OBJECTIVE
Investigate how cross-sectional area (CSA) variations affect the porcine posterior cruciate ligament (PCL) apparent properties using linear and non-linear functions.

Specific Aims:
- Utilizing finite element analysis (FEA) to obtain force-displacement curves that can be compared to the experimental porcine PCL force-displacement curve

INTRODUCTION
Clinical Importance:
- PCL rupture occurs in 5-20% of all acute ligament knee injuries
- PCL reconstruction is a procedure performed to restore knee stability after ligament rupture
- Procedure requires knowledge of mechanical properties to optimize patient outcomes

Background:
- The CSA of the PCL varies along its length
- It is not clear how regional variations of the CSA contributes to the assessment of ligament properties
- Which CSA should be used to calculate stress?

METHODS
Computational Model Setup
- Magnetic Resonance Imaging (MRI): 3-Tesla Siemens Trio Scanner (voxel size: 0.47x0.47x0.003 mm)
- Femur, PCL, and Tibia were segmented and smoothed in Geomagic Design X (3D Systems)

Elasto and neo-Hookean hyperelastic models were performed in Abaqus (DS Simulia)

Biomechanical Testing:
- Setup: Femur-PCL-Tibia construct mounted into a materials test machine
- Loading: Specimens elastically loaded to 100 N at 50 mm/min
- Motion capture camera tracks displacement

RESULTS
Table 1: PCL Material Properties

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Proximal</th>
<th>Middle</th>
<th>Distal</th>
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<tr>
<td>E</td>
<td>106.58</td>
<td>83.58</td>
<td>100.34</td>
<td>103.08</td>
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<tr>
<td>C10</td>
<td>10.48</td>
<td>8.22</td>
<td>9.87</td>
<td>10.23</td>
</tr>
</tbody>
</table>

Figure 1: A) Posterior view of dissected porcine knee, B) Experimental testing setup, C) Abaqus assembly of femur-PCL-tibia

Figure 2: A) Sagittal view of porcine knee MRI, B) Segmented PCL with proximal, middle, and distal CSA labeled, C) Abaqus assembly of femur-PCL-tibia

Figure 3: A) Experimental stress-strain curve for determining elastic modulus, B) Curves for determining material constant, C10, for neo-Hookean hyperelastic model

Data Analysis
- Four different stress-strain curves based on the average, proximal, middle, and distal CSA
- Linear Model
  - Fit the slope of the linear region of the stress strain curve to find the elastic moduli, E_avg, E_prox, E_mid and E_dist
  - Use the following equation fit to a linear model
    \[ E = 2(\lambda + \mu)C_{10} \]

Neo-Hookean Hyperelastic Model
- Determine C10_avg, C10_prox, C10_mid, C10_dist

Figure 4: Percentage error of computational model force-displacement curves from experimental curves for points up to 0.5 mm and from 0.5 to 1 mm. A) Linear model and B) Neo-Hookean model

Findings
- Neither the linear or non-linear model closely approximates the non-linearity of the experimental force-displacement curves
- Neo-Hookean model matches the experimental curve (10-20% error) up to 0.5 mm of displacement

CONCLUSIONS
- Ligaments are highly heterogeneous and geometrically complex making them difficult to model accurately
- The linear model is unable to approximate the non-linear behavior of crimped collagen fibers straightening in the toe region
- Neo-Hookean model only accurately approximates toe region

Next steps
- Examining different hyperelastic non-linear models such as the Mooney-Rivlin model

REFERENCES

ACKNOWLEDGEMENTS
Beckman Institute, University of Illinois Urbana-Champaign