Can We Accurately Predict the Quadruple Hamstring Graft Diameter From Preoperative Magnetic Resonance Imaging?

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Background: Anterior cruciate ligament (ACL) reconstruction with a quadruple hamstring (QH) autograft is a widely utilized procedure with good outcomes. A graft diameter less than 8 mm, however, has been associated with higher revision rates. Accurately determining the diameter of the hamstring tendon preoperatively can help surgeons plan accordingly.

Purpose/Hypothesis: The purpose of our study was to determine whether QH graft size can be reliably predicted from preoperative magnetic resonance imaging (MRI) measurements. We hypothesized that we can achieve a high predicted QH graft size correlation with regard to preoperative and intraoperative measurements.

Study Design: Cohort study (diagnosis); Level of evidence, 2.

Methods: We evaluated patients undergoing ACL reconstruction using QH autografts. At the time of surgery, the semitendinosus tendon (ST) and gracilis tendon (GT) were harvested and sized and then sized as a QH graft. Preoperative individual ST and GT sizes were determined from T2-weighted fat-saturated MRI at 3 cm above the joint line using correlating axial and coronal images. We then used a predictive chart to predict what the size of the QH graft would be and compared this with the actual measurements. Pearson correlation coefficients between predicted and actual graft sizes were calculated.

Results: The predicted GT graft size was within 0.5 mm of the actual size in 45 of 60 (75%) patients and within 1 mm of the actual graft size in 59 of 60 (98%) patients. The predicted GT graft size from MRI measurements correlated with the actual GT graft size ($r = 0.62$, $P < .00001$). The predicted ST graft size was within 0.5 mm of the actual size in 45 of 60 (75%) patients and within 1 mm of the actual graft size in 56 of 60 (93%) patients. The predicted ST graft size from MRI measurements correlated with the actual ST graft size ($r = 0.71$, $P < .00001$). The predicted QH graft size was within 0.5 mm of the actual size in 52 of 60 (87%) patients and within 1 mm of the actual graft size in 60 of 60 (100%) patients. The predicted QH graft size from MRI measurements correlated with the actual QH graft size ($r = 0.81$, $P < .00001$).

Conclusion: The current technique can reliably predict the size of a QH graft within 1 mm of the final graft size.

Keywords: anterior cruciate ligament; hamstring; autograft; magnetic resonance imaging

Anterior cruciate ligament (ACL) reconstruction is a common procedure performed in the United States; however, the ideal selection for an autograft in reconstruction remains controversial between bone–patellar tendon–bone, quadruple hamstring (QH) tendon, and quadriceps tendon grafts.[14,19] Good results have been observed in terms of functional outcomes with the use of QH autografts.[10,15] One disadvantage of this technique is that a QH graft diameter less than 8 mm may be associated with early revision after ACL reconstruction in young patients.[3,9,13] Predicting which patients are at risk of a small graft size can be challenging, however, our belief is that if such patients can be identified before surgery, alternative choices, such as the use of bone–patellar tendon–bone or quadriceps tendon autografts, could be discussed with the patients and included in their preoperative plan.

Historically, predicting the expected QH graft size from preoperative imaging or anthropometric measurements has shown fair to moderate correlation with actual intraoperative measurements.[8,12,17,20] There have been several imaging studies using ultrasound, computed tomography, and magnetic resonance imaging (MRI). A study using computed tomography demonstrated no statistical significance in predicting the graft diameter.[21] A recent study using ultrasound proved to be unreliable for predicting the final graft diameter.[11] The other imaging-based studies utilizing

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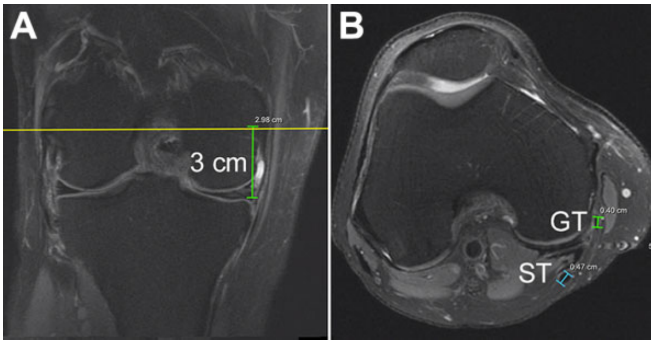

Figure 1. T2-weighted (A) coronal and (B) axial magnetic resonance imaging of a knee. The diameters of the gracilis tendon (GT) and semitendinosus tendon (ST) were measured at 3 cm from the joint line.

MRI used cross-sectional area to determine the expected QH graft diameter; however, only a moderate correlation was achieved.[2,4,5,7,16,18] This is likely because a nonlinear relationship exists between the individual hamstring tendon diameters and the actual QH graft size.

The purpose of the current project was 3-fold. First, we aimed to determine the most accurate level above the joint line at which to measure the diameter of the gracilis tendon (GT) and semitendinosus tendon (ST) on MRI. Next, we sought to develop a predictive chart to accurately determine the QH graft diameter based on the individual GT and ST diameters. Finally, by using our predictive table and the MRI-measured diameter of each hamstring tendon, we investigated whether we could accurately determine the actual intraoperative QH graft diameter.

METHODS

Part 1: Determining the Most Accurate Distance Along the Hamstring Tendon to Measure the Diameter

We retrospectively reviewed 40 consecutive ACL reconstructions performed from March 2009 to February 2011 by a single surgeon (S.A.) using a QH autograft. During surgery, both the GT and ST diameters were individually measured with a standard graft sizer to the nearest 0.5 mm and recorded in the operative report. The first part of our study was determining the most accurate level above the joint line at which to measure the diameter of the GT and ST. For this, we paired coronal and axial T2-weighted sequences with fat saturation from patients' preoperative MRI scans. The coronal images were used to measure 1-cm increments from the medial joint line. The corresponding axial images for each 1-cm increment were then used to measure the diameter of both the ST and GT at their widest portion (Figure 1). These diameters were then recorded for each tendon at 1, 2, 3, 4, and 5 cm above the joint line. We then used these values and correlated them with the actual intraoperatively measured ST and GT diameters.

Part 2: Determining the QH Graft Diameter

To elucidate the nonlinear relationship between individual hamstring tendons and the QH graft diameter, 31 GT allografts, ranging in diameter from 2.5 to 6.5 mm, were each paired with 31 ST allografts, ranging in diameter from 3.5 to 7.5 mm. Each allograft was allowed to thaw to room temperature. Each end of the tendon was then whipstitched with a No. 2 absorbable suture to secure it when passing through the sizing block. With each combination of allografts, the final QH graft diameter was measured using a standard graft sizing block with holes in 0.5-mm increments (Arthrex).

Part 3: Predicting the QH Graft Diameter

We performed parts 1 and 2 of our study to prospectively predict individual GT and ST sizes as well as QH graft sizes in 60 consecutive patients undergoing ACL reconstruction performed by 2 sports medicine fellowship–trained surgeons (G.A., S.A.). To qualify for the study, patients had to have had MRI scans available for review within our picture archiving and communication system (PACS) and to have undergone ACL reconstruction using a QH autograft. Patients included in this study either underwent ACL reconstruction with a standard QH graft or continuous loop all-inside reconstruction, depending on surgeon preference.

MRI Measurements

MRI was performed with a 1.5-T magnet (GE Healthcare) using a knee-specific coil. All MRI scans were reviewed and measured by 1 of 2 authors (N.V., B.M.), who were blinded to operatively measured hamstring tendon diameters. The PACS was set to view the T2-weighted coronal and axial images. The measuring tool was then used to measure a

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Ethical approval for this study was waived by the Allegheny Health Network Institutional Review Board.

TABLE 1
Correlation of ST and GT Diameters on MRI at 1-cm Increments to Intraoperatively Measured ST and GT Diameters[a]

Distance	*r* Value	*P* Value
1 cm	0.352	.024
2 cm	0.438	.004
3 cm	0.554	.0001
4 cm	0.513	.001
5 cm	0.275	.082

[a]GT, gracilis tendon; MRI, magnetic resonance imaging; ST, semitendinosus tendon.

distance of 3 cm cephalad from the medial tibial plateau. The cross-hair tool was then used to find the corresponding axial cut 3 cm above the joint line. At this point, the diameters of the ST and GT were determined from the widest dimension at that level (Figure 1).

Graft Harvest

All ACL reconstructions were performed using a standard technique. Briefly, a standard anteromedial incision was made, the distal ends of the ST and GT were peeled off with a periosteal flap, and the tendons were harvested with a tendon stripper. The tendons were then prepared on a back table by removing all muscle and fatty tissue and using a looped No. 2 nonabsorbable suture to whipstitch both ends with 4 to 5 passes on each end of the tendon. The tendons were then individually measured with a graft sizer and recorded. Both tendons were then doubled over a single suture and passed through the graft sizing block. The smallest 0.5-mm increment sizing hole through which the QH graft could be pulled was the final recorded diameter.

Statistical Analysis

Pearson correlation coefficients were calculated to determine (1) the distance above the joint line that was most predictive of the actual individual hamstring tendon sizes, (2) the relationship between the predicted individual hamstring tendon diameters (ST and GT) and the measured intraoperative diameters, and (3) the relationship between the predicted QH graft diameter and the actual measured diameter. All of the analyses were performed with Minitab statistical software (version 16; Minitab).

RESULTS

Part 1: Determining the Most Accurate Distance Along the Hamstring Tendon to Measure the Diameter

The GT and ST measured at 3 cm above the medial joint line had the highest correlation with the actual measured graft diameter ($r = 0.554$, $P = .0001$) (Table 1). Of the 40 cases reviewed, 32 (80%) had a graft diameter within 0.5 mm when measured at 3 cm from the medial joint line.

Part 2: Determining the QH Graft Diameter

The most common cadaveric graft sizes for the GT and ST were 3.5 mm and 4.5 mm, respectively. There were 215 QH grafts created from that combination. In all, 961 combinations were measured, and the average diameter for each combination was calculated (Table 2).

We then used the average diameters to create a predictive chart for the QH graft diameter. Given the fact that the hamstring tendon is typically measured intraoperatively in 0.5-mm increments via a sizing block, we rounded all average QH graft diameters to the next 0.5-mm diameter (Table 3). For example, if a QH graft measured 9.65 mm intraoperatively, it would not fit through a 9.5-mm block and would instead receive an intraoperative measurement of 10 mm.

Part 3: Predicting the QH Graft Diameter

After applying the inclusion and exclusion criteria for the final part of our study, a total of 60 patients (34 male and 26 female) qualified for the study and underwent ACL reconstruction using a QH autograft from January 2016 to December 2018. The average age of the patients was 21.1 years (range, 11-43 years). The average MRI-measured GT diameter was 3.50 ± 0.47 mm. The average MRI-measured ST diameter was 4.53 ± 0.63 mm. The average intraoperatively measured GT diameter was 3.47 ± 0.42 mm. The average intraoperatively measured ST diameter was 4.42 ± 0.47 mm. The average intraoperatively measured QH graft diameter was 7.71 ± 0.73 mm. The average predicted QH graft diameter was 7.63 ± 0.89 mm. The percentage of patients in our study with QH graft diameters less than 8 mm was 50%.

The predicted GT graft size was within 0.5 mm of the actual size in 45 of 60 (75%) patients and within 1 mm of the actual graft size in 59 of 60 (98%) patients. The predicted GT graft size from MRI measurements correlated with the actual GT graft size ($r = 0.62$, $P < .00001$). The predicted ST graft size was within 0.5 mm of the actual size in 45 of 60 (75%) patients and within 1 mm of the actual graft size in 56 of 60 (93%) patients. The predicted ST graft size from MRI measurements correlated with the actual ST graft size ($r = 0.71$, $P < .00001$). The predicted QH graft size was within 0.5 mm of the actual size in 52 of 60 (87%) patients and within 1 mm of the actual graft size in 60 of 60 (100%) patients. The predicted QH graft size from MRI measurements had a high correlation with the actual QH graft size ($r = 0.81$, $P < .00001$) (Table 4).

DISCUSSION

The hamstring tendon diameter plays an important role in predicting ACL reconstruction failure.[12-14] Unlike patellar tendon or quadriceps tendon autografts, in which a consistent diameter can be attained, the diameter of a hamstring tendon autograft is highly variable and traditionally not known until harvested.

TABLE 2
Graft Diameter Combinations[a]

GT Diameter	ST Diameter 3.5 mm	4.0 mm	4.5 mm	5.0 mm	5.5 mm	6.0 mm	6.5 mm	7.5 mm
2.5 mm	5.25 (2)	6.25 (2)	6.25 (2)	7.33 (3)	8.00 (1)	—	—	—
3.0 mm	5.75 (2)	6.25 (2)	7.50 (18)	7.82 (11)	8.20 (3)	9.50 (2)	10.00 (1)	10.50 (1)
3.5 mm	6.13 (8)	6.94 (8)	7.87 (215)	8.09 (116)	8.52 (26)	9.69 (24)	10.15 (12)	10.61 (12)
4.0 mm	6.75 (4)	7.38 (4)	8.03 (116)	8.24 (62)	8.59 (16)	9.85 (14)	10.07 (7)	10.71 (7)
4.5 mm	7.25 (4)	7.75 (4)	8.49 (100)	8.75 (54)	9.28 (14)	10.33 (12)	10.67 (6)	11.00 (6)
5.0 mm	—	—	7.88 (16)	8.13 (8)	8.50 (2)	9.75 (2)	10.00 (1)	10.50 (1)
6.5 mm	—	—	11.06 (16)	11.25 (8)	11.50 (2)	12.25 (2)	12.50 (1)	13.00 (1)

[a]Data are reported as diameter of graft in millimeters (No. of graft combinations). Dashes indicate that there were no graft combinations of that particular diameter. GT, gracilis tendon; ST, semitendinosus tendon.

TABLE 3
Quadruple Hamstring Graft Predictive Table[a]

GT Diameter	ST Diameter 3.5 mm	4.0 mm	4.5 mm	5.0 mm	5.5 mm
2.5 mm	5.5	6.5	6.5	7.5	8.0
3.0 mm	6.0	6.5	7.5	8.0	8.5
3.5 mm	6.5	7.0	8.0	8.5	9.0
4.0 mm	7.0	7.5	8.5	8.5	9.0
4.5 mm	7.5	8.0	8.5	9.0	9.5

[a]Data are reported as diameter of graft in millimeters. Diameters rounded up to the nearest 0.5 mm correspond with standard graft sizing blocks. GT, gracilis tendon; ST, semitendinosus tendon.

TABLE 4
Combined Accuracy of Preoperative MRI Measurements and Quadruple Hamstring Graft Predictive Table[a]

	≤0.5-cm Difference	≤1.0-cm Difference	*r* Value	*P* Value
GT	45/60 (75)	59/60 (98)	0.6211	<.00001
ST	45/60 (75)	56/60 (93)	0.7110	<.00001
Quadruple hamstring graft	52/60 (87)	60/60 (100)	0.8107	<.00001

[a]Data are reported as n (%) unless otherwise specified. GT, gracilis tendon; MRI, magnetic resonance imaging; ST, semitendinosus tendon.

TABLE 5
Previous Studies Using Preoperative MRI to Predict Intraoperative Hamstring Tendon Diameter[a]

Study	Population	Imaging Modality	Protocol Used	Correlation
Wernecke et al[18] (2011)	N = 34 (9 F, 25 M) Mean age, 30 y	1.5-T MRI	CSA measured via ROI tool	$r = 0.53$, $P = .001$
Beyzadeoglu et al[1] (2012)	N = 51 (7 F, 44 M) Mean age, 30.5 y	3.0-T MRI	CSA measured via ROI tool	$r = 0.419$, $P = .002$
Erquicia et al[4] (2013)	N = 33 (8 F, 25 M) Mean age, 32 y	3.0-T MRI and US	MRI: CSA measured via ROI tool US: ellipse tool	MRI (4× magnification): $r = 0.86$, $P < .001$ US: $r = 0.506$, $P = .03$
Grawe et al[5] (2016)	N = 84 (42 F, 42 M) Mean age, 36 y	1.5-T or 3.0-T MRI	CSA measured via ROI tool	$r = 0.416$, $P < .001$
Leiter et al[7] (2017)	N = 109 (44 F, 65 M) Mean age, 27.8 y	1.5-T MRI	CSA measured via ROI tool	$r = 0.495$, $P < .001$
Current study	N = 60 (26 F, 34 M) Mean age, 21.1 y	1.5-T MRI	Diameter of tendon at 3 cm from joint line	$r = 0.81$, $P < .00001$

[a]CSA, cross-sectional area; F, female; M, male; MRI, magnetic resonance imaging; ROI, region of interest; US, ultrasound.

Through our 3-part study, we were able to develop a predictive table to accurately determine the QH graft diameter based on individual cadaveric GT and ST diameters. We were also able to determine the most accurate distance from the joint line for which to accurately measure the hamstring tendon diameter. Finally, we were able to show one of the highest correlations between the MRI-measured tendon diameters and actual intraoperative diameters for both the ST and GT when compared with previous studies (Table 5). More importantly, using the predictive table that we developed, we were able to show an even higher correlation between the predicted QH graft diameter and the actual intraoperatively measured diameter.

Our study is in agreement with previous studies demonstrating that the use of preoperative measurements of the hamstring tendon by MRI can accurately predict the final intraoperative graft diameter. Our study differs from previous work, however, in that we have one of the highest correlations between the MRI measurement and actual graft diameter. We also have made the measurements technically easier and accessible to all by using a standard tool to measure the diameter and not a region-of-interest tool as described in previous studies.[1,2,4,18] Converting from a cross-sectional area to the final graft diameter, as in previous studies, may also not be as intuitive and straightforward as our method.

Previous studies have used measurements of the hamstring tendon at the level of the physis or physeal scar.[1,2,5,16,18] This level was arbitrarily chosen in a previous study by Bickel et al[2] along the tendon in which it is more tubular and easier to measure on MRI. We were able to objectively show that 3 cm above the joint line had the highest correlation with the actual graft size. By establishing a discrete level at which to measure the tendon, we were able to further simplify and standardize the preoperative measurement process.

Our study cohort had a high percentage of patients (50%) with QH graft diameters less than 8 mm. By accurately measuring graft diameters preoperatively, we are able to plan accordingly for smaller graft diameters. Previous studies have shown that allograft augmentation for small hamstring graft diameters does not reduce graft failure rates and in fact may increase the risk of graft ruptures.[13] Recent studies have shown that a 5-strand hamstring autograft provides a larger graft diameter compared with a QH autograft in ACL reconstruction.[6] It has therefore become our standard practice to perform continuous loop all-inside ACL reconstruction with a quadruple ST ± GT graft in patients with predicted QH graft sizes less than 8 mm.

Limitations

There are several limitations to our investigation. MRI measurements were not performed by multiple investigators for each patient, and therefore, the interrater reliability of our measurements was not calculated. Also, unlike previous studies, we did not collect any anthropometric data to analyze the relationship between patient height and/or weight and graft size. The retrospective nature and moderate sample size are also inherent weaknesses to our study.

CONCLUSION

Our results suggest that MRI-based measurements of the hamstring tendon diameter are a simple, effective, and accurate method for predicting the final QH graft diameter.

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