Two-Dimensional Magnetic Resonance Imaging in Preparation for Autograft Anterior Cruciate Ligament Reconstruction Demonstrates Quadriceps Tendon Is Thicker Than Patellar Tendon

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Purpose: The purpose of this study was to assess patellar tendon (PT) and quadriceps tendon (QT) thickness on preoperative magnetic resonance imaging (MRI), in both the sagittal and axial planes, at multiple points along each tendon, and to correlate these findings to anthropometric patient data before anterior cruciate ligament (ACL) surgery. **Methods:** Patients who underwent PT or QT autograft ACL reconstruction between 2020 and 2022 and who had preoperative MRIs with adequate visualization of the proximal QT and distal PT were retrospectively identified. Patient demographics were recorded (age, height, weight, sex, injury side). Preoperative MRI measurements were performed by 3 independent examiners using standardized protocol. Preoperative MRI measurements were the QT anterior-posterior (AP) thickness at 1, 2, and 4 cm from the proximal patella on axial and sagittal MRI images at the central aspect of the tendon, as well as PT AP thickness at 1, 2, and 4 cm from the distal patella on axial and sagittal MRI images at the central aspect of the tendon. **Results:** Forty-one patients (21 females, 20 males) were evaluated, with a mean age of 33.4 years. The quadriceps tendon was significantly thicker than the patellar tendon at all measured locations ($P < .0001$) with average QT versus PT thickness (in mm) at each level sagittal 1 cm (7.13 vs 4.35), sagittal 2 cm (7.41 vs 4.44), sagittal 4 cm (7.26 vs 4.81), axial 1 cm (7.35 vs 4.50), axial 2 cm (7.63 vs 4.47), axial 4 cm (7.46 vs 4.62), respectively. There were no significant correlations between tendon size and patient body mass index. **Conclusion:** The quadriceps tendon is significantly thicker than the patellar tendon at 1, 2, and 4 cm from the patella in both males and females based on preoperative MRI before ACL surgery. **Clinical relevance:** Investigating the thickness of the tendons available for autograft harvest before surgery will give us a better understanding of tendon anatomy in the setting of ACL reconstruction.

Current literature estimates greater than 200,000 anterior cruciate ligament (ACL) injuries occur in the United States each year.[1-3] Accordingly, ACL reconstruction is one of the most performed orthopaedic surgical procedures, with an estimated 100,000 to 175,000 reconstructions performed annually in the United States.[3-5] Optimal graft choice for reconstruction continues to be an area of ongoing debate and intense clinical research. Since the 1980s, bone-patellar tendon-bone (BTB) autograft has been considered the gold standard, particularly among reconstruction in athletes playing contact or pivoting sports.[6-8] Hamstring (HS) autograft has also become a popular graft option, often because of less donor site morbidity than a BTB

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graft harvest.[9] Recent literature has shown increased failure rates associated with the use of HS autograft, particularly in young athletes, which, combined with BTB donor site morbidity, has led to the emergence of quadriceps tendon (QT) autograft as an increasingly popular option.[10-21] Overall, however, multiple studies have generally shown similar clinical results among all of these grafts.[22-29]

Autograft selection is a complex process that involves a multitude of factors including patient age, patient expectations and desired activity level, quality of host tissue, sex, donor site morbidity, cosmesis concerns, type of fixation, concomitant pathology/injury, remodeling capability at the donor site, and graft ligamentization. Additionally, graft size has been shown to have clinical implications. Multiple studies have reported worse outcomes and higher failure rates in ACL reconstruction performed with HS autografts less than 8 mm in diameter.[30-32] Outcomes relating to preoperative tendon thickness as measured by magnetic resonance imaging (MRI) with respect to PT and QT are less well defined. Roach et al. found that BTB reconstruction failures were associated with significantly thicker patellar tendons at the inferior pole of the patella, likely indicative of preexisting patellar tendinopathy.[33] In a review of the New Zealand ACL Registry, Murgier et al. reported that, in skeletally mature patients under age 20 who had undergone ACL reconstruction with either HS or BTB autograft, BTB grafts had the largest mean diameter and lowest overall failure rate.[34]

Given the association of graft size with clinical outcomes, predictability of autograft size may be important. Multiple studies have attempted to predict HS tendon size using anthropometric patient characteristics, with relatively poor resultant reliability.[30,35-37] Literature pertaining to predictability of PT and QT graft size is less prevalent. MRI is ubiquitous in the preoperative assessment of ACL injury and has been shown to be an effective and reliable means of confirming the existence and location of injury.[38,39]The ability to, at best, reliably predict eventual graft size based on preoperative MRI evaluation or, at minimum, have a solid understanding of the quality and thickness of the tendon available may therefore help guide the surgeon in both graft choice and overall surgical planning and decision making.

The purposes of this study were to assess PT and QT thickness on preoperative MRI, in both the sagittal and axial planes, at multiple points along each tendon, and to correlate these findings to anthropometric patient data before ACL surgery. Our hypothesis was that the QT would be larger (thicker) than the PT at all measurement points and that males would have significantly larger tendons than females.

Material and Methods

Institutional review board approval was obtained for this study. A retrospective chart review was performed of patients who underwent PT or QT autograft ACL reconstruction between 2020 and 2022 at a single, high-volume academic medical center who had preoperative MRIs with identified adequate scope of the proximal QT and distal PT. Inclusion criteria included patients over 18 years of age with an MRI having adequate field of view in the sagittal and axial planes. Exclusion criteria included patients younger than 18 years of age, an inadequate MRI (if the MRI cut off before 4 cm proximal or distal to the proximal or distal pole of the patella in either the axial or sagittal plane), any prior knee surgery including prior ACL reconstruction, or any documented history of either patellar or quadriceps tendonitis, tendon tears, or other pathology. Data collected included patient age, height, weight, sex, and injury side. Body mass index (BMI) was calculated using height and weight (kg/m^2). MRI imaging was routinely performed using a standardized protocol on a 1.5T or 3T closed bore magnet. The MRI examinations were performed at our institution and used 16 cm × 16 cm field of view in each plane. The McKesson “Radiology Station Lite” PACs (picture archiving and communication system) viewer system was used for image review and measurements. This viewer system reports accuracy in distance measurement to 0.1 mm and angular measurement to 0.1°.

Three observers, a fellowship-trained board-certified musculoskeletal radiologist (L.K.P.), a sports medicine fellowship—trained board-certified orthopaedic surgeon (C.W.N.), and an orthopaedic sports medicine fellow (D.S.), independently evaluated the MRIs and were blinded to the assessments of the other observers. MRI measurements were recorded as follows: cross-linked images in the axial (proton density with fat saturation) and sagittal planes (proton density without fat saturation) were used to determine the sagittal slice that best bisected the tendon in the axial plane (Fig 1). Distances of 1, 2, and 4 cm were then measured on the chosen sagittal slice, from either the proximal pole (QT) or distal pole of the patella (PT) (Fig 2). For sagittal plane measurement of anterior-to-posterior (AP) thickness, lines were drawn perpendicular to the proximal/distal measurement lines, and the AP thickness was recorded (Fig 3). For axial plane measurements, the slice best corresponding to the sagittal distances of 1, 2, and 4 cm was obtained, the medial-to-lateral width of the tendon was measured, and a perpendicular line bisecting the width was used to measure AP thickness (Fig 4). A total of 12 tendon thickness measurements were recorded for each MRI: PT AP thickness at each measurement point (1, 2, and 4

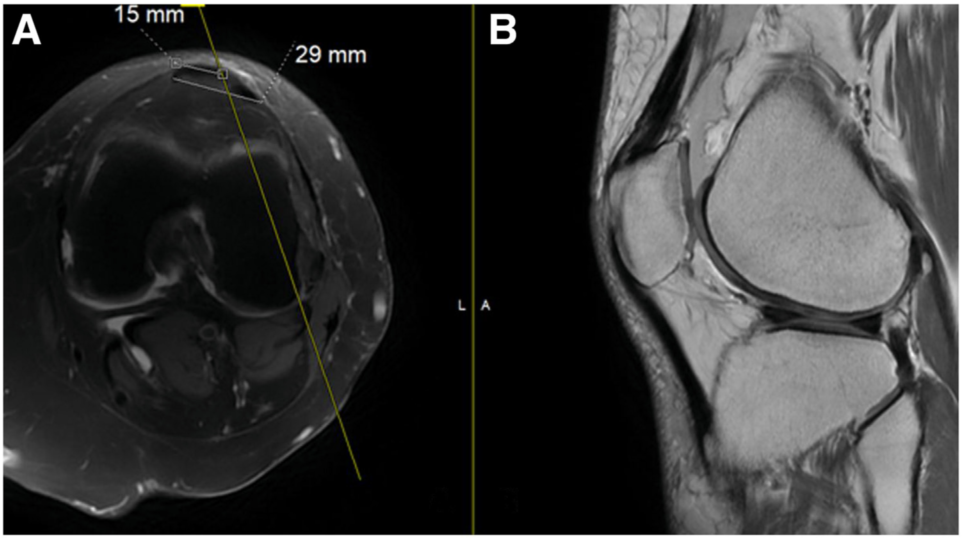

Fig 1. Proton density fat-suppressed axial (A) and proton density non-fat-suppressed sagittal (B) magnetic resonance images in a right knee depicting the method using a localizer line on the axial slice (A) to determine the midsagittal position of the quadriceps tendon to then measure thickness in the sagittal plane (B).

cm) on axial slices, PT AP thickness at each point on sagittal slices, QT AP thickness at each point on axial slices, and QT AP thickness at each point on sagittal slices.

Statistical Analysis

All data were summarized using measures of center and spread, to include means with standard deviations and medians and interquartile ranges. A power analysis was performed that yielded a total of 20 male and 20 female patients needed to be powered to >0.80. Paired *t*-tests (or a paired Mann-Whitney test if normality could not be assumed) were used to compare mean differences of the QT and PT from the same sample. Mann-Whitney or independent t-tests were utilized to test sex differences. Inter-observer reliability was measured by the reliability coefficient, Krippendorff's alpha. A threshold coefficient greater than 0.667 indicates sufficient inter-rater reliability. The 95% confidence intervals were calculated using the bootstrap method, and inference was used with a threshold *P* value <.05 and testing for differences, indicating sufficient interobserver reliability. The pairwise differences between each combination of two observers were further checked and the patients with poor consistency of assessments were identified. When insufficient reliability was indicated, the reliabilities were recalculated after removing patients with poor consistency of assessments. The relationships between injury side/laterality and the difference in QT and PT AP thickness at

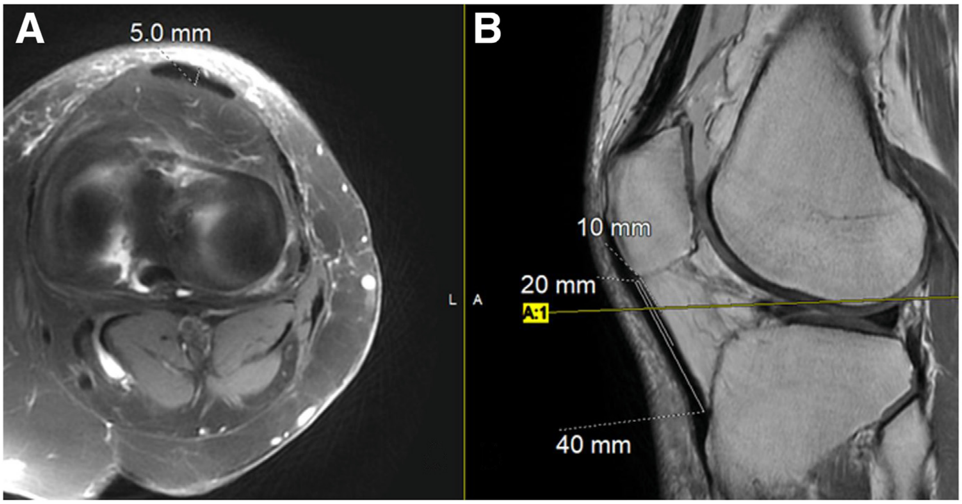

Fig 2. Proton density fat-suppressed axial (A) and proton density non-fat-suppressed sagittal (B) magnetic resonance images in a left knee showing the method for measuring the thickness of the patellar tendon at 1, 2 and 4 cm from the distal patella in both the axial and sagittal planes.

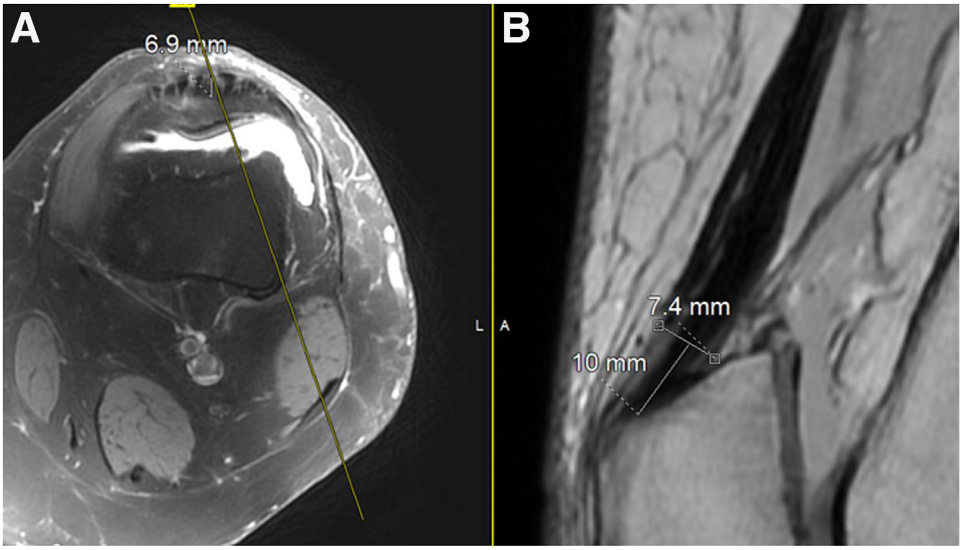

Fig 3. Proton density fat-suppressed axial (A) and proton density non-fat-suppressed sagittal (B) magnetic resonance images in a left knee depicting the method for measuring the thickness of the quadriceps tendon at 1 cm from the proximal patella in both the axial and sagittal planes.

each measurement point was assessed using simple linear regression. All statistical assumptions were checked and met.

Results

A total of 20 male and 21 female patients who met inclusion criteria were identified, providing an approximate 1:1 male (48.8%) to female (51.2%) ratio, with a mean age of 33.4 years (18-54) and average BMI 31.67 ± 6.49. There were 20 left knees and 21 right knees evaluated. The mean QT and PT AP thicknesses across all observers at each measurement distance were calculated and used for statistical comparisons. The QT was significantly thicker than the PT at all measured locations, with the largest difference observed in the axial plane at 2 cm (Table 1; $P < .0001$). The QT ranged from 7.13 to 7.46 cm in thickness, whereas the PT ranged from 4.35 to 4.81 cm (Table 1). Males averaged thicker QT and PT than females at all locations, but only the PT at 1 cm and 2 cm in the axial plane and at 2 cm in the sagittal plane were statistically thicker (Table 2). There was no significant association between the difference in QT and PT thickness at any of the measured distances with respect to laterality or separately with respect to BMI.

Interobserver reliability was moderate (Table 3), with no reliability coefficient greater than the threshold 0.667. In addition, these reliability values were quite variable. However, when considering reliability across pairs of raters, stronger reliability was observed, particularly among the most experienced raters. However, removing outliers did not increase the number of

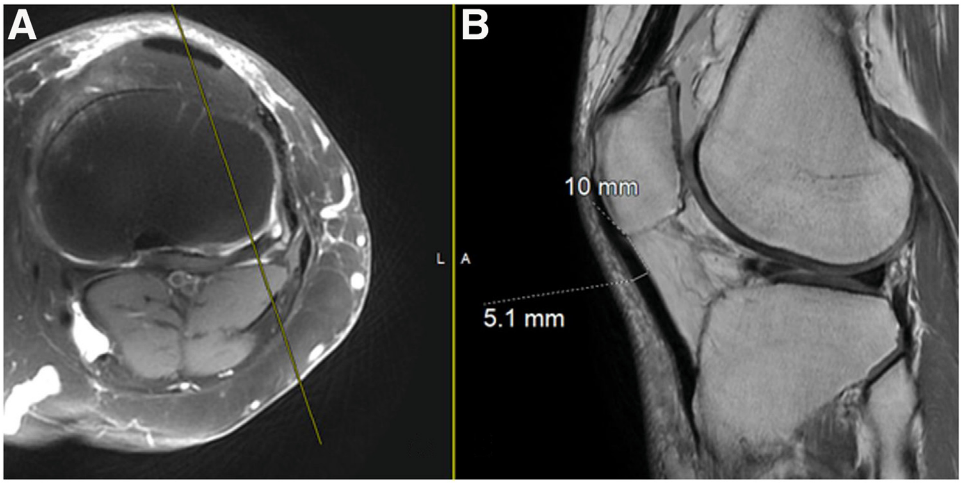

Fig 4. Proton density fat-suppressed axial (A) and proton density non-fat-suppressed sagittal (B) magnetic resonance images in a left knee depicting the method for measuring the thickness of the patellar tendon at 1 cm from the distal patella in both the axial and sagittal planes.

Table 1. Measures of Center and Spread for the QT and PT at 1, 2, and 4 Cm in Both the Sagittal and Axial Planes for the Entire Study Cohort

Measurements	Mean	SD	Median	IQR	*P* Value
Sagittal 1 cm					**<.001**
QT	7.09	1.02	7.07	[6.37, 8]	
PT	4.24	0.77	4.20	[3.73, 4.63]	
Sagittal 2 cm					**<.001**
QT	7.35	0.95	7.40	[6.93, 7.87]	
PT	4.33	0.72	4.33	[3.7, 4.57]	
Sagittal 4 cm					**<.001**
QT	7.25	0.96	7.20	[6.7, 7.73]	
PT	4.66	0.60	4.67	[4.3, 5.03]	
Axial 1 cm					**<.001**
QT	7.31	1.03	7.30	[6.4, 8.13]	
PT	4.41	0.69	4.37	[4, 4.63]	
Axial 2 cm					**<.001**[*]
QT	7.58	0.94	7.47	[7.1, 8.17]	
PT	4.32	0.64	4.23	[3.9, 4.7]	
Axial 4 cm					**<.001**
QT	7.40	1.02	7.23	[6.7, 7.97]	
PT	4.41	0.55	4.27	[4.13, 4.83]	

IQR, interquartile range; PT, patellar tendon; QT, quadriceps tendon; SD, standard deviation.

Bolding indicates statistical significance at the .05 level.

*Indicates use of paired Mann-Whitney test, all others used paired *t* test.

reliability measures beyond the threshold value of 0.667 in across pairs of raters but only increased the reliability as anticipated.

Discussion

The present study shows that the QT is a substantially thicker tendon than the PT at 1, 2, and 4 cm from the proximal and distal pole of the patella, respectively, confirming our hypothesis that the QT would be significantly larger at all measurement distances. This finding is in line with other literature where the tendons were assessed in a single plane at shorter distances from the patella.[40] The difference in thickness also remained significant regardless of patient sex, independent of BMI and laterality. The measurement data in this study also supports the notion that the QT is a reliable source of a graft of larger size, which is in line with previous literature correlating MRI determined cross-sectional area with intraoperative graft dimensions.[41] In contrast, multistrand HS tendons, the other most commonly used soft tissue graft, are not as uniform and may be less predictable with regard to tendon thickness and overall size.[42] Weltsch et al.[43] found that circumferential preconditioning of a multistrand HS graft resulted in a 1 mm decrease in graft diameter before implantation and consequently the ability to place a more uniform graft into a smaller tunnel. The clinical and tunnel widening implications of this remain unclear.

There is a paucity of literature evaluating the size of the tendinous component of a BTB ACL autograft with regard to clinical outcomes, and, invariably in the existing literature, the "size" as it pertains to a BTB graft most commonly refers to the size of the bone plug. Although the bone plugs are the primary area of graft fixation for a BTB graft, the tendon is frequently what is present at the joint aperture, particularly on the tibial side. Given this finding and its thinner size, some authors have therefore described the PT as more of a "ribbon," as opposed to a circumferential graft such as a HS or QT. Along those lines, biomechanical studies have shown that the residual tensile strength of a QT after harvest of a 10 mm wide graft is stronger than that of an intact PT and significantly greater than a PT after a 10 mm central harvest.[44] The true clinical implication of the actual size of the PT itself on definitive graft function, kinematics, and re-tear rates, however, remains to be seen.

Table 2. Measures of Center and Spread for the QT and PT Size Stratified by Sex (Male and Female) at 1, 2, and 4 cm From the Patella, Measured in Both the Sagittal and Axial Planes

	Female				Male				
Measurement	Mean	SD	Median	IQR	Mean	SD	Median	IQR	*P* Value
QT Sagittal 1 cm	6.93	0.99	6.87	[6.33, 7.47]	7.26	1.05	7.47	[6.37, 8.14]	.303
QT Sagittal 2 cm	7.28	0.81	7.40	[7.03, 7.57]	7.43	1.10	7.38	[6.48, 8.42]	.614
QT Sagittal 4 cm	7.01	0.86	7.20	[6.53, 7.47]	7.50	1.02	7.18	[6.76, 8.12]	.104
QT Axial 1 cm	7.13	1.08	7.17	[6.27, 7.9]	7.50	0.97	7.38	[6.79, 8.3]	.267
QT Axial 2 cm	7.51	0.81	7.43	[7.1, 8.17]	7.66	1.07	7.48	[7.07, 8.48]	.613
QT Axial 4 cm	7.16	0.83	7.23	[6.7, 7.67]	7.66	1.15	7.37	[6.69, 8.47]	.322
PT Sagittal 1 cm	4.04	0.60	4.00	[3.73, 4.57]	4.45	0.89	4.32	[3.92, 4.98]	.092
PT Sagittal 2 cm	4.11	0.56	4.23	[3.7, 4.53]	4.56	0.80	4.42	[4.08, 4.94]	**.046**
PT Sagittal 4 cm	4.53	0.53	4.43	[4.17, 4.87]	4.80	0.65	4.73	[4.43, 5.11]	.158
PT Axial 1 cm	4.12	0.50	4.33	[3.87, 4.47]	4.72	0.74	4.58	[4.31, 5.34]	**.005**
PT Axial 2 cm	3.99	0.44	3.97	[3.67, 4.3]	4.68	0.63	4.67	[4.17, 4.94]	**.000**
PT Axial 4 cm	4.26	0.56	4.23	[3.9, 4.47]	4.58	0.50	4.57	[4.22, 4.95]	.059

PT, patellar tendon; QT, quadriceps tendon.

Bolding indicates statistical significance at the 0.05 level.

Table 3. Interobserver Reliability (Krippendorf's alpha) of Both QT and PT Thickness Measurements From 3 Independent Observers at 1, 2, and 4 Cm From the Patella Across All Raters and Before and After Outlier Removal Between Rater Pairs

	Overall, Across Raters			Before Outlier Removal Alpha Between Raters			After Outlier Removal Alpha Between Raters		
Measurement	Alpha	95% CI alpha	*P* Value	A vs B	A vs C	B vs C	A vs B	A vs C	B vs C
QT Sagittal 1 cm	0.571	[0.4324, 0.7]	.923	0.562	0.737	0.473	0.643	**0.838**	0.555
QT Sagittal 2 cm	0.574	[0.4381, 0.6841]	.574	0.945	0.455	0.581	0.555	**0.784**	0.651
QT Sagittal 4 cm	0.525	[0.3681, 0.6583]	.980	0.496	0.419	0.653	0.624	0.524	0.716
QT Axial 1 cm	0.530	[0.4154, 0.644]	.992	0.522	0.674	0.419	0.602	0.722	0.502
QT Axial 2 cm	0.591	[0.4671, 0.7023]	.896	0.657	0.616	0.520	0.736	0.695	0.584
QT Axial 4 cm	0.589	[0.4598, 0.7066]	.905	0.626	0.480	0.654	0.689	0.568	0.718
PT Sagittal 1 cm	0.626	[0.521, 0.723]	.795	0.513	0.694	0.691	0.578	**0.762**	0.754
PT Sagittal 2 cm	0.609	[0.5075, 0.7086]	.880	0.515	0.707	0.612	0.603	**0.770**	0.678
PT Sagittal 4 cm	0.322	[0.121, 0.5101]	1.000	0.152	0.330	0.459	0.273	0.472	0.567
PT Axial 1 cm	0.583	[0.4749, 0.6836]	.943	0.574	0.493	0.668	0.661	0.578	0.712
PT Axial 2 cm	0.546	[0.3947, 0.6721]	.968	0.394	0.598	0.646	0.498	0.665	0.747
PT Axial 4 cm	0.316	[0.0298, 0.5446]	.999	0.114	0.457	0.354	0.215	0.597	0.491

CI, confidence interval; PT, patellar tendon; QT, quadriceps tendon.

Raters were a sports medicine fellowship-trained board-certified orthopaedic surgeon (rater A), a fellowship-trained board-certified musculoskeletal radiologist (rater B), and an orthopaedic sports medicine fellow (rater C). Bolded denotes thresholds statistically greater than 0.667.

Other studies have also sought to correlate preoperative MRI to patient characteristics. Zakko et al.[40] examined MRI imaging of HS, PT, and QT of 62 ACL reconstruction patients and correlated sagittal dimensions of QT and PT and axial dimensions of HS tendons to anthropometric characteristics, finding high interobserver reliability in measurement and significant correlation of sagittal QT and PT thickness with anthropometric data. In a review of pediatric ACL reconstruction patients, Baghdadi et al. found a QT sagittal thickness of 6.7 mm, as measured on preoperative MRI, to be reliably predictive for obtaining a graft of 8 mm in diameter, as measured intraoperatively. Takeuchi et al.[45] reviewed 31 QT ACL reconstruction patients and found that cross-sectional area of the tendon, as measured at a single point of maximum thickness, significantly correlated with intraoperative graft diameter.[41] Given these findings, using preoperative MRI measurements may therefore be beneficial in predicting intraoperative graft size. Knowing potential graft size before surgery may aid the surgeon in graft choice and surgical planning.

Similar to these studies, we found some differences between PT thickness in males and females. In particular, we found proximal PT axial AP thickness in females was found to be statistically significantly smaller than in males. Previous studies have shown that central harvest of a 10 mm graft leaves a larger residual volume in the QT as compared to the PT, with PT volume reduced by a mean of 43.4%.[46] Clinical implication of this finding could be that a central harvest of the standard 10 mm central graft from the PT of females could proportionately reduce residual volume more than a 10 mm graft from the QT, where no such relationship between tendon thickness and sex was identified. Although the measurements at each data point were larger for males than females, they were not all statistically significant.

Some studies have evaluated correlating preoperative tendon size estimation using MRI to final intraoperative graft size. In a study using 3-dimensional MRI to predict QT and HS tendon graft size, Ashford et al.[47] found mean cross-sectional area of quadrupled HS and QT grafts were 47.2 mm^2 and 84.4 mm^2, respectively. Nine of the 54 patients in the study had predicted quadrupled HS grafts deemed insufficient for use in ACL reconstruction (<8 mm diameter), whereas all predicted QT grafts were sufficient. Similar to their study, our study showed the quadriceps to have large tendon thickness, with similar size ratios to their findings. Also similar to their study, QT thickness did not significantly correlate with patient specific parameters, specifically height, weight, or BMI. In contrast to their study, we measured the tendon thickness at multiple levels (1, 2, and 4 cm), whereas they measured thickness at only one point (3 cm). Given differences in patient size, a harvested graft may result in the graft being at a tunnel aperture (on either the femur or the tibia) at varying distances from the end of the graft itself (1 or 2 cm or more) during an ACL reconstruction; we therefore elected to obtain size measurements at each of these graft distances.

This study has clinical relevance in that use of preoperative MRI to assess QT and PT size is relatively simple to do, widely available, and potentially valuable. In some imaging centers, smaller fields of view may not include a full 4 cm of QT within the study and could limit ability to conduct full preoperative measurements unless MRI protocols were adjusted, but most centers would afford being able to measure at least 2 cm from the tendon insertion (which would typically be the amount within a bone socket or tunnel). Knowledge of approximate graft size before surgery can aid in selection of the appropriate graft, guide joint decision-making discussions with the patient and help avoid the pitfall of harvesting an inadequate graft. Additionally, the ability to assess graft size before surgery could lead to shorter operative times and, ultimately, fewer complications. Finally, having relative means provides a useful reference point for future comparisons and future study.

Limitations

There are limitations to this study. One limitation was moderate inter-observer reliability of measurements. The protocol to select MRI slices and take measurements was well defined, yet the mean reliability coefficient value was moderate at best. When adjusted for outliers and observers were matched pairwise, reliability improved, but was not consistently greater than the 0.667 threshold for Krippendorff's alpha. This is likely due to the precision capabilities of the imaging system within the context of the overall dimensions of the tendon. The smallest incremental change in measurement possible with the system employed was 0.1 mm, and reliability was worse on the smaller PT, where 0.1 mm differences make up a larger percentage of the overall tendon size. Additionally, the viewer only displayed up to 2 numerical places, so measurements above 10 mm did not include tenths of millimeters. It is also possible that despite the detailed protocol, the observers did not all measure at the exact same points on the MRIs to perform measurements, which would predispose to slight differences in measurements. Obtaining tendon dimensions at multiple points in two planes, however, likely increases the accuracy of the measurements and the overall tendon size evaluations and makes the final means useful as part of the overall evaluation.

Other limitations of the study include the retrospective nature, lack of correlation with intraoperative graft size, and the exclusion of MRIs that did not extend far enough proximally or distally to meet the 4 cm measurement point. Some patients did not have imaging that extended to 4 cm above or below, thus resulting in a cohort that was not a consecutive subset of surgical patients.

Conclusions

The QT is significantly thicker than the PT at 1, 2, and 4 cm from the patella in both males and females based on preoperative MRI before ACL surgery.

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