Material Properties of Skeletally Immature Human Patellar Tendons and the Associations with Age and BMI

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INTRODUCTION: The material properties of ligaments and tendons provide biomechanical information regarding their vulnerability to injury but have mostly been characterized in older age groups or throughout development in animal models[1,2]. Given the difficulty of obtaining skeletally immature human ligaments/tendons, porcine models of the knee are often used to investigate changes throughout development. However, the translation of this information to humans can be difficult due to differences between porcine and human knees. Furthermore, the material properties of tissue may change with age or body composition (e.g. body mass index, BMI) given increased functional demands which has implications for developing representative computational models and understanding injury. The objective of the study was to quantify the material properties of the central region of skeletally immature human patellar tendons and the associations with age and BMI. It was hypothesized that material properties would increase with age and BMI.

METHODS: Eleven skeletally immature human extensor mechanisms were acquired (4.3 ± 3.1 years, BMI 19.2 ± 5.5 kg/m^2, 7 males, 4 females). The complex consisting of the central region of the patellar tendon and patella was scanned using a 3D laser scanning system (NextEngine 3D Scanner HD, Santa Monica, CA) with 2.0% accuracy and 1.8% repeatability to measure cross sectional area at the midsubstance of the patellar tendon after being dog-boned to a 5:1 ratio[3]. The extensor mechanisms were then mounted in a material testing machine (Instron Model 5965, Norwood, MA). The patellar tendons underwent a mechanical testing protocol with loading criteria normalized to cross sectional area based on previous literature values[3,4]. The patellar tendons were preloaded (1% of ultimate stress), preconditioned for 20 cycles (1-5% of ultimate stress) and then loaded to failure at 10mm/min. Markers were placed below and above the midsubstance to calculate strain using a custom video tracking system and software[4] (DMAS7, 0.01mm accuracy). The modulus, ultimate stress, ultimate strain and strain energy density of the central region of the tendons were quantified from the obtained stress-strain curves. Modulus was determined in the linear region of the stress-strain curve and the strain energy density was quantified using the trapezoidal rule from 0% to the ultimate strain. Pearson or Spearman's correlations were used to determine the associations between age, BMI and material properties. Significance was set at $p < 0.05$.

RESULTS: Eleven skeletally immature human patellar tendons were loaded to failure. Ten patellar tendons failed at the midsubstance and one patellar tendon failed at the clamp interface. Overall, the cross-sectional area at the midsubstance of the central region was 7.8 ± 5.3 mm^2. The ultimate stress and strain were 25.5 ± 8.3 MPa and 0.12 ± 0.05, respectively (Table 1). The modulus and strain energy density were 296.4 ± 97.5 MPa and 1.6 ± 1.0 MPa, respectively. No associations were found between age, BMI and material properties ($p > 0.05$), with the exception of a positive association between BMI and ultimate strain (r^2=0.45, p=0.02, Figure 1). Thus, as BMI increased, ultimate strain increased and changes in BMI accounted for 45% of the variation in ultimate strain.

DISCUSSION: The main findings from the current study were that the material properties of skeletally immature human patellar tendons were not associated with age (between 0.1 and 8.7 years) or BMI, with the exception of the association between BMI and ultimate strain. The lack of association between material properties and age may be due to minimal changes in the microstructure of the tissue throughout the age range included in the current study. The association between BMI and ultimate strain indicates that the patellar tendon may adapt to changes in mass and height to accommodate increased range of motion at the knee throughout maturation. The ultimate stress and modulus were greater in the current study compared to previous work, and the ultimate strain and strain energy density were less[4]. Discrepancies between the two studies are likely due to the method used to calculate strain, where the method used in the current study more accurately tracks the deformation at the midsubstance. Compared to the material properties of cadaveric patellar tendons from older age groups (29-50 and 64-93 years)[5], the current study found 44.9% smaller moduli, 39.4% smaller ultimate stresses, 37.2% smaller strain energy densities and similar ultimate strains. Computational models can utilize the findings of the current study to better represent the pediatric population and provide information to surgeons performing ligament reconstruction in skeletally immature patients. Future work will determine associations within certain age groups defined as when pediatric patients would be crawling or walking.

SIGNIFICANCE/CLINICAL RELEVANCE: Understanding the material properties of skeletally immature human patellar tendons can be used to develop representative computational models for the pediatric population, where body composition may play a larger role than age in patellar tendon development.

REFERENCES: [1] Howe D et al. J Orthop Res 2022, [2] Castile RM et al. JOR 2021, [3] Miller RM et al. KSSTA 2017, [4] Schmidt EC et al. OJSM 2019, [5] Johnson GA et al. JOR 1994

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Table 1: Age, BMI and material properties of skeletally immature human patellar tendons.

Specimen	Age (years)	BMI (kg/m2)	Ultimate Stress (MPa)	Ultimate Strain	Modulus (MPa)	Strain Energy Density (MPa)
1	0.1	19.1	24.4	0.07	457.8	0.64
2	0.3	27.1	21.7	0.20	161.4	2.80
3	0.8	21.3	17.6	0.20	156.4	1.35
4	3.1	20.7	36.8	0.12	369.6	2.00
5	3.5	13.7	22.6	0.11	282.1	1.70
6	4.0	18.0	31.6	0.09	377.2	1.33
7	5.5	15.9	13.3	0.07	347.8	0.31
8	6.2	19.5	35.7	0.16	366.9	3.52
9	7.3	18.2	32.1	0.15	258.6	2.44
10	8.1	17.5	14.8	0.07	285.9	0.59
11	8.7	20.1	29.9	0.12	196.9	1.30

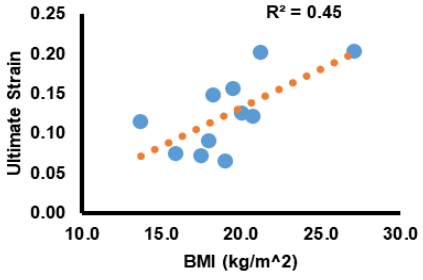

Figure 1: Positive association between BMI and ultimate strain in skeletally immature human patellar tendons.