Mechanical and Microstructural Properties of Native Pediatric Posterior Cruciate and Collateral Ligaments

Elaine C. Schmidt[1]
Matthew Chin[1]
Julien T. Aoyama[2]
Theodore J. Ganley[2]
Kevin G. Shea[3]
Michael W. Hast[1]

1 University of Pennsylvania, Philadelphia, PA,

2 Children's Hospital of Philadelphia, Philadelphia, PA

3 Stanford University, Stanford, CA

Introduction

Increases in youth sport participation has come with a concomitant rise in the number of diagnosed knee ligament tears in pediatric patients.[1] High rates of injury to the medial collateral ligament (MCL) have been reported, and although injuries to the lateral collateral ligament (LCL) and posterior cruciate ligament (PCL) occur with less frequency, they can be severe and may require surgical intervention.[2,3] There is currently a lack of knowledge about the mechanical and microstructural properties of native pediatric ligaments, which impedes the improvement and optimization of surgical treatment for this young population. The purpose of this study was to provide a detailed characterization of mechanical and microstructural properties of pediatric MCLs, LCLs, and PCLs using a rare cadaveric cohort.

Methods

MCLs, LCLs, and PCLs were fine dissected from five fresh-frozen pediatric knee specimens (3 male, 2 female, average age 9.2 years) (AlloSource, Centennial, CO). Ligaments were prepared for uniaxial tensile testing by cutting them into dog-bone shapes at the mid-substance with a custom-built jig (Figure 1A). Cross sectional areas were measured using a laser-based measurement system (Figure 1B). Grip-to-grip uniaxial testing was performed in a universal test frame (ElectroForce 3330, TA Instruments, New Castle, DE) (Figure 1C). The tensile testing protocol consisted of preconditioning, stress-relaxation, and a ramp-to-failure at 0.03% strain/s. Ligaments from the contralateral knee of one donor (female, age 9) were available for microstructural analyses. Brightfield, polarized light, and transmission electron microscopy were conducted to measure cellularity, collagen crimp frequency, and collagen fibril diameter distribution, respectively. Statistical differences between groups were determined by performing one-way ANOVAs with $\alpha = 0.05$.

Results

MCLs and LCLs demonstrated similar values for ultimate stress, ultimate strain, and Young's Modulus that were similar to values for the LCLs (Table 1). The LCL exhibited mechanical properties that had greater variability than the LCL or PCL. PCLs exhibited diminished ultimate stress, stiffness, Young's modulus, and strain energy density when compared to the collateral ligaments, but none of these findings were statistically significant. All three tissues had similar crimp wavelengths (MCL 32.8 ± 3.6 μm; LCL 27.2 ± 3.5 μm; PCL 25.8 ± 3.5 μm) and collagen fibril diameters (MCL 88.0 ± 26.0 nm; LCL 93.3 ± 34.6 nm; PCL 90.9 ± 34.0 nm) (Figure 2). However, the distribution of their profiles had distinct modalities, with the MCL

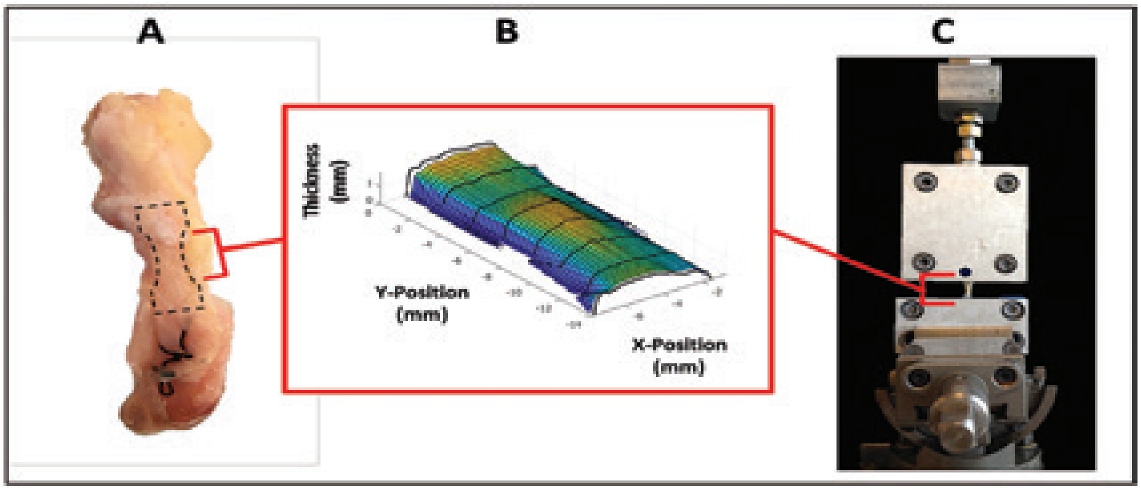

Figure 1. Overview of the mechanical testing protocol. Pediatric specimens were sectioned into dog-bone shapes **(A)**; the CSA of the gauge length was measured using a laser-based scanner **(B)**; and the ends of the specimens were clamped and attached to the testing frame **(C)**.

Table 1. Results (mean ± standard deviation and p-values) for the pediatric MCL, LCL, and PCL specimens obtained from tensile testing.

	Ultimate Stress (MPa}	Ultimate Strain(%)	Young's Modulus (MPa}	Stiffnes (N/mm)	Strain Energy Density (MPa)
MCL	11.7 ± 6.7	18.2 ± 6.8	93.7 ± 56.5	28.6 ± 6.1	1.2 ± 0.9
LCL	11.4 ± 11.5	27.7 ± 12.9	64.4 ± 76.6	30.8 ± 37.5	1.3 ± 1.0
PCL	4.2 ± 1.8	28.8 ± 11.9	19.8 ± 10.4	19.8 ± 10.8	0.7 ± 0.4
			P-values		
MCL v. LCL	0.952	0.347	0.418	0.881	0.849
MCL v. PCL	0.390	0.384	0.159	0.800	0.576
LCL v. PCL	0.307	0.876	0.401	0.843	0.602

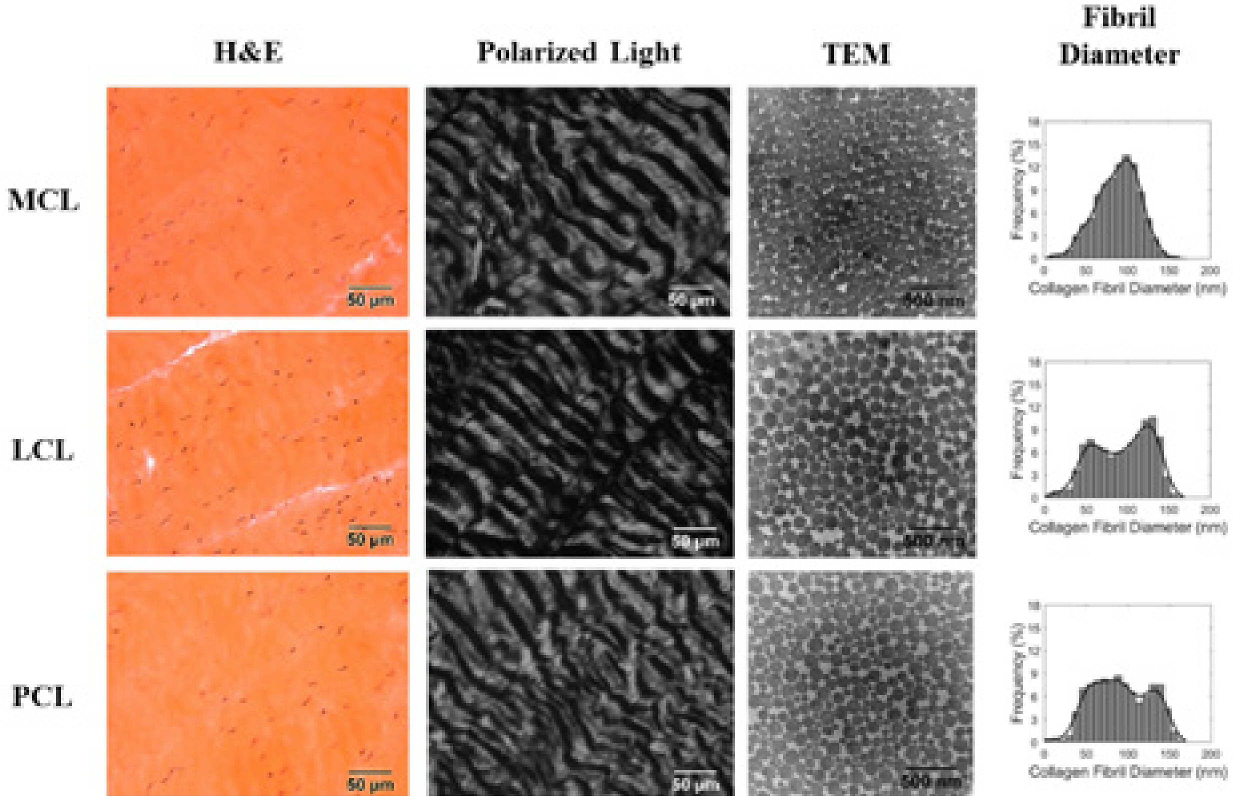

Figure 2. Microstructural results for the contralateral MCL, LCL, and PCL from one donor. First column: representative H&E images for each specimen; Second column: polarized light images demonstrating crimp morphology; Third column: TEM micrographs of collagen fibril cross sections; Fourth column: histograms of relative frequency of collagen diameters.

exhibiting a unimodal profile and the LCL and PCL trending towards bimodal profiles.

Discussion

Pediatric MCLs and LCLs within this small cohort possessed similar mechanical properties. The pediatric PCL may be weaker, but it is able to tolerate high amounts of strain before failure. All tested specimens exhibited weaker mechanical properties than what has been reported in the literature for adult cohorts. Based on a previous study with the same donor cohort, the microstructural properties of the pediatric MCL appear to be most similar to that for pediatric iliotibial band (ITB).[4] Pediatric ITBs are also stronger than the native MCL and when used as a graft source for extra-articular augmentation could prevent re-rupture in cases of multi-ligament injuries and severe instability. Results from this study are inherently limited due to the small sample size associated with this rare cohort of donors.

The results from this study represent the first attempt to establish baseline mechanical and microstructural data for pediatric collateral and posterior cruciate ligaments. In the context of graft augmentation for the pediatric knee, the ITB may be a promising source of knee tendon graft.

References

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