# Material properties of the quadriceps tendon in skeletally immature knees

Svenja A. Höger[1,3], Luke T. Mattar[1], Jayson J. Baggett[2], Armin Runer[1,3], Kevin G. Shea[4], Volker Musahl[1,2], Richard E. Debski[1,2]
[1]Department of Orthopaedic Surgery and [2]Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, USA
[3]Department for Orthopaedic Sports Medicine, Klinikum rechts der Isar, Technical University of Munich, Munich, Germany
[4]Stanford University Department of Orthopaedic Surgery 450 Broadway, Redwood City, CA 94063, USA
svenjahoeger@gmail.com

**Disclosures:** Höger (N), Mattar (N), Baggett (N), Runer (N), Shea (Research support from Allosource, Stanford Maternal Child Health Research Institute, Educational support from Arthrex, Evolution Surgical), Musahl (NIH and US Department of Defense: funding grants; Newclip Technics and Smith and Nephew Inc: consulting or advisory; Ostesys SAS: equity or stocks; ACL Study Group: board membership), Debski (N)

INTRODUCTION: The role of the knee evolves rapidly throughout maturation, paralleling the shift from predominantly non-weightbearing and crawling to walking and running. As functional demands increase, tendons need to adjust to different loading conditions to support necessary joint function.[1] Therefore, alterations in material properties of quadriceps tendons might occur and be associated with age. Understanding the development of this tissue might have implications for ligament reconstructions. Thus, the objective of the study was to quantify the material properties of skeletally immature human quadriceps tendons and the associations with age. It was hypothesized that material properties would be positively associated with age, given increases in functional demand.

METHODS: Eleven skeletally immature human extensor mechanisms were acquired (4.3 ± 3.1 years (range 1 month – 8.7 years), BMI 19.2 ± 5.5 kg/m$^2$, 7 males, 4 females). The complex consisting of the central region of the quadriceps tendon and patella was scanned using a 3D laser scanning system (NextEngine 3D Scanner HD, Santa Monica, CA) with 2% accuracy and 1.8% repeatability to measure cross sectional area at midsubstance of each tendon after being dog-boned focused on central region of the tendon at a 5:1 ratio.[2] The complex was then mounted in a material testing machine (Instron Model 5965, Norwood, MA). The quadriceps tendons underwent a mechanical testing protocol with loading criteria normalized to cross sectional area based on previous literatures values.[2, 3] The quadriceps tendons were preloaded (1% ultimate stress), preconditioned for 20 cycles (1-5% ultimate stress) and then loaded to failure at 10mm/min. Markers were placed below and above the midsubstance (Figure 1) to determine strain using a custom video tracking system and software (DMAS7, Spica Technology Corporation, 0.01mm accuracy).[3] The modulus, ultimate stress, ultimate strain and strain energy density 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. Spearman's correlations were used to determine the associations between material properties and age. Significance was set at $p < 0.05$.

RESULTS: During dissection, the midsubstance of some quadriceps tendons were observed to consist of multiple layers. Strain tracking markers were placed only on the superficial layer. All specimens failed at the midsubstance during load to failure. Cross-sectional area at the midsubstance of the central region after the dog-boning procedure was 7.6 ± 4.7 mm$^2$. The modulus and strain energy density were 237.7 ± 135.4 MPa (range 63.0 and 419.2 MPa) and 0.9 MPa (IQR 0.4-1.7, range 0.2 to 1.9 MPa), respectively. The ultimate stress and strain were 17.6 ± 8.4 MPa (range 6.5 to 28.9 MPa) and 0.11 ± 0.05 (range 5.2 to 16.9%), respectively (Table 1). The variability in modulus and strain energy density were 57.0% and 70%, respectively ((SD/mean)*100%). The variability in ultimate stress and strain were 47.7% and 45.5%, respectively. No associations were found between ultimate stress, ultimate strain, modulus, strain energy density, and age ($r^2$ ranged 0.05-0.6, $p > 0.05$, Figure 1).

DISCUSSION: The main findings from the current study were that the material properties of skeletally immature human quadriceps tendons were not associated with age in specimens between 1 month and 8.7 years of age. These findings could be attributed to the absence of changes in tissue composition during development or the large variability in material properties. The standard deviation of quadriceps tendons from specimens with an average age of 9.2 years was also considerably large where the modulus was 61.9 ± 65.0 MPa.[3] This considerable standard deviation aligns with the variability that has been observed in this study and could potentially be attributed to the observed multi-layered composition of the tendons, as well as the loads experienced by the tendons. Therefore, this research yields valuable insights into the behavior of quadriceps tendons in skeletally immature subjects.

SIGNIFICANCE/CLINICAL RELEVANCE: Material properties of skeletally immature quadriceps tendons remain constant within the pediatric age range of 1 month to 9 years, implying that while their function undergoes significant changes during maturation, tissue composition experiences relatively minor alterations.

REFERENCES:[1]Wren J Biomech 1998, [2]Miller KSSTA 2017, [3]Schmidt OJSM 2019

ACKNOWLEDGEMENTS: We gratefully acknowledge the donations from the respective families and Allosource which made the current study possible.

*Table 1 Age and material properties of quadriceps tendons for skeletally immature specimens.*

| Specimen | Age (months) | Ultimate Stress (MPa) | Ultimate Strain (%) | Modulus (MPa) | Strain Energy Density (MPa) |
|---|---|---|---|---|---|
| 1 | 1 | 7.2 | 14.0 | 63.0 | 0.9 |
| 2 | 3 | 9.4 | 4.3 | 232.6 | 0.2 |
| 3 | 9 | 22.0 | 16.9 | 160.7 | 1.9 |
| 4 | 37 | 20.8 | 16.9 | 130.1 | 1.7 |
| 5 | 41 | 24.2 | 11.3 | 256.2 | 1.3 |
| 6 | 48 | 19.5 | 16.3 | 155.6 | 1.8 |
| 7 | 66 | 13.0 | 5.2 | 368.1 | 0.4 |
| 8 | 74 | 30.0 | 8.1 | 461.3 | 1.0 |
| 9 | 87 | 12.3 | 6.6 | 290.1 | 0.5 |
| 10 | 96 | 28.9 | 8.1 | 419.2 | 0.8 |
| 11 | 104 | 6.5 | 10.4 | 77.8 | 0.4 |

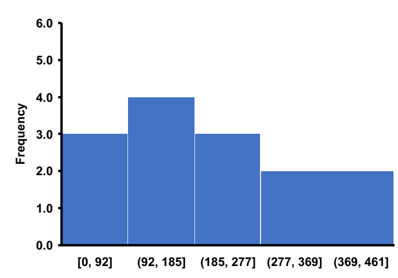


*Figure 1 Distribution of the modulus for skeletally immature specimens.*