How to Improve the Prediction of Quadrupled Semitendinosus and Gracilis Autograft Sizes With Magnetic Resonance Imaging and Ultrasonography

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Background: Hamstring tendon grafts may have an unacceptable size for use in anterior cruciate ligament (ACL) reconstruction. Magnetic resonance imaging (MRI) has been proposed to predict the diameters of hamstring tendon grafts.

Hypothesis: Preoperative ultrasonography (US) might reliably anticipate intraoperative 4-strand semitendinosus and gracilis tendon (4ST-GT) graft sizes similarly to MRI. An MRI evaluation of the hamstring tendons with a higher magnification may improve the accuracy of the method.

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

Methods: A total of 33 patients undergoing ACL reconstruction with a 4ST-GT graft and MRI performed at our institution were included. The cross-sectional area (CSA) of each semitendinosus tendon (ST) and gracilis tendon (GT) was calculated preoperatively with US and with MRI under 2× and 4× magnification. Intraoperative measurement of the final diameter of the 4ST-GT using a closed-hole sizing block with 0.5-mm increments was made. Pearson correlation coefficients were calculated to determine the relationship between the final intraoperative graft diameter of the 4ST-GT and the CSA of the ST and GT measured with US and MRI with 2× and 4× magnification. Simple linear regression was also calculated to attempt to predict the graft diameter based on given measurements.

Results: There were statistically significant correlations between the measured CSA with US and both MRI magnifications with the 4ST-GT diameter. However, MRI under 4× magnification showed a much higer correlation (0.86) than MRI under 2× magnification (0.54) or US (0.51). Final graft diameters $\geq$8 mm were observed in 80.8% of patients with a CSA $>$14 mm^2, in 76.9% of patients with a CSA $>$25 mm^2, and in 96.2% of patients with a CSA $>$17 mm^2 measured with US, 2× magnification of MRI, and 4× magnification of MRI, respectively.

Conclusion: Preoperative calculation of the CSA of the hamstring tendons with MRI and US can help to reliably estimate 4ST-GT grafts. In terms of correlation of the CSA with graft diameter, US was comparable to 2× MRI, but 4× MRI showed a much greater accuracy. Threshold values of the CSA of the ST and GT of 25 mm^2, 17 mm^2, and 14 mm^2 with the 2× MRI, 4× MRI, and US methods, respectively, are needed to reliably predict a 4ST-GT graft with a minimum diameter of 8 mm.

Keywords: graft size; hamstring; graft prediction; imaging techniques

Among the different options used to reconstruct the anterior cruciate ligament (ACL), autografts of the medial third of the patellar tendon as well as hamstring tendons are the two most frequently used.[4,5] Autogenous 4-strand semitendinosus and gracilis tendons (4ST-GT) provide postsurgical outcomes similar to those of patellar tendon autografts with the additional advantages of less donor site morbidity, fewer patellofemoral problems, and a lack of extensor mechanism dysfunction when compared with bone–patellar tendon–bone grafts.[1,6,15]

Substantial variability in graft diameter and length is often encountered when a combined semitendinosus tendon (ST) and gracilis tendon (GT) are harvested.[11,14] Although the graft size parameters required for

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a successful outcome after ACL reconstruction have not been clearly defined, the harvested grafts are occasionally found to have an unacceptable size for use in ACL reconstruction. Having a graft with a minimum diameter of 7 mm has been traditionally recommended.[7,11] However, a more recent investigation has shown a higher failure rate for the reconstructed ACL with grafts smaller than 8 mm in diameter.[12] In any case, it might be beneficial for the surgeon to be able to predict those patients at risk of having hamstring tendons that are considered to be of inadequate diameter. Identifying those patients would allow for proper preoperative planning, the arrangement of alternative graft sources, and appropriate patient counseling relative to graft selection.

Even though the results have been inconsistent, recent studies have attempted to identify simple anthropometric measurements that have a correlation with the size of the hamstring grafts.[10,14,16,18] On the other hand, different imaging techniques have been proposed to properly predict the size of the hamstring grafts. Preoperative 3-dimensional computed tomography (3D CT)[19] as well as magnetic resonance imaging (MRI)[2,3,8,17] have been shown to be capable of providing accurate preoperative measurements of the hamstring tendons. On MRI, calculation of the cross-sectional area (CSA) of the tendons has been shown to be a more precise predictive tool of the graft diameter than calculation of the diameter of the tendons. However, assessment of the CSA on MRI might also be influenced by the degree of magnification, the resolution of the images, or the measurement method.[3] To our knowledge, no evidence has been found relative to the use of ultrasonography (US) for this purpose.

The aim of this study was to determine if preoperative US measurements of the CSA of the ST and GT might predict the diameter of the 4ST-GT autograft as accurately as MRI and how different magnifications of MRI might influence the accuracy of the measurement. The first hypothesis was that preoperative US could be used to reliably anticipate intraoperative 4ST-GT graft sizes similarly to MRI. The second hypothesis was that the MRI evaluation of the hamstring tendons with a higher magnification would improve the accuracy of the method.

MATERIALS AND METHODS

After approval from our institutional review board was obtained, 40 patients scheduled for ACL reconstruction with a hamstring autograft and with preoperative MRI performed at our institution were included. Exclusion criteria included previous ACL surgery, partial ACL injuries, multiligament knee injuries, acute or previous hamstring injuries, and intraoperative graft amputation. Sex, age, height, weight, body mass index (BMI), and leg length were recorded for every patient.

Ultrasonography

Ultrasonography was performed by the same orthopaedic surgeon (J.L.D.), who has extensive experience in musculoskeletal US. The same ultrasound device (LOGIQe, GE Healthcare, Milwaukee, Wisconsin) and its linear array probe (7-12 MHz) were used for all measurements. The patients were positioned prone on the table, and with the knee at 90° of flexion, the GT and ST were identified. The tendons were then scanned just proximal to the medial joint line. The CSA of each GT and ST was automatically calculated with the ellipse tool (Figure 1), which is included in the US software device.

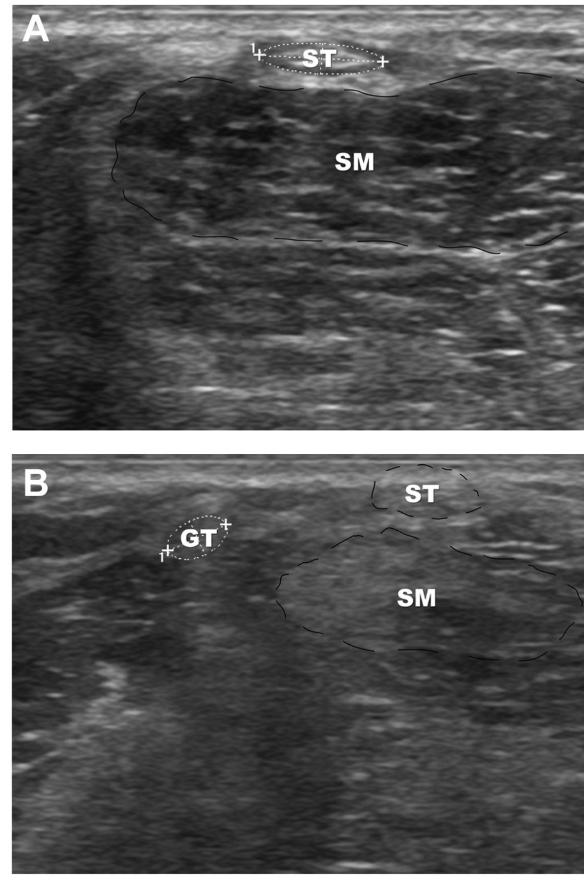

Figure 1. Ultrasound view of a medial aspect of a right knee just above the joint line. The cross-sectional area of every semitendinosus tendon (ST) (A) and gracilis tendon (B) was calculated with the ellipse tool (white dotted lines) of the ultrasound device. The semimembranosus muscle (SM) and ST are also seen delimited (black dotted lines).

MRI Technique

Preoperatively, MRI of the affected knee was performed in each case. All studies were performed with a 1.5-T superconducting magnet (Signa, GE Healthcare) using a knee-specific circular coil. A positioning device for the ankle was used to ensure uniformity. A 16-cm field of view with a 256 × 256 matrix size was used. Slices were 3 mm thick with no interslice gap for all studies. The standard knee protocol for each patient consisted of the following sequences: axial fast spin echo T2-weighted with fat saturation (repetition time [TR]: 2300 ms; echo time [TE]: 30 ms; flip angle [FA]: 90°; slice thickness [ST]: 3 mm; field of view [FOV]: 20 cm), coronal fast spin echo intermediate-weighted (TR: 2500 ms; TE: 30 ms; FA: 90°; ST: 4 mm; FOV: 18 cm), sagittal spin echo intermediate-weighted (TR: 700 ms; TE: 14 ms; FA: 90°; ST: 4 mm; FOV: 18 cm), and sagittal fast spin echo T2-weighted with fat saturation (TR: 2500 ms; TE: 85 ms; FA: 90°; ST: 4 mm; FOV: 18 cm).

Two different types of measurement were performed. In both cases, the tendons were measured in the axial fast spin echo T2-weighted sequence with fat saturation. The chosen level of CSA measurement was at the widest point of the medial femoral epicondyle, similar to that described in the Bickel et al[3] and Wernecke et al[17] studies. In the first type of measurement (2× MRI method), the images were all analyzed under a 2×-magnified view (Figure 2A). In the second type of measurement (4× MRI method), the images were analyzed under a 4×-magnified view according to the method described by Hamada et al.[8] In this method, the pixels with low signal intensity are considered to be intratendinous. These authors considered that pixels with high signal intensity constitute the surrounding structures. Finally, those pixels with intermediate signal intensity were considered to constitute both the tendon portion and that of the surrounding tissues (Figure 2B). Then, they arbitrarily assumed that half of the CSA of this intermediate signal intensity section had to be included in the calculation of the CSA of the selected tendon. Thus, the final CSA of each tendon with the 4× MRI method described in the current study was calculated by adding 50% of the CSA of the intermediate signal intensity area to the CSA of the low signal intensity area. This correction was not applied to the 2× MRI method.

Two of the authors (J.I.E. and P.E.G.) were involved in the measurements. Each of these authors performed 2 measurements of each variable with a 15-day interval. The average of the 4 calculated measures was the value considered for the purposes of the study. The CSA was calculated with a PACS workstation (Centricity Enterprise Web V3.0; GE Healthcare). This software has a region of interest tool that is a method for manually tracing an area, after which the software automatically calculates the CSA (in mm^2). Any tendon slips or vincula that were seen emanating from the tendon were not included in the area of interest because intraoperatively, these are debrided at the time of graft preparation. The region of interest tool is a tool approved by the US Food and Drug Administration (FDA) to accurately measure areas in any plane or volume.[3]

Finally, the intraclass and interclass correlation coefficients were calculated for the 2× MRI method and for the 4× MRI method separately. Values ranged between 0 (poor) to 1 (very good) agreement.

Hamstring Tendon Harvesting

A 2-cm longitudinal incision, 2 cm medial to the medial border of the tibial tuberosity, was first performed. Next, the pes anserinus bursa and the sartorius fascia were opened transversally on their upper halves. The GT and ST were consecutively harvested. First, the tendons were pulled strongly with a 90° curved dissector. Then, their corresponding insertions were released, and finally, the tendons were removed with a closed-end tendon harvester (ConMed Linvatec, Largo, Florida). After blunt removal of all muscle and fatty tissue around the tendons, each coupled GT and ST was doubled over around a suture and passed through a closed-hole sizing block (ConMed Linvatec). The sizing block measured 0.5-mm-diameter increments from 3 to 12 mm. Measurements were obtained before any further postharvest alteration such as graft pretensioning or trimming of the graft. The smallest sizing hole through which the proximal end of the 4ST-GT graft could be pulled with maximal manual force was the final diameter considered for the study's purpose.

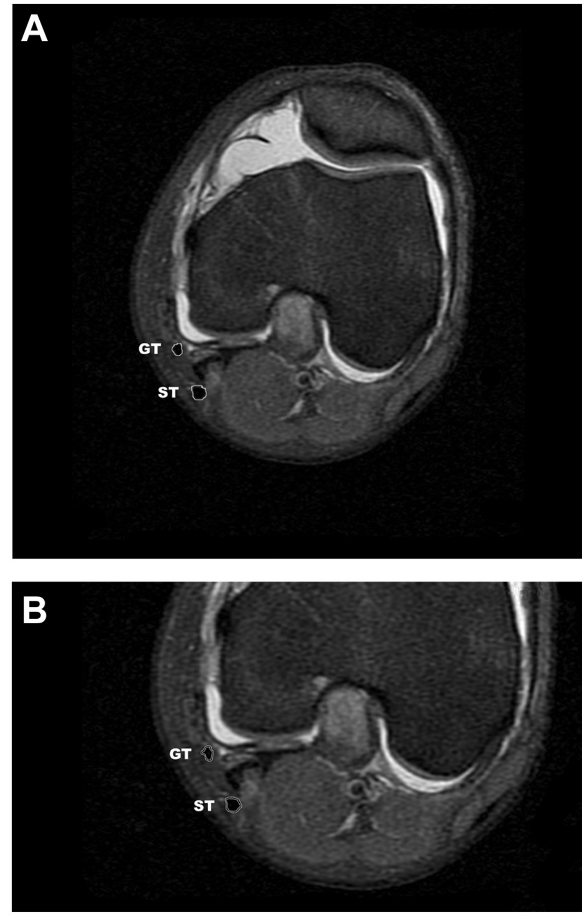

Figure 2. Axial fast spin echo T2-weighted sequence with fat saturation of a left knee. (A) Under 2× magnification, the semitendinosus tendon (ST) and gracilis tendon (GT) had a cross-sectional area (CSA) of 28.05 mm^2. (B) In the same view but under 4× magnification and following the method described by Hamada et al,[8] the CSA of the ST and GT was 19.21 mm^2. With this method, the CSA inside the inner circle (16.15 mm^2) was added to 50% of the CSA of the area between the outer and the inner circle, which had a CSA of 6.12 mm^2.

TABLE 1
Cross-sectional Area (CSA) Measured on Magnetic Resonance Imaging (MRI)[a]

Variable	Mean ± SD	Minimum	Median	Maximum
2× MRI				
CSA of GT	10.4 ± 1.7	7.6	10.1	14.1
CSA of ST	16.8 ± 3.4	10.5	15.8	24.6
CSA of GT + ST	27.2 ± 4.4	19.1	26.5	35.6
4× MRI				
CSA of GT	6.4 ± 1.4	4.7	6.4	11.5
CSA of ST	12.4 ± 1.6	9.4	12.3	17.5
CSA of GT + ST	18.8 ± 2.8	14.2	18.7	29

[a]All frequencies are expressed in mm^2. 2× MRI, MRI analyzed under 2× magnification; 4× MRI, MRI analyzed under 4× magnification and with the method described by Hamada et al.[8] GT, gracilis tendon; ST, semitendinosus tendon.

Statistical Analysis

Pearson correlation coefficients were calculated to determine the relationship between the final intraoperative graft diameter (4ST-GT) and the CSA of the GT and ST measured with US and with MRI at 2× and 4× magnifications. Higher correlation coefficients indicate stronger relationships between variables. Simple linear regression was also performed to attempt to predict the graft diameter based on given measurements. The best cut-off point of measurements was calculated to discriminate a sufficient graft diameter (≥8 mm) while indicating the sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) with each technique studied. We used independent-sample *t* tests to compare the diameter of hamstring grafts between sexes and to describe the relationship between the CSAs with MRI and whether the total graft diameter was ≥8 mm. Intraobserver and interobserver agreements were analyzed using the intraclass correlation coefficient. In those relevant cases, 95% confidence intervals (CIs) were calculated. A *P* value of .05 was considered statistically significant. All the analyses were performed with SPSS 19 (SPSS Inc, Chicago, Illinois).

RESULTS

Seven patients were excluded because of an intraoperative diagnosis of a partial ACL injury that was reconstructed, in every case, with only a 3-strand ST graft. Thus, a total of 33 patients were finally studied.

There were 25 male (75.8%) and 8 female (24.2%) patients with a median age of 32 years (range, 16-59 years). The median time period from the injury to surgery was 5 months (range, 1-240 months), and the median time from preoperative MRI to surgery was 17 days (range, 2-38 days). Height, weight, BMI, and leg length had a normal distribution and had a mean (±standard deviation) of 175 ± 8.9 cm, 77.2 ± 13.8 kg, 24.8 ± 3.1, and 90.9 ± 5.1 cm, respectively. Graft size frequencies among the current data were as follows: 7 mm (4 cases), 7.5 mm (3 cases), 8 mm (14 cases), 8.5 mm (8 cases), 9 mm (2 cases), and 10 mm (2 cases).

Ultrasonography

With the US assessment, the mean CSA of the GT was 6.2 ± 0.9 mm^2, and the mean CSA of the ST was 9.5 ± 1.7 mm^2, for a mean CSA of the GT and ST of 15.7 ± 2 mm^2. The Pearson correlation coefficient for the CSA with US to the true graft diameter was 0.506 (*P* = .003). As a result of a linear regression analysis describing the numerical relationship between the CSA with US and graft diameter, the 4ST-GT graft diameter can be calculated with the following formula: 4ST-GT graft diameter = 3.658 + 0.294 × CSA with US.

When the total CSA was greater than 14 mm^2, 17 of the 21 patients had a true 4-strand hamstring graft diameter ≥8 mm, giving a sensitivity of 80.8%. For those whose true graft diameter was less than 8 mm, 7 of 7 patients were correctly classified; therefore, the specificity was 100%. The PPV was 21 of 21 (100%), while the NPV was 4 of 7 (58.3%).

Magnetic Resonance Imaging

The mean CSAs on MRI of the GT and ST with the 2× MRI and 4× MRI methods were 27.2 ± 4.4 mm^2 and 18.8 ± 2.8 mm^2, respectively. All the frequencies regarding CSA measurements of the GT and ST are summarized in Table 1.

Measurements of the true graft diameter positively correlated with preoperative CSA tendon measurements on MRI with both measurement techniques. However, if the correlation was only moderate with the 2× MRI method (0.536; *P* = .001), it was much superior with the 4× MRI method (0.86; *P* < .001).

With the 2× MRI measurement method, true graft diameters ≥8 mm had a mean preoperative CSA of the GT and ST on MRI of 28.1 mm^2 compared with 23.7 mm^2 for grafts less than 8 mm. Regarding the predictive value of the total CSA, when it was greater than 25 mm^2, it resulted in a true graft diameter of at least 8 mm in 15 of 21 patients, giving a sensitivity of 76.9%. For those whose 4ST-GT graft diameter was ≥8 mm, 15 of 20 patients were correctly classified; therefore, sensitivity was 75%. For those whose true graft diameter was less than 8 mm, 5 of 6 patients were correctly classified; therefore, the specificity was 85.7%. The PPV was 19 of 20

(95.2%), while the NPV was 3 of 6 (50%), and sensitivity was 76.9%. For the 2× MRI method, the calculated intraclass correlation was qualified as good, with a coefficient of 0.72 (95% CI, 0.45-0.81). The interclass correlation between observers was also considered good, with a coefficient of 0.62 (95% CI, 0.35-0.79). As a result of a linear regression analysis describing the numerical relationship between the CSA with the 2× MRI method and graft diameter, the 4ST-GT graft diameter can be calculated with the following formula: 4ST-GT graft diameter = 5.81 + 0.667 × CSA with 2× MRI.

With the 4× MRI measurement method, 4ST-GT grafts ≥8 mm had a mean preoperative CSA of the GT and ST of 19.8 mm^2 compared with 15.24 mm^2 for grafts less than 8 mm. Relative to the predictive value of the total CSA, when it was greater than 17 mm^2, 24 of 25 patients whose true graft diameter was ≥8 mm were correctly classified, giving a sensitivity of 96.2%. For those whose true graft diameter was less than 8 mm, 7 of 7 patients were correctly classified; therefore, the specificity was 100%. The PPV was 25 of 25 (100%), while the NPV was 6 of 7 (87.5%). For the 4× MRI method, the intraclass correlation was very good, with a coefficient of 0.92 (95% CI, 0.81-0.98). The interclass correlation between observers was also considered very good, with a coefficient of 0.9 (95% CI, 0.82-0.95). As a result of a linear regression analysis describing the numerical relationship between the CSA with the 4× MRI method and true graft diameter, the 4ST-GT graft diameter can be reliably predicted with the plot shown in Figure 3 and with the following formula: 4ST-GT graft diameter = 3.843 + 0.228 × CSA with 4× MRI.

Comparing the 3 different studied techniques, the accuracy of the US and the 2× MRI methods showed no significant differences (P = .87). However, the accuracy of the 4× MRI method was clearly different from the US (P = .004) and 2× MRI (P = .007) methods.

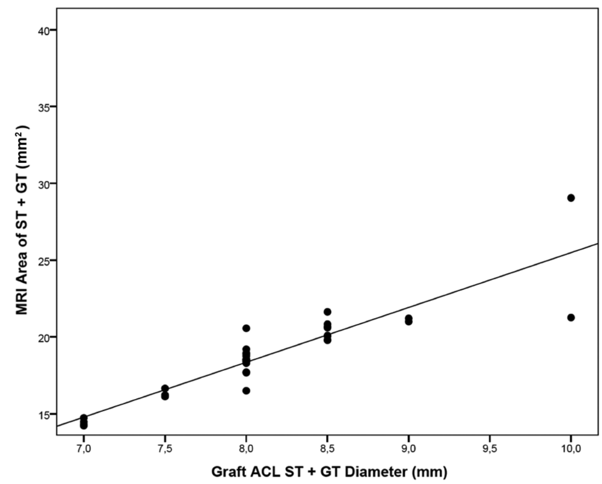

Figure 3. Correlation of area on magnetic resonance imaging with 4-strand semitendinosus tendon and gracilis tendon graft diameters. Graft of cross-sectional area versus graft diameter, showing a very high correlation.

DISCUSSION

The results observed in the current study showed that US can predict the diameter of hamstring grafts used for total ACL reconstruction similarly to MRI, which confirmed the first hypothesis. In addition, it was shown that not all MRI methods of measurement of the CSA had the same degree of correlation with the actual 4ST-GT graft. Hence, this confirmed the second hypothesis.

Although the graft size parameters required for a successful outcome after ACL reconstruction have not been clearly defined, it has been shown that the strength and stiffness of hamstring tendons increase with the number of strands included in the graft[9,10] and that anterior tibial translation has an inverse relationship with graft diameter.[7] In single-bundle ACL reconstructions, having a graft with a minimum diameter of 7 mm has been traditionally recommended for the past 20 years.[7,11] However, a more recent investigation has shown a higher revision rate in ACLs reconstructed with grafts smaller than 8 mm in diameter.[12] Although the authors of the current investigation believe that the minimum reliable graft diameter should be contextualized with the sex, age, anthropometric characteristics, and level of activity of each patient, 8 mm should generally be considered the minimum sufficient graft size.

Diameters of the autogenous ST and GT show clinically significant anatomic variations.[11,14] Thus, several studies have investigated how to properly predict the graft size preoperatively in every patient. Some of these studies attempted to find a correlation between patient anthropometric characteristics and hamstring graft sizes.[14,16,18] Although this might be considered an easy-to-use method, those investigations showed apparent disagreement between them. On the other hand, some authors have used different imaging techniques to predict hamstring graft size preoperatively. While Yasumoto et al[19] could preoperatively predict the length of the ST graft by using 3D CT, they did not find any correlation with graft diameters. In addition, CT is not routinely performed before primary ACL reconstruction. Hamada et al[8] were the first to find a good correlation between the CSA of the ST measured on MRI with intraoperative graft sizes. The authors reported a mean CSA of 10.1 mm^2 for the ST, which is approximatelly 6 mm^2 and 2 mm^2 smaller than the results of this study observed with the 2× MRI and 4× MRI methods, respectively. The difference might be explained by different measurement techniques. Although a 1.5-T imager was used in both studies, the image magnification was not described in the Hamada et al[8] study. Conversely, the images in the present investigation were systematically analyzed under a 2×- or 4×-magnified view. In addition, although we follow the recommendation of the Hamada et al[8] study with regard to considering 50% of the CSA of the intermediate signal intensity pixels that surrounded the low signal intensity as intratendinous, they calculated the CSA by simply multiplying the pixel number by a single pixel area of 0.22 mm^2. In contrast, the FDA-approved region of interest software tool was used in the present study. In the Bickel et al[3] study, the average CSA of the ST and GT was 19.9 mm^2, which is almost 8 mm^2 smaller than the CSA observed with the 2× MRI method using a similar method of measurement. Although they also used a 1.5-T imager, they did not measure the CSA of the hamstring tendons at the same magnification in every patient. This could be considered critical after the results observed in this investigation. Similarly, in the Beyzadeoglu et al[2] study, the average CSA of the GT and ST calculated with a 3-T imager at 2× magnification was almost 20 mm^2. Interestingly, all these previous studies have reported a positive correlation between the measured CSA on MRI with graft diameters. However, this correlation was, in all the cases, only moderate with Pearson coefficients of 0.697,[8] 0.641,[3] 0.53,[17] and 0.419.[2] This was similar to the correlation observed with the 2× MRI method of measurement in this study but was clearly much weaker than the excellent correlation (0.86) observed with the 4× MRI method. This is the highest correlation ever reported and represents a clear advantage over the other techniques for a more accurate prediction of the actual graft diameter. With this 4× MRI method, which showed a sensitivity and specificity around 100%, it was observed that a CSA of the ST and GT greater than 17 mm^2 is required to accurately predict a 4ST-GT autograft of at least 8 mm in diameter. In addition, the proposed formula resulting from a linear regression analysis allows for a precise prediction of 4ST-GT diameters.

With regard to US, no study has yet been reported that evaluates its value as a predictive tool for true hamstring graft size. The user dependency of US is well known. For instance, the transducer always needs to compress the tendon for scanning, so the tendon shape or cross-sectional view may be different and variable depending on the different pressures applied. However, it has been recently demonstrated that minimum experience is needed for the accuracy and reproducibility of the CSA measurement of tendinous structures.[13] The results observed in this study were comparable to those of previous MRI studies and also with the 2× MRI method of this investigation in terms of CSA and the moderately positive correlation with the true graft size. In this case, using a cutoff of 16.5 mm^2 resulted in a 4-strand graft diameter of at least 8 mm in 100% of cases.

Comparing the 3 measurement methods used in this study, the 2× MRI and US methods were shown to be comparable but were clearly inferior to the 4× MRI method in terms of the accurate prediction and correlation with graft size. The main advantage of the MRI methods is that the CSA measurement is performed using routine knee images, and no additional scans are neccessary. That is to say that routine MRI used to assess ligaments and menisci can also be used to asssess the dimensions of prospective autogenous graft tissue. However, the high variability observed among different studies because of different MRI scanners, resolutions, and magnifications suggests that all MRI should be performed with the same MRI device and with the same CSA measurement technique. In clinical practice, it is usual for patients to have undergone MRI performed at other medical centers. In these cases, the accessibility to US and its low cost might be a valuable alternative tool to predict the graft size preoperatively, thus avoiding the need to perform more MRI.

One of the limitations of the study was that no clinical measurement of ST and GT diameters was performed separately. The tendon length was not measured either. This might help to preoperatively decide if a double-bundle ACL reconstruction can be reliably performed with an autogenous hamstring graft or if a tripled or quadrupled GT or ST can be used instead of a 4ST-GT. Another weakness might be that intraobserver or interobserver variability of the US method was not assessed. This would have required a longer US examination and more than one session with a specific time-frame interval. However, calculation of the CSA of rounded structures with US has shown high reproducibility with low variability between examiners.[13]

CONCLUSION

Preoperative calculation of the CSA of the hamstring tendons with MRI and US can help to reliably estimate 4ST-GT grafts. In terms of correlation of the CSA with graft diameter, US was comparable to MRI at 2× magnification, but MRI at 4× magnification showed a much greater accuracy. Threshold values of the CSA of the ST and GT of 25 mm^2, 17 mm^2, and 14 mm^2 with the 2× MRI, 4× MRI, and US methods, respectively, are needed to reliably predict a 4-strand graft of a minimum diameter of 8 mm.

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