The Effect of Structural Variation on Ligament Apparent Properties

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INTRODUCTION: Posterior cruciate ligament (PCL) rupture occurs in 5-20% of all acute ligament knee injuries and causes pain, swelling, instability, and functional disability of the knee joint [1]. Up to one-third of patients suffer from late knee osteoarthritis as a result of this joint instability [2]. PCL reconstruction is an increasingly common procedure to restore knee stability and function after ligament ruptures, and requires knowledge of the intact PCL mechanical properties for optimal PCL reconstruction outcome. Several experiments have been performed to measure the PCL properties of different species [3-6] and have shown that the cross-sectional area (CSA) of the PCL is significantly different along its length [3, 7]. However, it is not clear how these structural variations contribute to the assessment of PCL properties; specifically, which CSA should be considered to calculate stress. Therefore, the aim of this study was to investigate the effect of regional variation in CSA of the PCL on the calculation of material properties using linear and non-linear functions. In addition, the local strain distribution along PCL was measured and compared with analytical strain solutions.

METHODS: Porcine knee specimens (n=6) of the same age were collected from the Meat Science Laboratory at the University of Illinois. All soft tissues, except the PCL, were dissected leaving a bone(femur)-ligament(PCL)-bone(tibia) construct (Fig. 1A). A custom fixture was developed to mount the construct into a materials test machine (Instron Corporation) (Fig. 1B). Thirteen surface dots were marked along the PCL and digitized before and after testing to measure the local strain (Fig. 1C). Each specimen was preconditioned with 5 cycles of loading-unloading with deformations from 0 to 1.5mm at an extension rate of 50mm/min. Finally, specimens were elastically loaded to 100N at 50mm/min. A loadcell (ATI Industrial Automation) was used to measure the reaction forces at the insertion site while a motion capture system (Optotrak Certus) tracked the global displacement of the ligament. Magnetic resonance images were acquired on a 3-Tesla Siemens Trio scanner using a proton density weighted sequence (voxel size: 0.47x0.47x0.003mm, TE=38ms, TR=1300ms). These images were segmented and reconstructed into three-dimensional models of the PCL to calculate the CSA in two ways: 1) average CSA=ligament volume divided by measured length of the PCL, and 2) CSA at 25%, 50%, and 75% along the length of the PCL from the femoral insertion site and termed as proximal, mid, and distal areas respectively. Based on these CSA, elastic moduli, E (E^{avg}, E^{prox}, E^{mid}, and E^{dist}) were calculated from the slope of the linear region of corresponding stress-strain curves. The experimental stress-strain data were also fit to a neo-Hookean hyperelastic model to obtain the material constant, C_{10} (C_{10}^{avg}, C_{10}^{prox}, C_{10}^{mid}, C_{10}^{dist}). Percentage changes for proximal, mid, and distal sites were calculated with respect to average values and one sample t-test was conducted (α=0.05). Using E^{avg} and C_{10}^{avg}, we analytically calculated the strains at proximal, mid, and distal regions.

RESULTS: Elastic modulus based on the average area was highest (67.46MPa with 31% standard deviation compared to the mean) whereas the mid-regions had highest C_{10} (3.56MPa with 32% standard deviation) (Table 1). E and C_{10} values based on the proximal CSA underestimated the average modulus by 26% ($p < 0.001$) (Figure 2). However, there was no significant difference when properties were calculated based on the mid and distal areas compared to the average area (Figure 2). Strain within the PCL was non-uniformly distributed over the ligament as shown in Figure 3A. The largest strain was observed at the proximal site (~40%) and was 4 times higher than the global strain (10%). However, the proximal local strain predicted analytically by E^{avg} was 69% lower than the experimental mean strain, but was better predicted by C_{10}^{avg} which was 29% (Fig 3B).

DISCUSSION: Characterizing the ligaments by defining apparent property is a challenge due to their inhomogeneous variations. Our results suggest that to consider only the proximal area to define material properties using E and C_{10}, is not a good choice. Care should also be taken while interpreting the ligament strain as it shows region dependency. Higher local strains at the insertion sites may be masked if only the global strain is considered. Ligament failure is often at the insertion sites as confirmed by our experimental data indicating high strains towards the ligament ends. Finite element model based predictions allow for consideration of geometric nonlinearities but require accurate materials characterization. Our data indicates that the range of material properties may be a result of local inhomogeneity such as collagen structure or content. Analytical predictions of local strain using global properties is limited in accuracy, and further work is needed to better understand how to experimentally assess the local material and mechanical properties of ligaments to improve both surgical outcome and allograft development.

SIGNIFICANCE: This study presents the significance of structural variability to ligament properties which are important for ligament reconstruction. It also elucidates the local strain behavior to interpret ligament injury more precisely.

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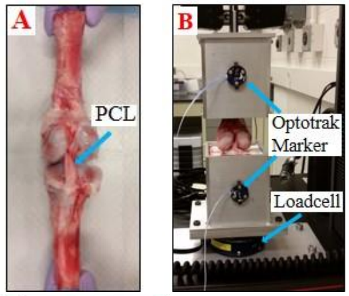

Figure1: A) Posterior view of dissected porcine knee, B) Experimental setup with potted knee, C) Marked dots to measure local strain

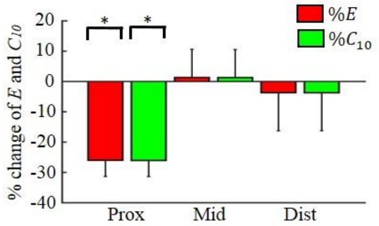

Figure 2: % change of E and C_{10} for proximal, mid, and distal regions (* indicates statistically different from zero (p<0.001)

Table 1: PCL material properties

	Elastic modulus E (MPa)		**neo-Hookean constant, C_{10} (MPa)**
E^{avg}	67.46±21.09	C_{10}^{avg}	3.47±0.93
E^{prox}	50.30±17.89	C_{10}^{prox}	2.53±0.50
E^{mid}	67.31±17.51	C_{10}^{mid}	3.56±1.15
E^{dist}	65.56±23.27	C_{10}^{dist}	3.39±1.27

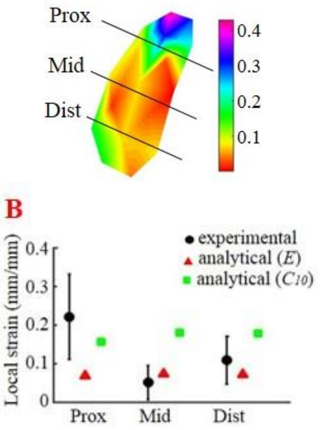

Figure 3: A) Local stress distribution, B) Strain comparisons between experimental and analytical solutions