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SCIENTIFIC ARTICLE

Prediction of quadriceps tendon–patellar bone autograft diameter in adolescents with 2-dimensional magnetic resonance imaging and anthropometric measures

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Abstract

Objectives This study evaluates the correlation between the bone end and soft tissue end of the quadriceps tendon–patellar bone autograft (QPA) size and pre-operative MRI measurements of the quadriceps tendon along sections to be included in the graft harvest in adolescents. We also assessed association between graft diameter and anthropometric measures (height, weight, and BMI), age, and sex.

Methods Patients (10–18 years) who underwent QPA ACL reconstruction and had a pre-operative MRI were considered for inclusion. Age, height, and weight, tibial and femoral side graft diameter, and patellar bone block dimensions were collected. Using a pre-operative 2D sagittal plane MRI, we measured the quadriceps at 10-mm increments above the patella, up to 40 mm. We assessed correlation between the bone-end graft diameter and the AP measure at 10 mm above the patella, and correlation between the soft-tissue end graft diameter and the most proximal AP measure.

Results A total of 103 patients were included. A significant correlation between the soft-tissue side graft diameter and most proximal AP measurement was observed ($r_s = 0.51$; $p < 0.001$). However, measurements significantly underestimated the soft-tissue end graft diameter (9.6 ± 0.8 vs. 7.4 ± 1.1; $p < 0.001$). There was no correlation between the bone-end graft diameter and AP measurement 10 mm above the patella. Anthropometric measures were not associated with graft size. Skeletal maturity was associated with smaller graft size ($p = 0.08$).

Conclusion Soft-tissue end graft diameter is associated with the AP measure of the quadriceps at 20–40 mm above the superior pole of the patella.

Keywords ACL reconstruction · Quadriceps tendon · Magnetic resonance imaging · Anthropomorphic measures · Pediatrics

Introduction

Anterior cruciate ligament (ACL) tears are increasingly common among young people [1–3]. For young, active patients, ACL reconstruction (ACLR) is recommended soon after injury to prevent further chondral or meniscal damage [3, 4]. Thus, many physeal-respecting anatomic ACL reconstruction techniques using either a hamstring tendon or quadriceps tendon autograft have been developed [5–7]. Low failure rates, good patient-reported outcomes, and high return to sport rates have been associated with both graft types in adolescents and adults [6, 8–12]. Although superiority of hamstring or quadriceps tendon autograft has not been definitively determined, a benefit of choosing the quadriceps graft over a hamstring graft for young patients is the ease of harvesting a more reliably sufficient graft size [8, 10–14].

Small graft diameter (less than 8 mm) has been associated with hamstring tendon graft failure. Although the quadriceps tendon has been shown to yield a larger graft diameter compared to the hamstring tendon in young patients, pre-operative confirmation of adequate quadriceps tendon girth for graft harvest may still benefit surgeons and their patients [15–19]. Pre-operative planning for graft size may

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be particularly important prepubescent or small patients whose tendon girth is not yet well developed.

MRI-based and anthropometric measures (height, weight, BMI), as well as age and sex, have been correlated with both the quadriceps and hamstring autograft size among adults, although these techniques have not been assessed in young patients [14, 20–23]. Understanding predictive measures of graft size may in young patients will help providers determine the most appropriate graft choice for each case, especially when adequate tendon girth is in question. Thus, the purpose of our study is to assess the reliability of using an anterior–posterior (AP) measure of the quadriceps on a sagittal plane of a 2D MRI taken preoperatively to predict the harvested diameter of the quadriceps tendon–patellar bone autograft in adolescent patients. We hypothesized a strong correlation between MRI measurement and harvested graft size.

Methods

Patient selection and medical record review

After institutional review board approval, we reviewed a single provider's surgical cases to identify all patients ages 10–18 who underwent ACL reconstruction in 2017. Patients who did not have a pre-operative MRI available in the medical records ($n=10$), did not receive the QPA graft ($n=4$), and had undergone a lower limb surgery on the involved limb ($n=6$) were excluded. From the medical chart, we recorded sex, age, height, and weight, and body mass index at the time of surgery. From the pre-operative MRI, we determined skeletal maturity at the knee based on physeal status.

The QPA graft harvest and reconstruction has been described in detail [7]. In short, a 1 cm wide by 1.5 cm long by 1 cm deep trapezoidal bone block is cut from the patella and removed with a curved 3/8th inch osteotome. As the bone block is excised and elevated, a 10-mm-wide central section of the quadriceps tendon is separated from the remaining quadriceps fibers until the entire graft reaches 65 mm in length including the bone block. The graft is prepared, and the diameters of the soft-tissue and the bone-block ends are each measured to the nearest 0.5 mm. The intraoperative graft diameter measurements were completed with a sizing block and recorded as the smallest hole each end of the graft could fit through. Of note, the bone-end side of the graft was measured at the soft tissue immediately proximal to the bone block. The soft tissue diameter immediately proximal to the bone block does necessarily match the size of the bone block for each patient. After graft preparation, the patellar-bone block is seated into the femoral tunnel and the soft-tissue end is seated into the tibial tunnel.

Imaging review

Two board-certified, pediatric musculoskeletal radiologists who were blinded to patient information, the operative report, and each other's measurements, independently reviewed each 2D pre-operative MRI. The raters identified the sagittal image that showed the thickest portion of the quadriceps tendon and measured the anterior–posterior width of the quadriceps tendon at 10-mm increments, up to 40 mm as able based on the field-of-view, superior to the central aspect proximal pole of the patella (Fig. 1), as demonstrated previously by Zakko et al. Because the quadriceps autograft differs in diameter at the soft-tissue end (which becomes the tibial end of the neoligament) and the bone-end (which becomes the femoral end of the neoligament), the average measure at 10 mm superior to the patella was used to predict the bone-end diameter, and the average most proximal available measure was used to predict the soft-tissue end.

Statistical analysis

Continuous variables are presented as means (standard deviations), and categorical variables are presented as the number included and corresponding percentage. We analyzed the correlation between the two radiologist's measurements for

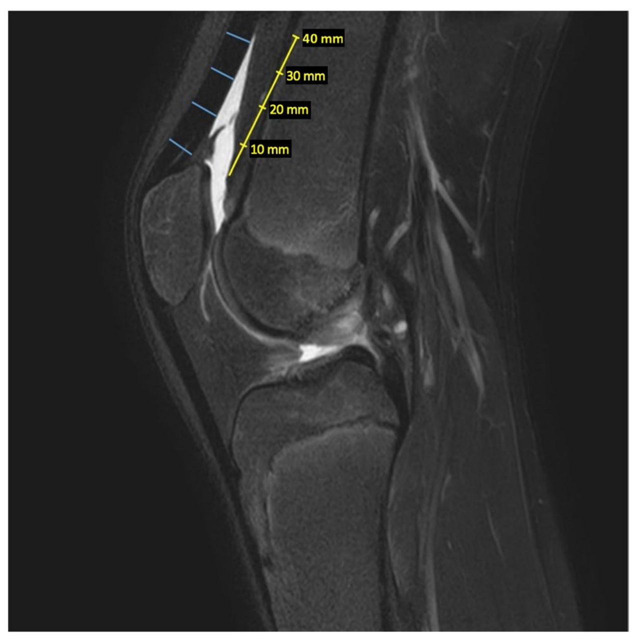

Fig. 1 Sagittal T2 fat-saturated MRI of the knee shows the quadriceps tendon measurement technique. AP dimension of the quadriceps tendon was measured perpendicular to the tendon axis at 10-mm increments superior to the central aspect patellar superior pole, up to 40 mm based on field-of-view

each mark (10, 20, 30, and 40 mm) using Pearson correlation coefficients. If these values were > 0.8, we elected to use the average measure between the two raters at each location.

We then examined the correlation between the bone-end graft diameter and the MRI-measured diameter 10 mm above the patella using a Spearman rho (r_s) correlation coefficient, given the non-normal distribution of the ACL graft diameter. We performed the same correlation analysis between the soft-tissue end ACL graft diameter and the most proximal available MRI measurement (50% at 40 mm, 22% at 30 mm, 18% at 20 mm; 10% at 10 mm). In addition, we calculated the individual differences between the harvested graft diameter at both the bone-end and soft-tissue end and the predicted diameter based on MRI on each end of the graft. We classified the accuracy of the MRI measurement (defined as within 1 mm of the harvested graft diameter).

Finally, in order to assess the demographic and anthropometric predictors (height, weight, and BMI) of the harvested soft-tissue end graft diameter, we constructed a multivariable regression model. All statistical tests were two-sided and performed using Stata Statistical Software: Version 15 (College Station, TX: StataCorp, LLC).

Results

A total of $n = 122$ patients were considered for inclusion in our analysis. We removed $n = 20$ ($n = 10$ with no preoperative MRI available, $n = 6$ who had a previous surgery to the involved limb, $n = 4$ who had a non-QPA graft). There were no significant differences between those who were included and excluded in the proportion of females (55% vs. 31%; $p = 0.11$), proportion of skeletally mature patients (73% vs. 45%; $p = 0.08$), or in the mean age (15.9 ± 1.9 vs. 15.1 ± 4.4 years; $p = 0.18$). Thus, our analyzed sample included $n = 102$ patients. Among those included in the sample, the average time between the MRI and ACLR surgery was 44 days (95% confidence interval: 32–56 days). Age at surgery, anthropometric data, and surgical information is presented in Table 1.

Table 1 Demographic characteristics of the analyzed patient sample ($n = 102$)

Variable	Mean (sd) or *n* (%)
Age at the time of surgery (years)	15.9 (1.9)
Height (cm)	168.7 (10.2)
Weight (kg)	66.8 (14.8)
BMI (kg/m^2)	23.6 (4.3)
Sex (female)	55 (54%)
Skeletally mature	72 (71%)

The inter-rater correlation for the MRI measurements of the quadriceps completed by the two radiologists was high at 10 mm ($r = 0.82$), 20 mm ($r = 0.87$), 30 mm ($r = 0.88$), and 40 mm ($r = 0.88$) proximal to the superior pole of the patella. Thus, when comparing MRI measurements to the harvested graft diameter, we used the average of each radiologist's measurement at each level.

The correlation between the bone-end graft diameter and the MRI AP measure (mm) of the quadriceps at 10 mm above patella was weak and non-significant (Fig. 2; $r_s = -0.03$; $p = 0.76$). The MRI diameter significantly underestimated bone-end graft diameter (7.3 ± 1.1 mm vs. 10.6 ± 0.3 mm; $p < 0.001$). The correlation between the soft-tissue side graft diameter and the MRI-predicted graft diameter at the most proximal available measurement above the patella was strong and significant (Fig. 3; $r_s = 0.51$; $p < 0.001$). As with the bone-end, however, the MRI measurement significantly underestimated the harvested soft-tissue graft diameter (7.4 ± 1.1 vs. 9.6 ± 0.8; $p < 0.001$).

On the bone-end of the graft, the difference between the harvested graft diameter and MRI measurement was 3.3 ± 1.2 mm, while the difference on the soft-tissue end was 2.2 ± 1.0 mm. Defining an accurate MRI measurement as within 1 mm of the true graft size, the MRI was accurate 5% of the time on the bone-end, and 11% of the time on the soft-tissue end.

The multivariable regression model indicated that skeletal maturity was significantly associated with a smaller

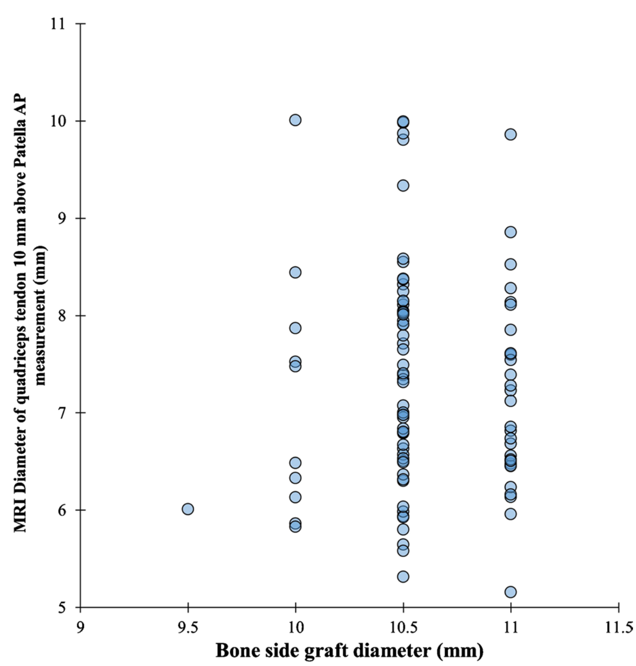

Fig. 2 Scatterplot describing the relationship between the bone side graft diameter and the MRI diameter of the quadriceps tendon 10 mm above the patella

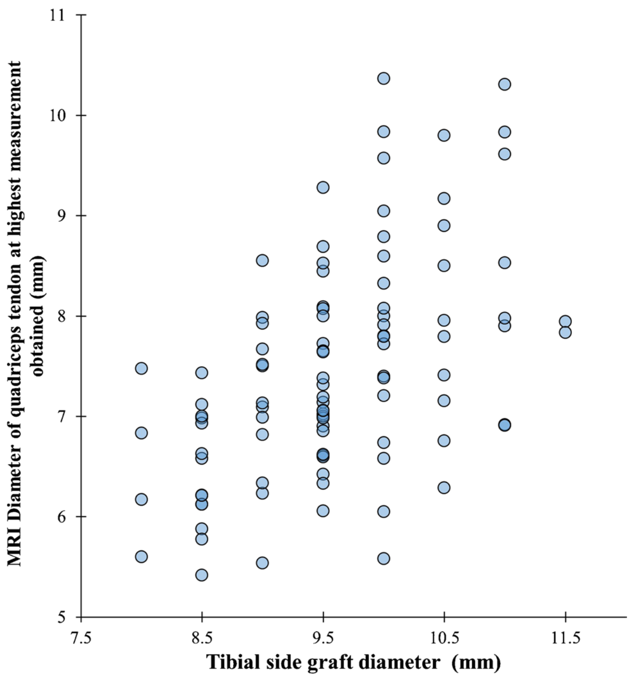

Fig. 3 Scatterplot describing the relationship between the tibial side graft diameter and the MRI diameter of the quadriceps tendon at the highest measurement above the patella obtained

Table 2 Multivariable regression results examining the association of demographic characteristics with tibial side graft diameter

Variable	β coefficient	95% confidence interval	*p* value
Sex	0.097	−0.312, 0.506	0.64
Age	0.358	−0.071, 0.143	0.51
Height	0.008	−0.079, 0.096	0.85
Weight	0.019	−0.095, 0.133	0.77
BMI	−0.047	−0.370, 0.276	0.77
Skeletally mature	−0.708	−1.228, −0.188*	0.008 + 7

*95% confidence interval does not cross zero

soft-tissue end graft diameter, but that no other demographic characteristics were significantly associated with tibial side graft diameter (Table 2).

Discussion

The results from our investigation indicate a moderately strong, significant linear correlation between the soft-tissue side graft diameter and the MRI-measured graft diameter at the most superior measurement above the patella, although the MRI underestimated the graft size. Our technique for estimating the soft-tissue end graft diameter significantly underestimated the harvested diameter by about 2.2 mm. This inaccuracy is favored to reflect the inherent limitation of a single 2-dimensional AP measurement to estimate size of the 3-dimensional autograft, without the ability to measure cross-sectional area. Measurements of a three-dimensional MRI may yield a more accurate representation of the autograft thickness by accounting for the radial quadriceps tendon thickness [14]. As well, the consistency of the surgical technique for harvesting a 10 mm wide by 10 mm deep by 15 mm long bone plug and elevating the bone block with attached fibers likely dictates the bone-end graft size. This surgical technique explains the lack of correlation and inaccuracy of the MRI measured quadriceps thickness at 10 mm above the patella and the actual harvested bone-end diameter. The morphology of the quadriceps tendon is variable from patient to patient, creating difficulty to account for the linearity of the tendon fibers on MRI. Interestingly, Zakko et al. [20] accurately predicted quadriceps graft size with a similar technique using the average of quadriceps thickness measurements from a sagittal view at 10 mm, 20 mm, and 30 mm. Furthermore, the quadriceps autograft predicted in Zakko et al. [20] was not specified as a free graft or with an attached bone plug, which may explain differences in the results of our studies.

A limitation of this study includes the use of 2-dimensional MRI as mentioned above, which does not allow volumetric reconstruction of image planes aligned with the quadriceps tendon axis. While both the high inter-rater agreement and strong correlation of the graft soft tissue end with the most proximal quadriceps tendon measurement are promising for the value of MRI measures, the accuracy may be improved by using 3-dimensional image data in order to perform more robust area measurements of the tendon and therefore account for the radial thickness of the autograft [14].

Other studies have identified anthropometric measures that are correlated with quadriceps tendon graft size [20, 24]. Both Xerogeanes et al. [24] and Zakko et al. [20] found height to be a strong predictor of quadriceps tendon graft thickness in adults. Height, weight, and BMI were not associated with graft thickness in our cohort of adolescent patients. However, skeletal maturity was a predictor of smaller soft-tissue end tendon size, which was unexpected considering the normal hypertrophy of muscle girth that most often accompanies the onset of puberty. It is possible this finding among our cohort would become nonsignificant with a larger sample size. As well, the normal distribution of soft-tissue tendon size overlaps considerably between the skeletally mature and skeletally immature patients included in the analysis, and we do not feel this statistically significant finding bears clinical significance as well.

Conclusion

Pre-operative planning for expected diameter at the soft-tissue end quadriceps tendon–patellar bone autograft may help providers determine if an increased width of graft harvested is needed to be obtained for small patients when tendon girth is in question. Our method of measuring the pre-operative MRI did not directly yield an accurate measurement without adjustment. For this technique, consideration of adjusting the most superior available AP MRI measurement of the quadriceps tendon by approximately 2 mm may help to predict the soft-tissue end diameter of the QPA graft in young patients. Future research is necessary to determine the minimal quadriceps tendon–patellar bone graft diameter associated with low failure rates.

Declarations

Conflict of interest Dr. Albright is a consultant and speaker for Arthrex Inc. and Gemini Mountain Medical LLC. Unrelated to this study, Dr. Howell has received research support from the Eunice Kennedy Shriver National Institute of Child Health & Human Development (R03HD094560), the National Institute of Neurological Disorders And Stroke (R01NS100952, R03HD094560, and R43NS108823), and MINDSOURCE Brain Injury Network.
All other authors declare that they have no conflict of interest.

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