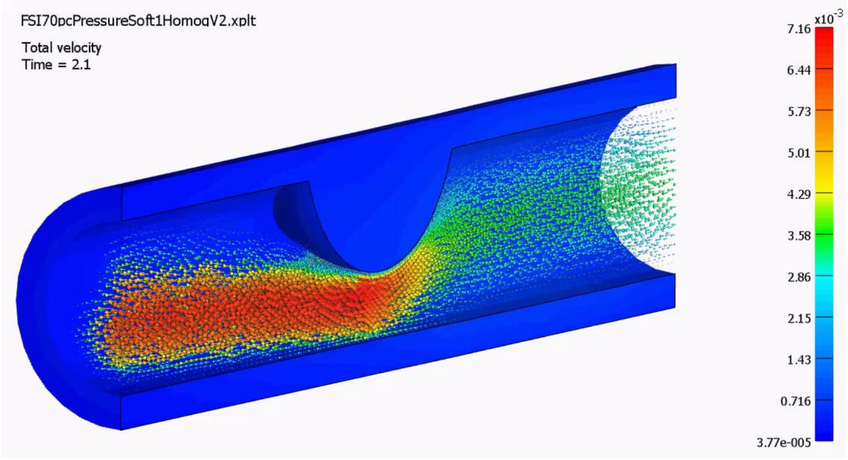
Fujikura *et al,* Ultrasonics (2007); Li et al., Ultrasound Med. Biol (2019)

Validation of Phantom with FE-FSI









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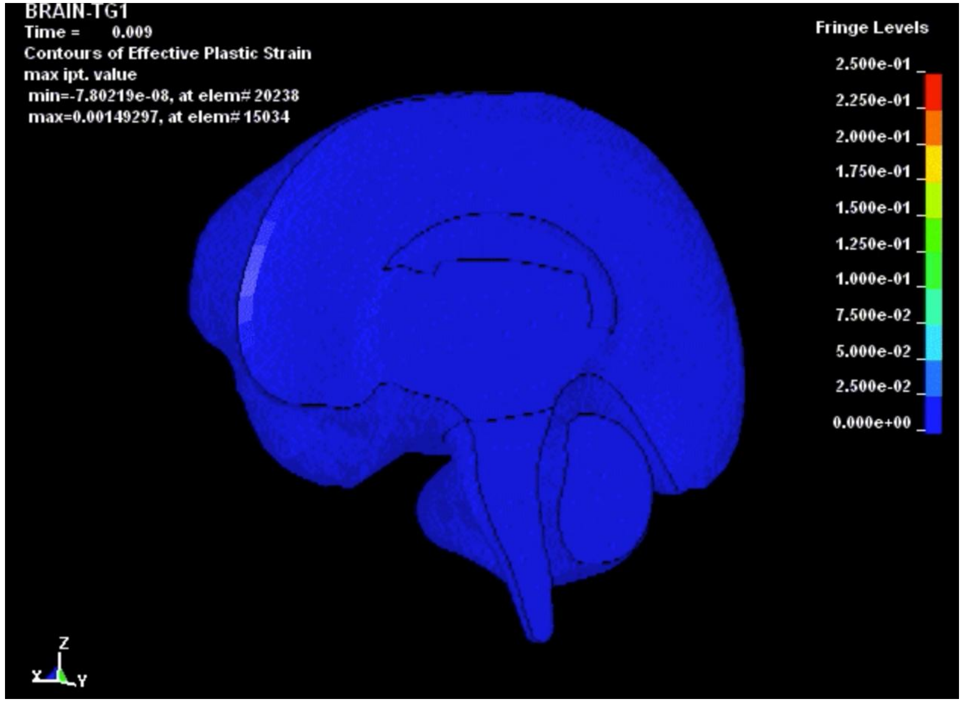
Modeling Traumatic Brain Injury Prevention

- Mechanical Event → Biological Response
  - Initiator → Primary Injury → Secondary Injury
    - Current FE models do not simulate secondary injury

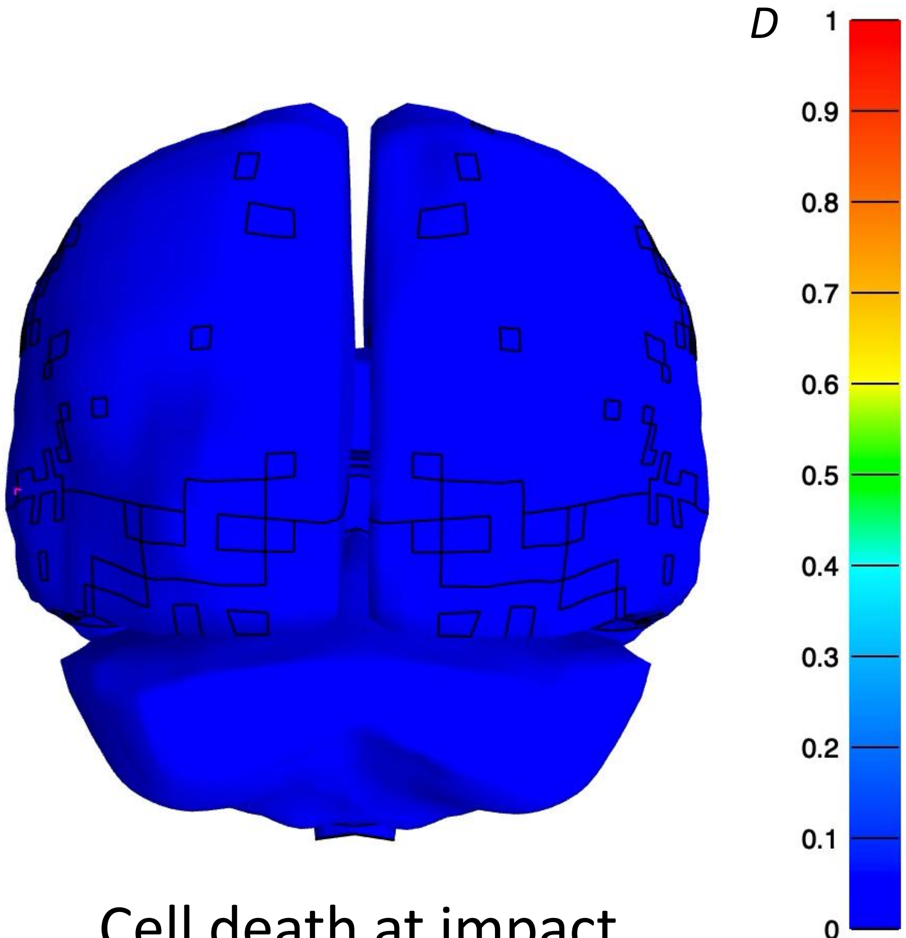


Barclay M. Morrison, Department of Biomedical Engineering, Columbia University + Honda Motor Co.

Modeling Traumatic Brain Injury Prevention

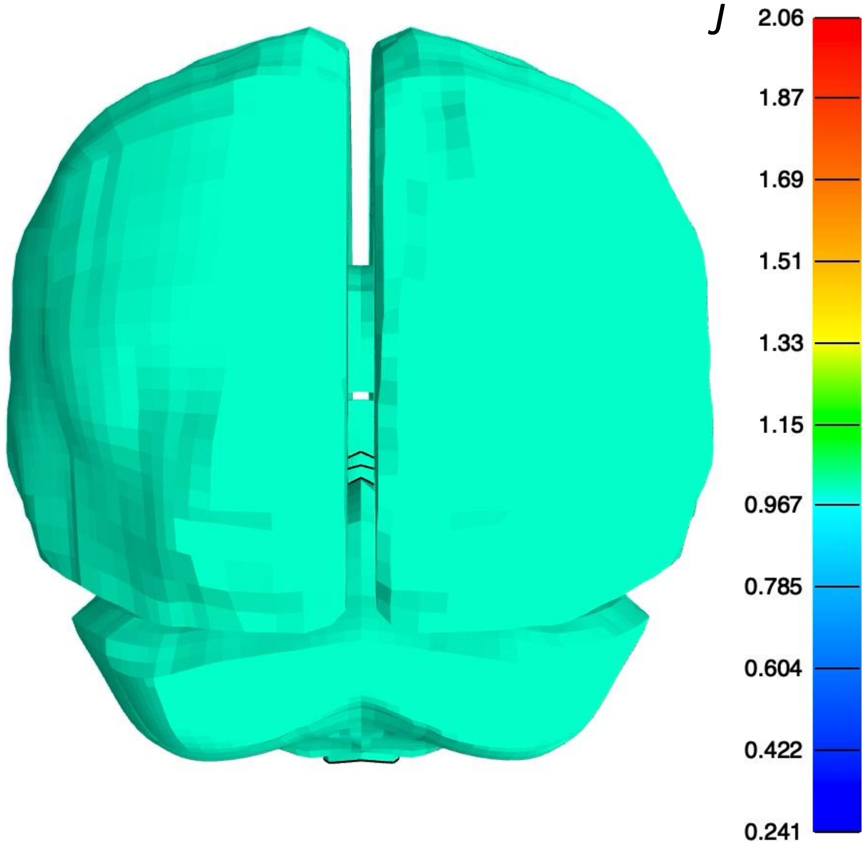
<u>Crash Injury Research (CIREN) database</u>

- fatal pedestrian lateral impact
- Impact speed: 62 km/hr



Cell death at impact

Osmotic swelling due to cell death



Volumetric strain

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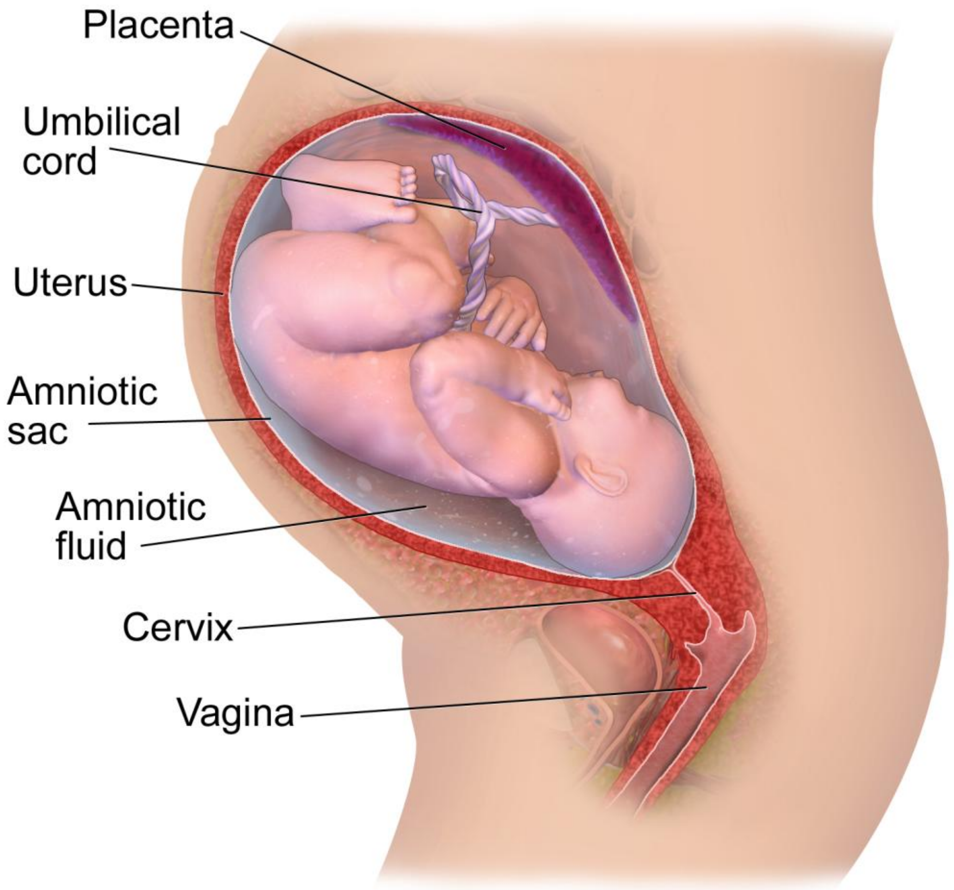
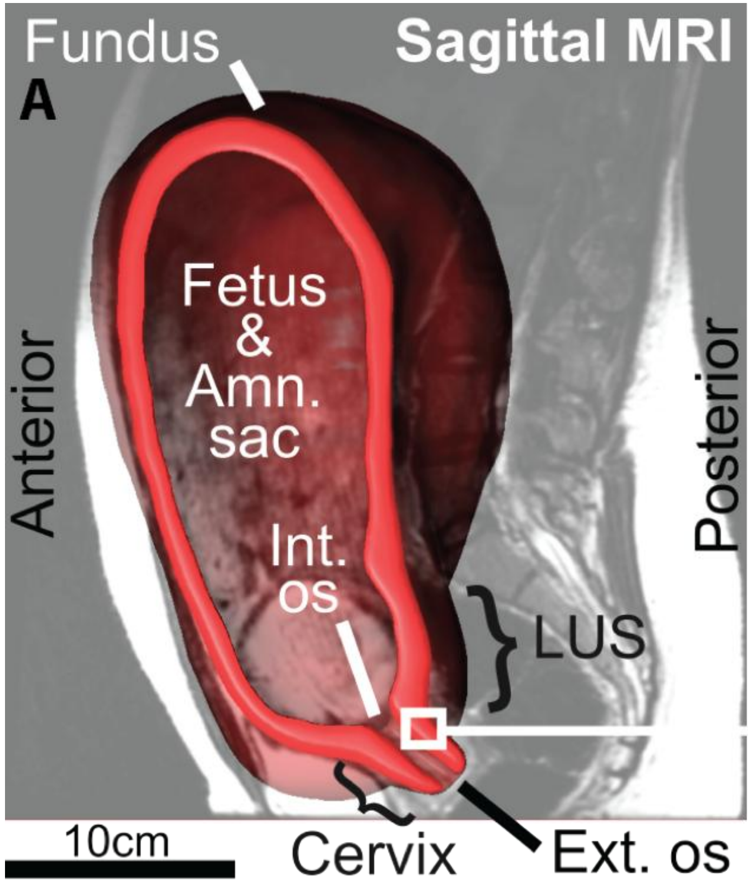
Biomechanical Simulation of Pre-Term Birth

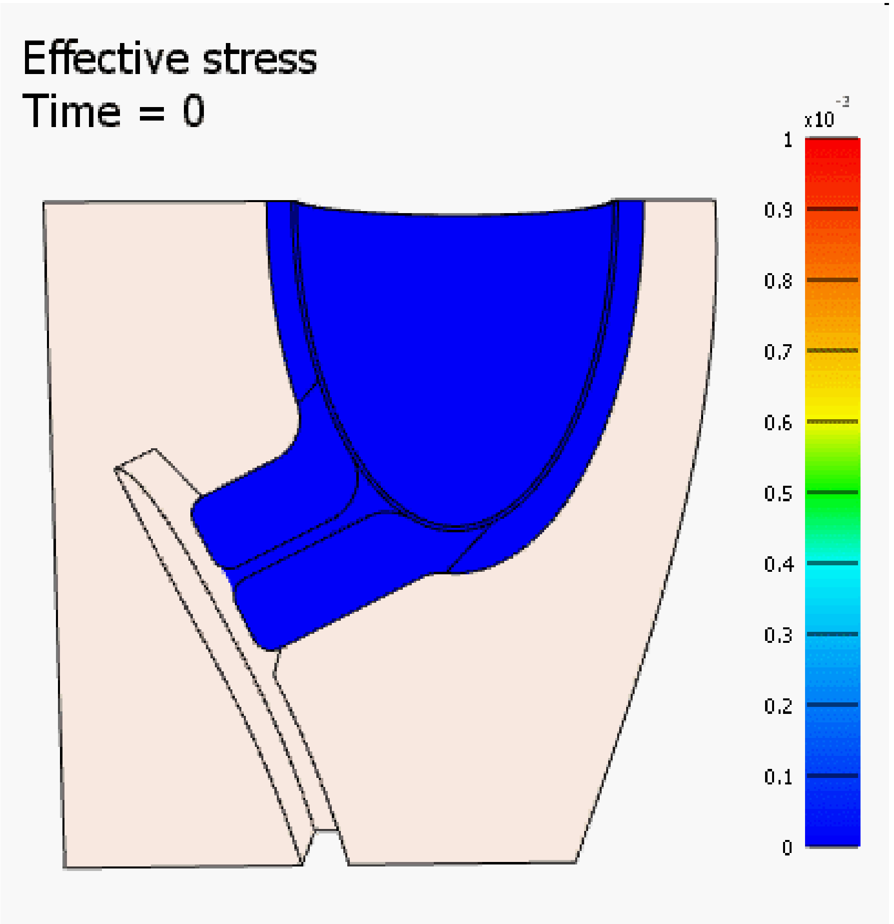


Fetal load shared by uterus, cervix, and fetal membranes

Patient-specific finite element modeling from ultrasound imaging

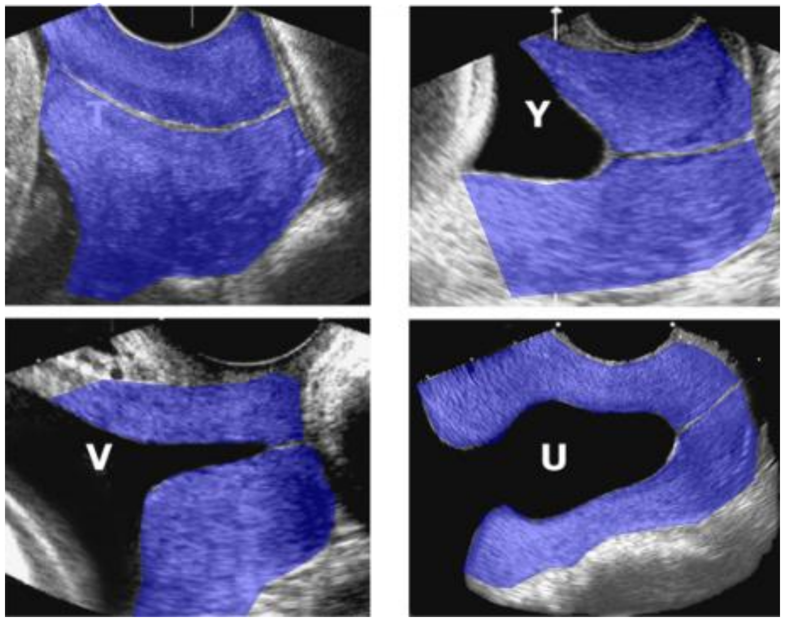


Biomechanical Simulation of Pre-Term Birth

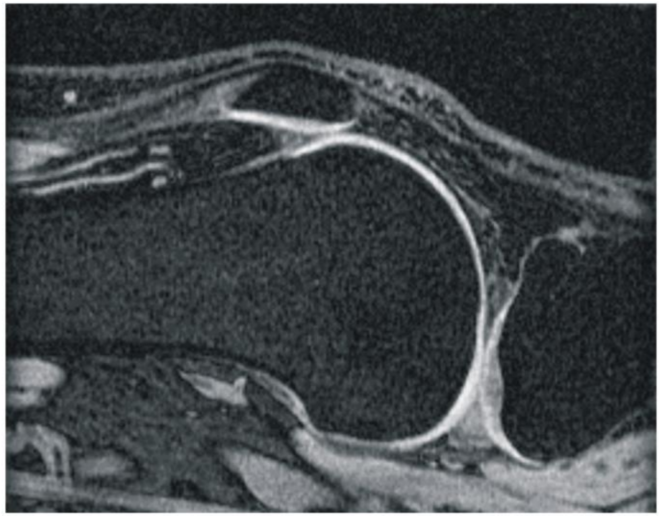


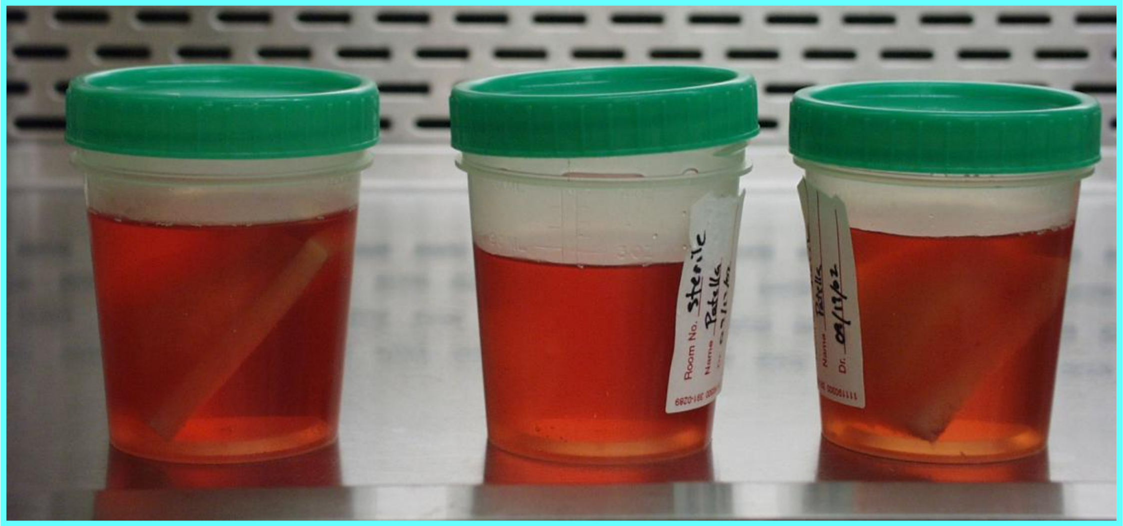
Finite element simulation of human pregnancy mid-gestation, illustrating the mechanics of clinically-observed funneling.

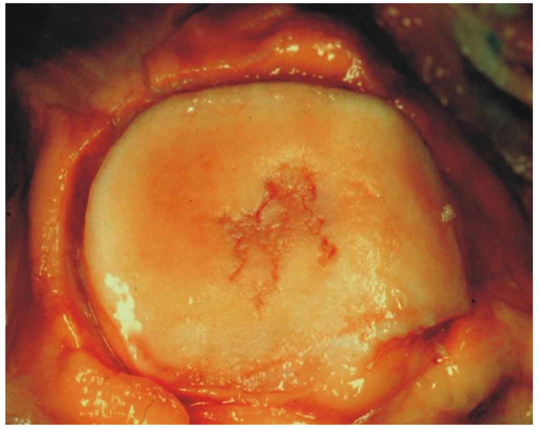
Cervical funnel shape

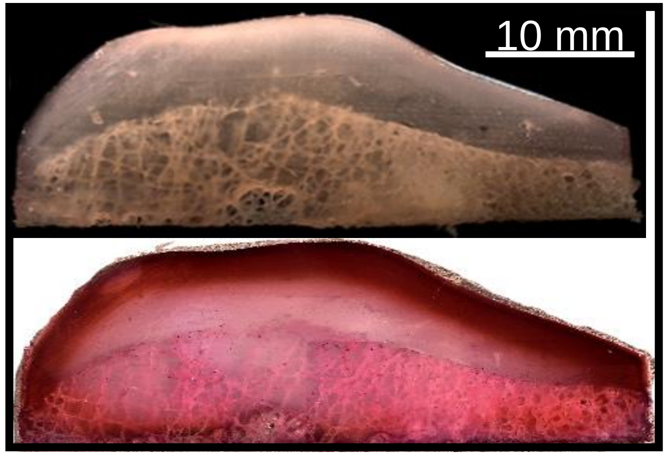


Cartilage Tissue Engineering for Osteoarthritis









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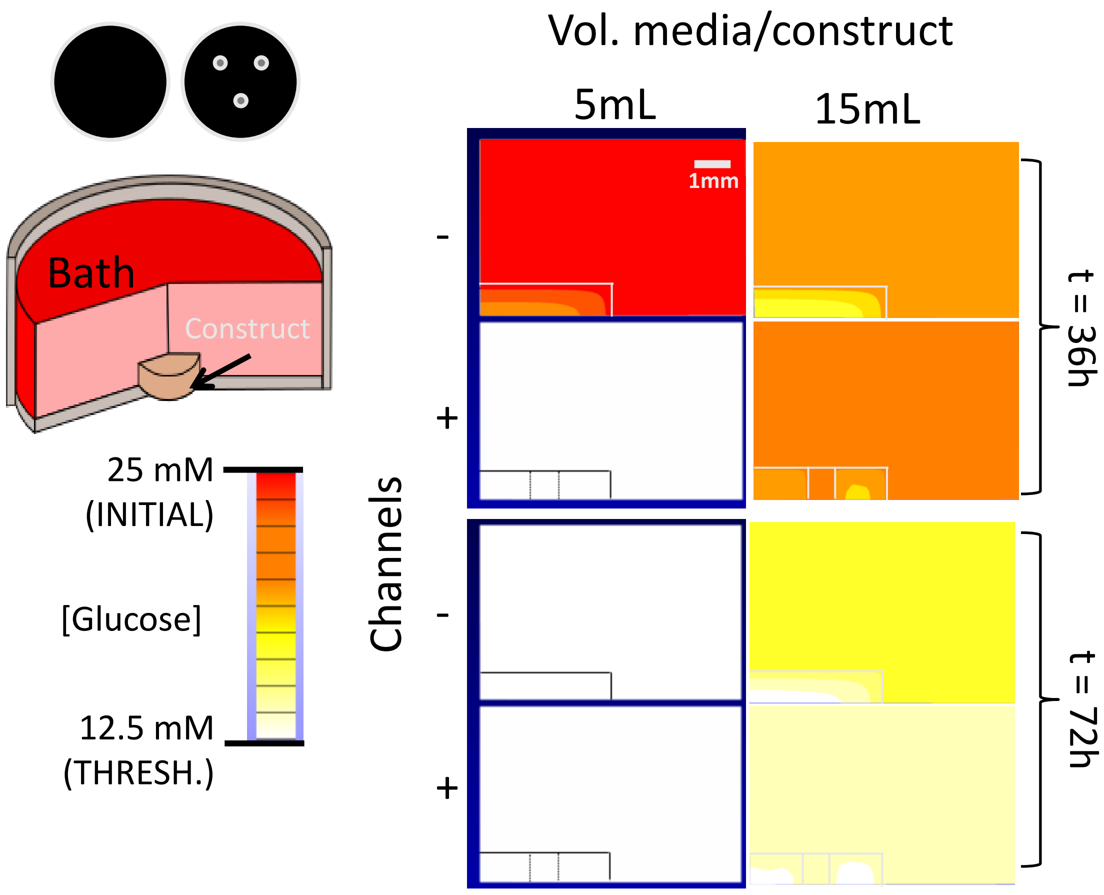
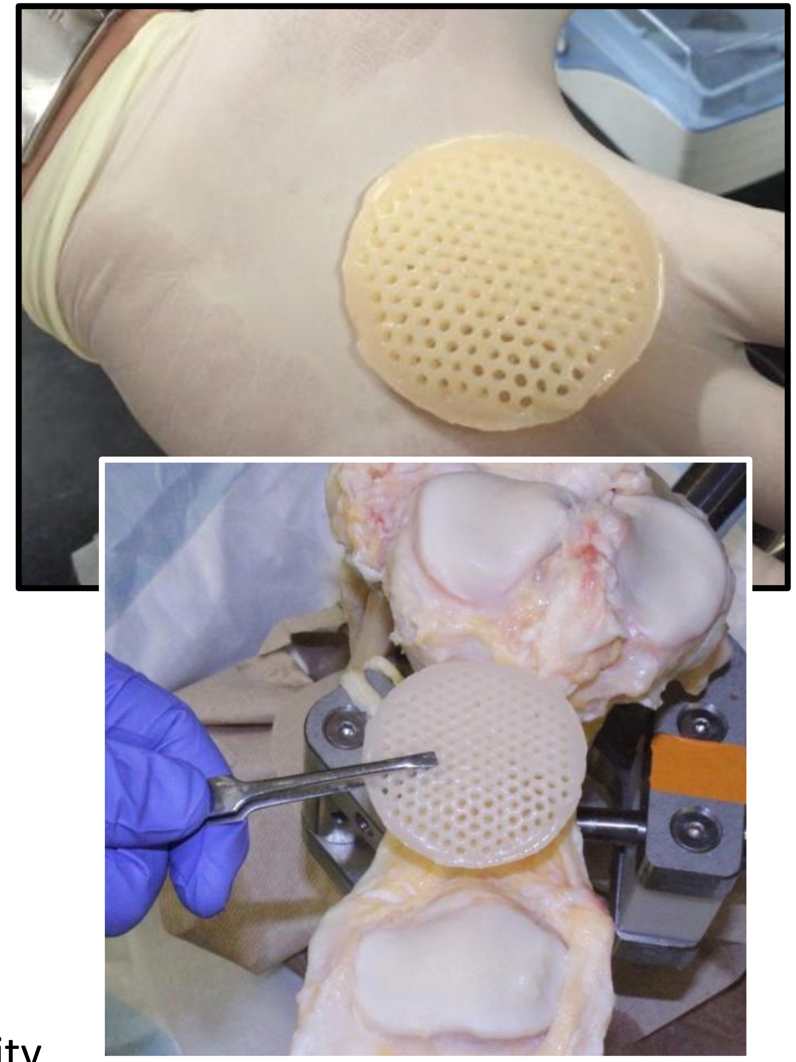
Modeling Glucose Transport & Consumption





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FEBio Resources

- The place to be for
  - Executables (Windows, Mac, Linux)
  - Documentation
  - Source code

www.febio.org

- Software forums:
  https://forums.febio.org
- Plugins:
  http://febio.org/plugins/

Twitter: @FEBioSoftware

National Institute of General Medical Sciences

NIH #R01GM083925

Github: https://github.com/febiosoftware

FEBio Software Suite