Modeling of articular cartilage growth using COMSOL

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Overview of the presentation

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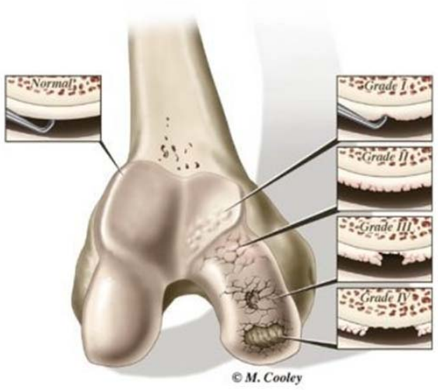
- Motivation
- Cartilage material modeling
- Biphasic implementation in COMSOL
- Cartilage growth model
- Results and conclusions
- Future work

Motivation



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- Articular cartilage is avascular load bearing tissue in the joints
- Metal implants proved as a better alternative: Animal and FE models
- The cartilage seen growing onto the implant
  - We believe that the growth is mechanically stimulated around implant
- Analytical modeling of biological growth is challenging
- Direct clinical impact

Cartilage structure

- Articular cartilage: anisotropic, multiphasic, nonlinear time dependent
- Biphasic→ Incompressible Fluid + Solid
- Volume fraction, $\phi_i = \frac{dV_i}{dV}, i = s, f,$

  $\phi_s + \phi_f = 1$
- Total stress, $\sigma^{tot} = \sigma^{fluid} + \sigma^{solid}$
- Continuity: $\nabla \cdot \overrightarrow{v_s} - \nabla \cdot (k \nabla p) = 0$

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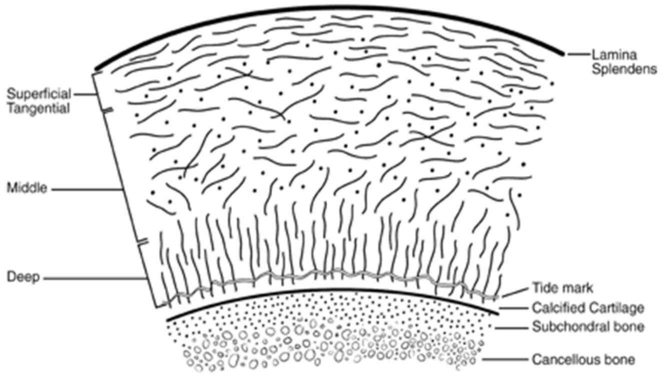

Fig.: Collagen orientation in cartilage

Human knee geometry

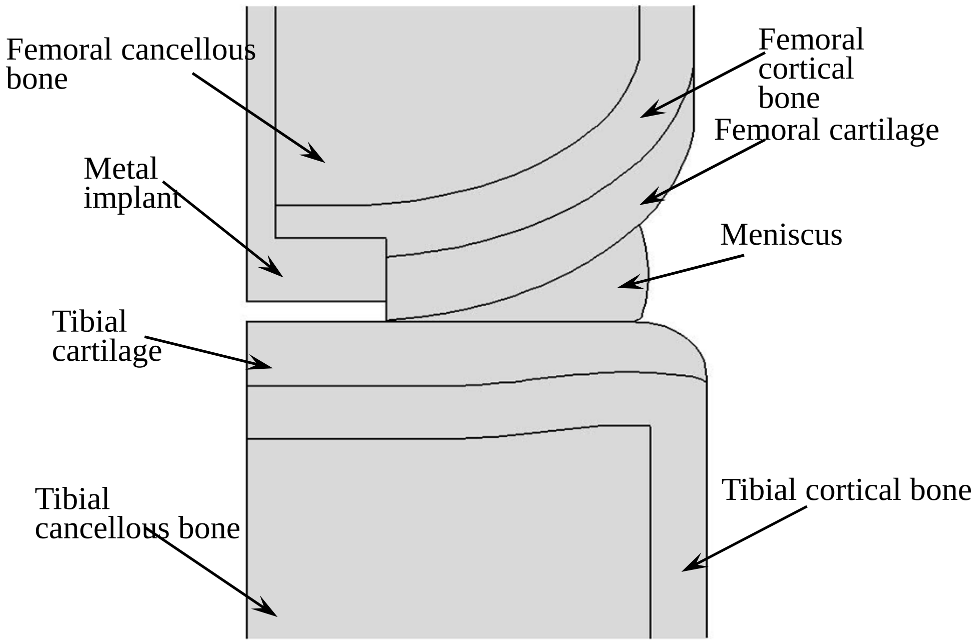

Fig: Axisymmetric representation of human knee condyle, adopted and modified from Wilson at al., 2005

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- Geometry modified to include implant of 10mm size
- Isotropic cartilage, transversely isotropic meniscus, elastic bones

Biphasic implementation in COMSOL

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- Biphasic equivalent to Poroelastic
- Solid matrix-stress equilibrium equation
- $\nabla.\sigma^{tot} = 0, \sigma^{solid} = -\emptyset^{s} pI + C\epsilon, \sigma^{fluid} = -\emptyset^{f} pI$
- Continuity-Darcy's law
  - $\rho_f S \frac{\partial p}{\partial t} + \nabla.\left[-\frac{k}{\mu}(\nabla p + \rho_f g \nabla D)\right] = -\rho_f \alpha_B \frac{\partial \epsilon_{vol}}{\partial t}$
- Boundary conditions
  - In $\partial_t \beta$: $\sigma^T . n = \bar{t}$, In $\partial_u \beta : u = \bar{u}$
- $u - p$ formulation

Biphasic implementation in COMSOL

- Porosity and permeability are strain dependent
  - $\epsilon_p = \frac{\epsilon_{p0}+e_{vol}}{1+e_{vol}}$,
  - $k = k_0 \left(\frac{1+e}{1+e_0}\right)^M$, $e = \frac{\phi_f}{\phi_s}$

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- The structural respective contact have been defined
- Fluid is free to flow on non-contacting surfaces
- Axial ramp compressive disp. applied on femoral top, tibial bottom plane is fixed
- Growth is introduced by thermal growth over time

Cartilage growth-Fe model

- Two constituents of solid matrix (PG's and collagen) are individually growing
- Growing elastic materials theory

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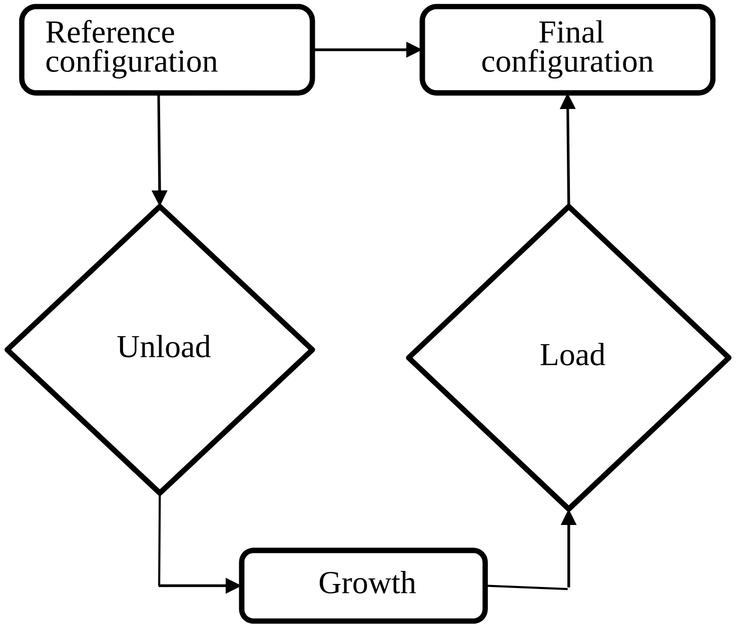

Fig: Flow chart for growth during on cycle

Results and conclusions

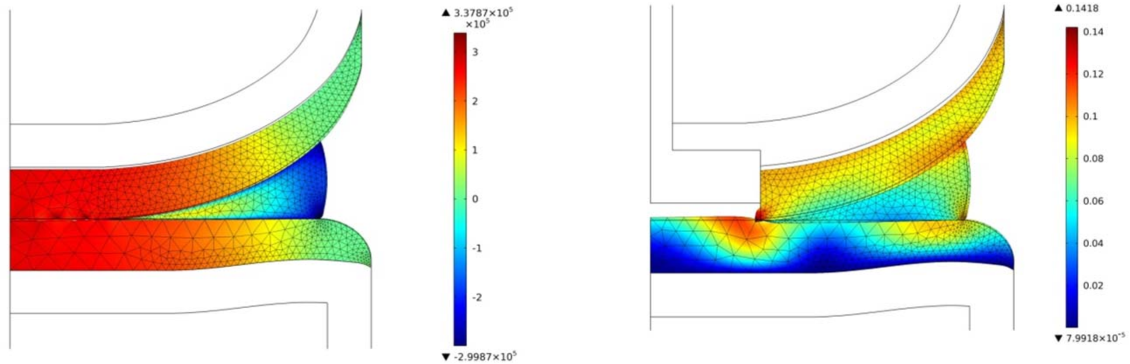

Fig: Total pressure in a model without implant (left), displacement in model with implant (right), at 1 sec

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- Model without implant is validated with literature
- Cartilage growing onto the implant, mechanical loading also contributes to it
- Thermal growth was uniform.
- Results are not so clinically relevant, as growth happens based on the stress level

Future work

- Dynamic mechanical loading during day and growth during night, for one year period
- Time scales for growth and mech loading are very different
- Aggressive constitutive relations of growth of constituents in solid matrix: Model becomes TRIPHASIC
- Investigate how mechanical loading affects growth, and implant size and depth on the growth
- Model will be validated with the available images from animal experiments

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