April 24, 2017
Lecture 26
Tissue biomechanics: cartilage

BIOE/ME 481: Whole body
musculoskeletal biomechanics
Cartilage

http://www.amwaw.edu.pl/~joan/scalch/scalchA/35.htm
http://www.coe.drexel.edu/ret/nano.html
http://www.raphaelmosseri.com/mi_genou_uk.html
Articular cartilage is thin coating on articulating ends of bones.

The composition and configuration is depth dependant ➔ 3 Major layers.
What is anisotropy?

Material strength = \( f(\text{material structure/architecture among other things}) \)
Levels of anisotropy

Materials strength variation = \( f(\text{material structure/architecture}) \)
Cartilage by weight

- Superficial Tangential (10-20%)
- Middle (40-60%) (transitional)
- Deep (30%)
- Radial

Zones:
- Articular Surface
- Tidemark
- Subchondral Bone
- Cancellous Bone

Calcified Cartilage
Cartilage Structure

From Mow et al. 2002

From Wilson et al. 2004

From Glaser 2005
Articular cartilage: chondrocyte distribution

Superficial tangential zone

Histological section
+ Split line pattern

- Lines follow directions of normal joint movement
- Collagen alignment with the split lines
Solid component: collagen + PGs

Proteoglycan (PG) macromolecules:
Composed of aggrecans bound to a hyaluronic acid chain by link proteins

From Mow et al. 2002
What component(s) of a tissue is(are) NOT present in articular cartilage?

How do the chondrocytes get nourished?
General mechanical behavior of articular cartilage
Cartilage exhibits **viscoelastic** behavior under compression:
Cartilage exhibits **viscoelastic** behavior under compression:

This figure is an example of what? Creep
Permeability

![Graph showing the relationship between permeability and strain. The permeability decreases as the strain increases, with different curves indicating varying levels of increasing ΔP.](image)
Cartilage exhibits **anisotropic** and **nonlinear** behavior under tension.
Cartilage is slippery!

Coefficients of friction for articular cartilage in synovial joints

<table>
<thead>
<tr>
<th>joint</th>
<th>coefficient</th>
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</thead>
<tbody>
<tr>
<td>human knee</td>
<td>0.005-0.02</td>
</tr>
<tr>
<td>porcine shoulder</td>
<td>0.02-0.35</td>
</tr>
<tr>
<td>canine hock</td>
<td>0.005-0.01</td>
</tr>
<tr>
<td>human hip</td>
<td>0.01-0.04</td>
</tr>
<tr>
<td>bovine shoulder</td>
<td>0.002-0.03</td>
</tr>
</tbody>
</table>

Steel on steel: 0.6
PTFE (e.g., Teflon) on steel: 0.04-0.2
Ice on ice at 0°C: 0.1
UHMWPE on cobalt chrome (artificial joints): 0.01-0.05
Cartilage properties

Achilles E: 0.67-1.07 GPa

Knee ligament E: 0.13-0.18 GPa

Cartilage E: 0.007-0.015 GPa

Failure > 20% strain

Ligaments ~ 60%

Tendon ~ 4-10%
PreOp® Patient Education Arthroscopic Meniscus Repair, Knee (animation)
http://www.youtube.com/watch?v=HocWnJlhKT4&feature=fvw

Arthroscopic Articular Cartilage Replacement (slide show of actual arthroscopic procedure; no blood)
http://www.youtube.com/watch?v=UC9k1MHlqpE

Articular Cartilage Paste Graft (Regeneration) Surgical Technique (note: actual surgery, minor blood)
http://www.youtube.com/watch?v=IlkwoPbCOwU
Cartilage models

Conclusion of Previous Models

- Experimental data driving all of the cartilage models are uniaxial compression tests.
- Most models are based on slow loading not representative of physiological loading.
- All models included in full joints do not include strain rate dependency.
- Most cartilage models have not been validated in full joints.
The anisotropy will be modelled by a collagen fibril reinforced composite.

Orientation and size of the fibres will correlate directly to the physiological properties of the collagen fibril network.
What are the stiffnesses of the matrix and the collagen fibres?

These will be non-linear functions of strain and strain rate
- For example in Wilson et al. 2004:

The parameters in these functions will be optimized to fit the experimental data.
5. Compression Rig Design and Experiments

- Stepper Motors
- Linear Actuator
- LVDT
- End Effector (Loading Platten)
- Load Cell
- Torque Cell
- Linear Guides
- Specimen Holder Container
- Inverted Microscope
5. Compression Rig Design and Experiments
Cartilage testing

- Compression, imaged to evaluate strain in multiple dimensions
Knee osteoarthritis

- Lateral part of patella often affected by knee osteoarthritis

Total arthritis costs in Australia in 2000

$A9 billion

(Arthritis Foundation of Australia 2001)
Can this stress pattern be changed with medial vasti strength training?
8 subjects with PFJOA
  - Diagnosed with radiographs

Stair rise task

Lower limb MRI

Kersh et al: Effect of increasing medial vasti
Finite element model

- Bone and cartilage geometry from MR
- Muscle initial vector from MR
- Muscle magnitude from musculoskeletal model
- Tibio-femoral kinematics from fluoroscopy
- Patella initial position from fluoroscopy then left free to move
Virtual physiotherapy

- Cartilage
  - Hyperelastic material

- Increase vastus medialis force by 15%

- Evaluate contact stress at contralateral toe-off

Kersh et al: Effect of increasing medial vasti
Line of action of muscle

- Muscle vector line of action
- Local vs global vectors
  - Is the model sensitive to this?

Kersh et al: Effect of increasing media vasti

**Results: new muscle vector**

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>115% VM</th>
</tr>
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<tbody>
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<td><strong>Original vector</strong></td>
<td><img src="Baseline_original_vector.png" alt="Image" /></td>
<td><img src="Baseline_115%VM_vector.png" alt="Image" /></td>
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<tr>
<td><strong>New vector</strong></td>
<td><img src="New_vector_original.png" alt="Image" /></td>
<td><img src="New_vector_115%VM.png" alt="Image" /></td>
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Kersh et al: Effect of increasing medial vasti