Smaller Width Quadriceps Tendon Grafts Maintain Advantageous Biomechanical Properties for ACL Reconstruction

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Background: Despite clinical evidence of risks in knee arthrofibrosis and graft impingement with larger grafts, the optimal size for quadriceps tendon (QT) autografts in anterior cruciate ligament reconstruction (ACLR) has not been established.

Purpose/Hypothesis: This study aimed to evaluate the mechanical properties of full-thickness 6-mm and 8-mm wide QT grafts compared with 10-mm patellar tendon (PT) and 10-mm QT grafts. The hypothesis was that both the 6- and 8-mm QT grafts would exhibit similar or superior ultimate tensile strength compared with the 10-mm PT graft.

Study Design: Controlled laboratory study.

Methods: A total of 18 matched pairs of cadaveric knees were used in this study. From each pair, a 10–mm wide full-thickness QT was harvested from 1 knee. Based on randomization, a 6–mm wide or 8–mm wide full-thickness QT along with a 10–mm wide PT were harvested from the contralateral knee. Each tendon was clamped, tensioned, and cycled on a servohydraulic testing machine before final loading to failure.

Results: The ultimate failure load was 1286 ± 237.3 N for the 10-mm QT, 1056 ± 226.7 N for the 8-mm QT, 935.1 ± 283.8 N for the 6-mm QT, and 816 ± 192.7 N for the 10-mm PT. Ultimate tensile strength differed significantly between the 10-mm and 8-mm QT (P = .004), 10-mm and 6-mm QT ($P < .001$), 10-mm QT and 10-mm PT ($P < .001$), and 8-mm QT and 10-mm PT grafts ($P < .001$), but not between the 6-mm QT and 10-mm PT grafts (P = .152).

Conclusion: The 8-mm QT had higher ultimate tensile strength than the 10-mm PT, and the 6-mm QT was comparable to the 10-mm PT. Full-thickness QT grafts <10 mm in width may maintain sufficient tensile strength for ACLR.

Clinical Relevance: Given these biomechanical properties, smaller QT graft sizes may be advantageous in minimizing arthrofibrosis risk while maintaining graft strength.

Keywords: anterior cruciate ligament reconstruction; biomechanics; quadriceps tendon graft

Anterior cruciate ligament (ACL) rupture is a common injury, with an incidence rate of 68.6 per 100,000 persons annually.[28] Anterior cruciate ligament reconstruction (ACLR) serves as the primary operative treatment for ACL rupture by utilizing autograft or allograft tendons to restore the anteroposterior and rotatory stability of the knee. Historically, the 10–mm wide patellar tendon (PT) autograft with bone blocks has been considered the gold standard for ACLR autografts.[26] The quadriceps tendon (QT) autograft has recently gained popularity based on promising clinical outcomes scores and reduced donor site morbidity.[2,3,6,21]

A full-thickness QT autograft is harvested from the central portion of the intact QT and is a composite structure comprised of 2 to 4 tendon layers based on the confluence of the quadriceps muscles.[4,6] Biomechanically, 10-mm QT grafts have demonstrated higher ultimate tensile strength than 10-mm PT grafts because of histological differences in collagen and fibroblast density.[13,21] Meta-analysis data of pooled randomized control trials show similarly low graft failure rates between QT and PT grafts.[8]

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Arthrofibrosis is a known complication of ACLR and is seen in up to 1.7% of adults and over 8.3% in children and adolescents.[22,27] Mechanical graft impingement and excessive fibrous tissue formation may explain the arthrofibrosis often seen in ACLR, but the exact pathophysiology is unknown.[4,32] Previous literature shows that a 1-mm increase in the diameter of an ACLR graft is associated with 3.2 times increased odds of knee arthrofibrosis.[32] Full-thickness 10-mm QT grafts have approximately twice the cross-sectional area of 10-mm PT grafts, which theoretically increases the postoperative arthrofibrosis risk.[4] While 10-mm in width for PT and >8 mm in diameter for hamstring tendon grafts have been cited as target graft sizes, there is a dearth of literature regarding the optimal size for QT autografts.[9,19,26] The increased risk of arthrofibrosis with larger grafts warrants an investigation that determines whether a smaller-sized QT graft is biomechanically feasible for ACLR.

This cadaveric study aimed to evaluate the mechanical properties of full-thickness QT grafts 6-mm and 8-mm in width compared with 10-mm PT and 10-mm QT grafts. The hypothesis was that both the 6- and 8-mm QT grafts would exhibit similar or superior ultimate tensile strength compared with the 10-mm PT graft.

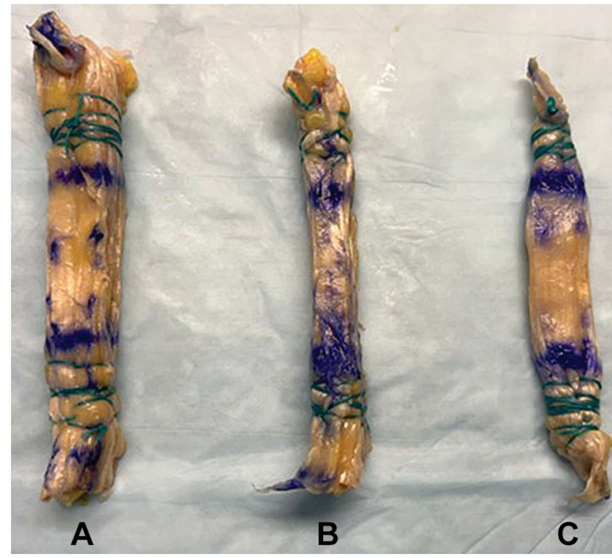

Figure 1. Harvested (A) 10-mm QT, (B) 6-mm QT, and (C) 10-mm PT grafts from a single cadaveric specimen. PT, patellar tendon; QT, quadriceps tendon.

METHODS

Specimen Preparation

After screening for any history of tendon pathologies and previous knee extensor mechanism procedures, 18 pairs of knees (10 male and 8 female cadaveric specimens; mean age, 80.33 ± 12.82 years) were selected from deidentified fresh cadaveric specimens donated to our affiliated university anatomy program. All specimens were stored at −30°C without concern for any tendon or ligament damage and were thawed to room temperature while wrapped in normal saline-soaked gauze when ready for testing.[18,36] From each pair, a 10–mm wide full-thickness QT was harvested from either the left or right knee. Based on randomization, an 8–mm wide or 6–mm wide full-thickness QT along with a 10–mm wide PT were harvested from the contralateral knee. Care was taken to match the age and sex distribution between the 8-mm and 6-mm QT groups. All QTs were 70 mm in length proximal to the superior patellar pole before harvest. All PTs were harvested at full length without bone blocks. In total, 54 tendons were included, distributed into the following graft groups: 10-mm QT (n = 18), 8-mm QT (n = 9), 6-mm QT (n = 9), and 10-mm PT (n = 18).

The central 30 mm of graft length was marked to designate the intra-articular portion of the QT and PT grafts. Each end of the graft outside of the central 30 mm was sutured with a size-0 polyethylene terephthalate coated suture (Ethibond Excel; Ethicon) using the Krackow technique followed by a wraparound of the suture ends 3 times before tying (Figure 1). Suturing the tendons added traction and prevented tendon splaying when placed in serrated clamps for failure testing.[13] After suturing, the width and thickness of each tendon were measured 3 times with a digital caliper to yield the mean cross-sectional geometry.[29]

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Ethical approval for this study was obtained from Walter Reed National Military Medical Center (protocol No. WRNMMC-EDO-2022-0994).

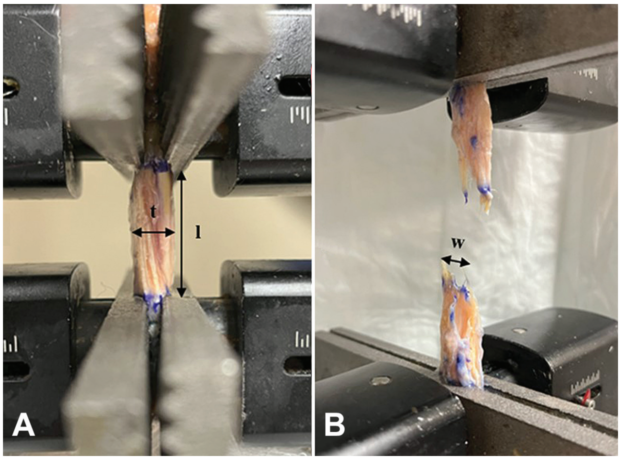

Figure 2. (A) Tendon clamp configuration and (B) midsubstance/shear-type failure of a quadriceps tendon. For orientation: l = length, t = thickness; w = width.

Each graft was mounted to a servohydraulic mechanical testing system (MTS 858 Mini Bionix II; MTS Systems), with the sutured ends of the tendon secured between serrated metal clamps.[12,31] The graft was clamped down across its width, leaving the central 30 mm exposed (Figure 2A). The distance between the clamps was calibrated before each test (measurement error, 0.05 mm) and tracked via crosshead measurement. Displacement and tendon forces were measured throughout experimental testing at 102 Hz. After clamping, each graft was tensioned at 50 N for 10 minutes for preconditioning. The resultant displacement was considered the initial tendon length (L_0) for strain calculations. Subsequently, the graft was cycled from 50 to 250 N at 1 Hz for 1000 cycles based on an a priori design.[24] Tendon width and thickness were remeasured after undergoing 1000 cycles to be used as final tendon dimension values for calculating stress mechanics before failure testing. There was no evidence of tendon slippage from the clamps based on reference points provided by the sutured ends. The graft was then loaded to failure at a distraction rate of 1 cm/sec to simulate catastrophic failure until complete tendon rupture occurred (Figure 2B).[30] All testing was conducted at room temperature, and each graft was periodically sprayed with normal saline spray to maintain hydration.

Data Reduction

Force and displacement data were low-pass filtered at 6 Hz using a second-order zero-lag Butterworth filter with custom MATLAB scripts Version R2023b (MathWorks). Creep displacement during cyclic loading was calculated as the difference in displacement of the tendon at the initial 50-N load at cycle 0 versus the 50-N load at cycle 1000. The time constant, defined as the time to reach 68% of the final creep value, was also calculated during cyclic loading. During failure load testing of each graft, the maximum load during failure, maximum displacement at failure (L_f), and mode of failure were recorded. Tendon stiffness was calculated based on the regression slope of the linear region of the load-displacement data from failure load testing. To minimize the effects of both the initial toe region and the yield region, the stiffness calculations excluded data from the beginning and ending portions of the load-to-failure curve until the linear regression coefficient of determination (R^2) of >0.99. Tendon strain was calculated as the engineering strain ($\varepsilon = \frac{\Delta L}{L_0}$), where ΔL is the change in tendon length from the initial position. For tendon strain at failure ($\Delta L = L_f - L_0$), the Young modulus of the material was calculated from the slope of the engineering stress ($\sigma = \frac{F}{A_0}$) over the engineering strain, where F is the force applied and A_0 is the cross-sectional area measured after 1000 cycles. The cross-sectional area was considered rectangular such that A_0 = *tendon width* × *tendon thickness*. To account for the inherent error in dimensional measurements, a Deming linear regression method was applied for the Young modulus calculations. Descriptive statistics (mean ± SD) were calculated for creep displacement after 1000 cycles, yield point displacement, maximum load to failure, and stiffness.

Statistical Analysis

The primary outcome measured was ultimate tensile strength, defined as the ultimate failure load before graft rupture. The secondary outcomes were the mechanical properties of the various tendon sizes. A generalized linear mixed-effects model was applied to each of the outcome variables with fixed (group: 10-mm QT, 8-mm QT, 6-mm QT, or 10-mm PT) and random (cadaveric donors) variables to allow for direct comparison of ultimate tensile strength and mechanical properties. Sex was initially included as a covariate but was found to be a nonsignificant contributor and was removed from the model. Estimated marginal means (± standard error) were calculated based on grouped variables for creep displacement, yield point displacement, maximum load to failure, and stiffness. Post hoc Wald tests were used to determine statistically significant differences between the PT group and each QT group. The threshold for significance was set a priori at $P < .05$. Post hoc power analysis with 54 tendons and their variations in ultimate failure load demonstrated a β of 0.001.

RESULTS

The mean age of the cadaveric specimens was 78.67 ± 10.75 years for the 8-mm QT group and 82 ± 15.09 years for the 6-mm QT group (P = .597, Student t test). The dimensions of each graft group are summarized in Table 1. The cross-sectional area of the 10-mm QT group was found to be >1.5 times the cross-sectional area of the 10-mm PT group at the time of harvest and after clamping, indicating a significant difference ($P < .001$, Student t test). The cross-sectional area of the 8-mm QT group was also significantly larger than that of the

TABLE 1
Graft Dimensions at Initial Tendon Harvest and After Clamping[a]

Dimensions	10-mm QT (n = 18)	8-mm QT (n = 9)	6-mm QT (n = 9)	10-mm PT (n = 18)
At harvest				
Width, mm	10.18 ± 0.21	8.21 ± 0.24	6.13 ± 0.17	10.29 ± 0.36
Thickness, mm	7.97 ± 0.81	7.96 ± 0.69	7.63 ± 0.59	4.77 ± 0.79
CSA, mm^2	81.12 ± 7.86	65.36 ± 6.53	46.75 ± 4.08	49.07 ± 8.36
After clamping				
Width, mm	13.26 ± 1.42	12.07 ± 2.40	10.03 ± 2.32	15.83 ± 2.64
Thickness, mm	7.48 ± 1.21	6.53 ± 1.14	5.69 ± 0.75	3.62 ± 0.89
CSA, mm^2	98.70 ± 16.23	78.23 ± 16.99	56.28 ± 10.68	56.14 ± 10.49

[a]Data are presented as mean ± SD. CSA, cross-sectional area; PT, patellar tendon; QT, quadriceps tendon.

TABLE 2
Mechanical Properties According to Tendon Group[a]

Mechanical Property	10-mm QT	8-mm QT	6-mm QT	10-mm PT
Failure load, N	1286 ± 237.3	1056 ± 226.7	935.1 ± 283.8	816 ± 192.7
Stiffness, N/mm	201.2 ± 52.13	205.4 ± 21.69	199.6 ± 49.51	239.2 ± 57.72
Time constant, sec	476.4 ± 116.1	453.4 ± 61.06	407.2 ± 49.24	366.1 ± 87.58
Creep strain, mm/mm	0.050 ± 0.020	0.048 ± 0.012	0.041 ± 0.016	0.046 ± 0.018
Failure strain, mm/mm	0.275 ± 0.090	0.214 ± 0.069	0.192 ± 0.023	0.163 ± 0.048
Young modulus, MPa	62.10 ± 21.36	79.52 ± 27.98	104.3 ± 39.86	116.7 ± 38.24

[a]Data are presented as mean ± SD. PT, patellar tendon; QT, quadriceps tendon.

10-mm PT group ($P < .001$, Student t test), while the 6-mm QT was not significantly different from the 10-mm PT ($P = .441$).

The ultimate failure load and mechanical properties of each tendon group are summarized in Table 2. Overall, 16.67% of the 10-mm QT (3 of 18) and 11.11% of the 8-mm QT (1 of 9), 6-mm QT (1 of 9), and 10-mm PT (2 of 18) grafts ruptured at the tendon-clamp interface during failure loading, while the remainder failed at the midsubstance level. Compared with the 10-mm QT control (reference: 100%) within each matched pair, the relative percentage of ultimate tensile strength was 84.40% ± 15.95% for the 8-mm QT, 71.41% ± 19.33% for the 6-mm QT, and 64.36% ± 14.64% for the 10-mm PT. One-way analysis of variance for the percentage of ultimate tensile strength resulted in a significant difference ($P = .017$), although post hoc Tukey-Kramer tests demonstrated significance only between the 8-mm QT and the 10-mm PT ($P = .013$).

Figure 3 demonstrates the comparison of the estimated marginal means from the generalized linear mixed-effects model—including statistical significance between each tendon group using the post hoc Wald tests. Within-sample statistical comparisons demonstrated significant differences in ultimate tensile strength between the 10-mm QT and 8-mm QT ($P = .004$), the 10-mm QT and 6-mm QT ($P < .001$), the 10-mm QT and 10-mm PT ($P < .001$), and the 8-mm QT and 10-mm PT ($P < .001$) (Figure 3A). However, no significant differences were found in the ultimate failure load between the 8-mm QT and 6-mm QT ($P = .093$) or the 6-mm QT and 10-mm PT ($P = .152$).

No significant differences were found in stiffness among the various QT sizes (Figure 3B) or in creep strain after cyclic loading among all graft types (Figure 3C). The time constant was significantly shorter in the 6-mm QT versus the 10-mm QT ($P = .014$), while it was significantly longer in the 8-mm QT versus the 10-mm PT ($P = .003$) (Figure 3D). The 10-mm PT had the highest calculated Young modulus, which was significantly larger than both the 10-mm QT ($P < .001$) and the 8-mm QT ($P = .002$) (Figure 3E). The Young modulus was significantly greater in the 6-mm QT than in the 10-mm QT ($P < .001$). The 10-mm QT had significantly higher failure strain than both the 8-mm QT ($P = .022$) and the 6-mm QT ($P = .002$) (Figure 3F). Both the 10-mm QT ($P < .001$) and the 8-mm QT ($P = .046$) failed at a higher strain than the 10-mm PT.

DISCUSSION

We found that the ultimate tensile strength was significantly larger in the 10-mm QT and 8-mm QT groups versus the 10-mm PT group, and it was not significantly different between the 6-mm QT and 10-mm PT groups, supporting our initial hypothesis. Previous biomechanical studies have shown that a 10-mm QT graft can range from 0.97 to 1.81 times the ultimate tensile strength of a 10-mm

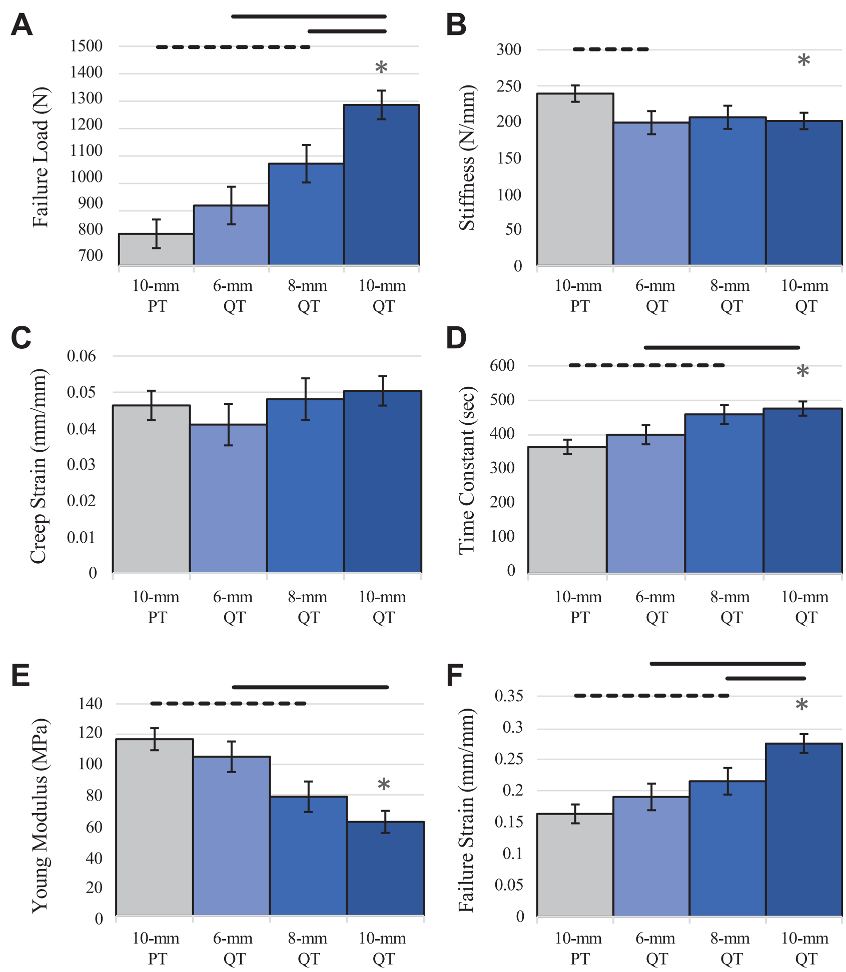

Figure 3. Mechanical properties and statistical significance ($P < .05$) according to tendon group. The dashed line indicates significant differences compared with the 10-mm PT; the solid line indicates significant differences compared with the 10-mm QT; the asterisk indicates a significant difference between the 10-mm QT and the 10-mm PT. PT, patellar tendon; QT, quadriceps tendon.

PT graft.[11,13,29] The present study showed that the 10-mm QT was 1.58 times stronger than the 10-mm PT. This relationship was also apparent for the smaller grafts; the 8-mm QT was found to be 1.31 times stronger than the 10-mm PT. Surprisingly, the 6-mm QT group appeared to have similar ultimate tensile strength compared with the 10-mm PT group.

The high ultimate tensile strength in even the smaller QT grafts may be explained by the differences in cross-sectional areas between QT and PT grafts. The cross-sectional areas of the 10-mm QT and 8-mm QT groups were significantly larger than that of the 10-mm PT group, while the 6-mm QT group had a similar cross-sectional area to the 10-mm PT group. This is consistent with previous comparative studies that reported the mean cross-sectional area as 71.4 to 91.2 mm^2 in 10-mm full-thickness QT grafts and 33.2 to 51.77 mm^2 in 10-mm PT grafts.[11,23,29,35]

A larger cross-sectional area for an ACLR graft may not be the most optimal, however. Fujimaki et al[10] found that the mean ACL tibial insertion area was 107.2 mm^2, but the cross-sectional area of the ACL at its midpoint is 50% of the tibial insertional area or approximately[7] 53 mm^2. A large cross-sectional area is associated with the risk of knee arthrofibrosis. Su et al[32] found that an increase of 1 mm in graft diameter was independently associated with 3.2 times increased odds of arthrofibrosis. This may be partly due to the graft incorporation process, in which fibroblast proliferation and collagen reorganization may result in excessive fibrous tissue formation on a larger scaffold.[5,32] Large cross-sectional area also risks graft impingement. Thein et al[33] reported that 70% of PT autografts resulted in either contact or impingement with the femoral notch while 80% of PT autografts showed contact or impingement with the posterior cruciate ligament. Based on these data, the incidence and magnitude of impingement are likely to be higher with a 10-mm QT graft that has nearly double the cross-sectional area of a 10-mm PT graft and a 6-mm QT graft.

Given the potential clinical disadvantages of knee arthrofibrosis and graft impingement seen with the 10-

mm QT despite its high ultimate tensile strength, a smaller QT graft may be considered. Despite the similarities in ultimate tensile strength and cross-sectional area between a 6-mm QT and a 10-mm PT, QT graft harvesting possesses an advantage over PT grafts in terms of less donor site pain and morbidity.[3,21] Residual harvest site strength is also a factor, as removing a 10-mm graft from the QT results in a higher residual ultimate tensile strength than removing it from the PT (2430 vs 1460 N, respectively).[1] The residual harvest site strength may be even higher if a smaller QT is utilized.

Aside from failure load, the creep response measured in the present study characterizes the elongation characteristics of grafts from low-load situations.[20] All tendon groups in this study creep strained to approximately 4% to 5% after 1000 cycles, with no group significantly different from one another, ultimately indicating that any QT graft choice is as sufficient as a PT. However, the shorter time constants of the 10-mm PT and the 6-mm QT indicate a much more rapid creep response with cyclic loading. This again may be due to the smaller cross-sectional areas of the 10-mm PT and 6-mm QT, which manifested as an increase in tendon stress during cyclic loading.[20] While ACLR graft preconditioning protocols lack clinical consensus to mitigate knee laxity, the present results indicate that the smaller grafts may require less time to reach desired creep values, but the final creep elongation is not expected to differ as compared with wider grafts.[15]

The Young modulus in this study was notably less in the QT groups than what has been previously reported in other biomechanical studies, and the failure strain of the 10-mm QT group was higher than previous values.[11,29] Notably, the present study demonstrated that the 6-mm QT group had a significantly larger Young modulus than the 10-mm QT group. However, by definition, material properties such as the Young modulus are intrinsic to the material and should not vary based on geometry. A probable explanation is the unavoidable consequence of the tested aspect ratio (the ratio of tendon length to width) of the tendons. An aspect ratio of <40 to 1 induces large increases in the stress field at the grip end.[14,25] By using a 30-mm tendon length in this study, the aspect ratio of the 10-mm, 8-mm, and 6-mm widths were found to be 3 to 1, 3.75 to 1, and 5 to 1, respectively. Tendon samples with small aspect ratios demonstrate a lower Young modulus with artificially large failure strains, which is more evident in composite materials such as multilaminar QT grafts.[17] The PT graft may have been less affected by the limited aspect ratio, as it is a single-layer structure. The low Young modulus values for the 10-mm and 8-mm QT grafts suggest an underestimation of the true stiffness and potentially ultimate failure load. Thus, the stiffness and ultimate tensile strength calculations for the QT in this study may be conservative and may be larger in reality.

Limitations

One limitation of the present study was that we explored the biomechanical properties of only full-thickness QT grafts and did not include partial-thickness QT grafts. Future studies are needed to investigate the biomechanical properties of QT grafts based on various graft thickness, not just width. Another limitation of this study may be the use of PT graft without bone blocks. However, the tendinous portion provided enough length for clamping outside of the simulated intra-articular length. Only 11.11% of the PT grafts failed at the tendon-clamp interface, while the rest of the PT grafts failed at the midsubstance level. All ultimate tensile strength and mechanical property calculations for the PT graft were consistent with those reported in previous literature.

In addition, the older age of the cadaveric specimens used in this study may limit the generalizability of its findings to a younger population. Although there is no clear conclusion about the effect of aging on tendon mechanical properties, an association between aging and reduced ultimate tensile strength, stiffness, and Young modulus exists.[16] Woo et al[37] found that the ultimate tensile strength and stiffness of the native ACL was 2160 N and 242 N/mm in younger patients compared with 658 N and 124 N/mm in older patients. Previous studies on QT grafts have reported a mean cadaveric age range from 41.5 to 79 years (with overall age ranges between 19 and 108 years).[11,13,29,34]

Last, this study used metal serrated clamps as validated by Shi et al[31] due to their ability to sustain loads of 2500 to 6870 N. The mode of clamping the graft for failure testing can affect mechanical properties. For example, cryogenic clamps have been shown to increase the maximum level of load.[12,30] The use of cryogenic clamps may have mitigated the effects of clamped tendon aspect ratios on mechanical property calculations.

CONCLUSION

The 8-mm QT graft had higher ultimate tensile strength than the 10-mm PT graft, and the 6-mm QT graft was comparable to the 10-mm PT graft. Given these biomechanical properties, smaller QT graft sizes may be advantageous in minimizing arthrofibrosis risk while maintaining graft strength.

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