Modeling fiber anisotropy in multiscale musculoskeletal soft tissues

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Introduction

Anatomical modeling

Static evaluation:
geometry, volumes, ...


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Introduction

Anatomical modeling → Static evaluation: geometry, volumes, ...

Tissue structure modeling → Mechanical response: elasticity, anisotropy, ....

Physical simulations → Dynamic evaluation: deformation, articulation, ...
Introduction

- Fiber architecture important determinant for function:

**Muscles:**
- force and moment generating capacity

**Connective tissue:**
- tensile strength
- weight bearing
- joint stability

\[
\mathbf{F} \times \mathbf{r} = \frac{\partial l}{\partial \theta}(t)
\]

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Motivation

• Medical images provide geometry for anatomical models:

• How to incorporate internal fiber structure?

http://people.fmarion.edu/tbarbeau
Motivation

- Measurement anatomical fiber arrangements
  
  **Cadaver dissection**
  - Expensive, invasive
  - usually not 3D
  - Sparse measurements
  - Translation to subject-specific models?
    
    
    
    
  
  **Ultrasound**
  - Mostly planar measurements
  - limited scan depth
    
    [HCK11]
  
  **DT-MRI**
  - Noisy data
  - Fiber tracing not robust
  - Only works for muscles
    
    [BLD07]
  
    [KBK10]
Motivation

- Medical images provide geometry for anatomical models:
- How to incorporate internal fiber structure?

Computational approaches to generate plausible representations

http://people.fmarion.edu/tbarbeau
Related work

- Variety of computational methods proposed

Muscles:
- Action lines
- Template warping

Ligaments/menisci:
- Centerline + diffusion gradient
- Hexahedral mesh

References:


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Related work

- Multitude of methods not practical for medical applications

Research question

- Multitude of methods not practical for medical applications
- Common approach possible?
  - Fiber architecture is similar across tissues:
    - Ordering in bundles running between attachments

Muscles

Ligament, tendon

(www.rheumatologynetwork.com)

Meniscus

(en.wikipedia.org)

(ubcmedicalart.wordpress.com)
Laplacian Method

- Generation fiber orientations based on physical properties:

\[ \nabla \cdot \vec{v} = 0 \]
\[ \nabla \times \vec{v} = 0 \]

Laplacian Method

Finite Element (FE) solver

Laplace equation
\[ \Delta \cdot \phi = 0 \]

Finite Volume (FV) solver

\[ \hat{v} = - \sum_i f_i / nV \]

\[ t_i = -x_i / \hat{v}_i \]

Stress and strain

FE simulations of deformation

Not robust

Robust

trajectory tracing

Application in muscles

\[ \Delta \phi = 0 \]

Application in muscles

• Extended approach:
  – muscles with internal tendon

\[ \Delta \cdot \phi = 0 \]

- Awkward surface geometry
- Difficult to mesh

\[ \Delta \cdot \phi = f \]

- Modify equation to indicate tendon with source term
- Difficult meshing avoided
Application in connective tissues

Meniscus: Multiple fibers

Apply in different directions:

Δ · φ = 0

Simulations of knee displacement

Anterior Cruciate Ligament

Lateral Collateral Ligament

Lateral meniscus

Experiments

With fibers

Isotropic
Application in connective tissues

Comparison with OpenKnee model:

OpenKnee  Laplacian

\[ \mathbf{f}_1 \leftrightarrow \mathbf{f}_2 \]

\[ \cos(\mathbf{f}_1 \cdot \mathbf{f}_2) \]

Conclusions

- A Laplacian based approach provides a feasible collective methodological basis for multiscale tissues
  
  - Advantages:
    - Equation based = reproducible
    - Templates, parameter tuning avoided
    - Fast linear solvers available
    - Independent of mesh topology
    - Multiple attachments
  
  - Limitations:
    - Dependency on boundary conditions

Further validations needed when experimental data are more available
Conclusions

• Impact on computer assisted intervention applications:
  – Simulations of mechanical behavior soft tissue
    • Incorporating fiber anisotropy needed for accurate simulation
  – A collective method for fiber modeling provides a practical strategy for implementation with broad range of usability.
  – Important applications:
    • Predictive deformation modeling for surgical planning
    • Simulations for surgical training in arthroscopy (still isotropic tissues in simulators)

Thank you for your attention

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• multiscalehuman.miralab.ch