Estimating Lengths of Semitendinosus and Gracilis Tendons by Magnetic Resonance Imaging

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Purpose: To determine whether preoperative magnetic resonance imaging (MRI) can help predict the tendon-only length of the semitendinosus (ST) and the gracilis (G). **Methods:** The distance from the tibial insertion to the distal-most aspect of the musculotendinous junction (MTJ) of the ST and G was estimated on preoperative MRI scans of patients undergoing primary anterior cruciate ligament (ACL) reconstruction with single-bundle, quadruple-stranded hamstring autograft. This MRI tendon-only length, measured by a musculoskeletal radiologist blinded to surgical findings, was compared to the actual tendon-only length measured upon harvesting each tendon. **Results:** Among the 42 patients comprising the study population, there was very strong correlation between the estimates of tendon-only length made by MRI and surgical measurements for both the ST (Spearman coefficient = 0.83; $P < .0001$) and the G (Spearman coefficient = 0.82; $P < .0001$). The difference between MRI and surgical measurements did not exceed 3 cm for any of the 84 harvested hamstring tendons. Bland-Altman plots confirmed agreement between the 2 measurement methods. There was also strong correlation between the surgically measured tendon-only length of the ST and its G counterpart (Spearman coefficient = 0.68; $P < .0001$). **Conclusions:** MRI estimates of tendon-only length for both the ST and G very strongly correlate with operative measurements of these lengths; the discrepancy between these 2 measurement methods was found to not exceed 3 cm when the MTJ of these tendons is visible on MRI scans. **Level of Evidence:** Level III, comparative study.

Hamstring autografts continue to be widely used for anterior cruciate ligament (ACL) reconstruction surgery, and a very recent systematic review of higher quality investigations using independent femoral tunnel drilling techniques found outcome and failure rates to be comparable to bone-patellar tendon-bone autografts.[1] The standard technique for single-bundle ACL reconstruction is to use a quadruple-stranded graft, created by harvesting both the semitendinosus (ST) and gracilis (G) tendons and folding each over itself after any attached muscle fibers and other non-tendinous tissues are removed. Although there is some evidence that the diameter of the such grafts does not correlate with risk of clinical failure after single-bundle ACL reconstruction,[2] other clinical studies have linked higher failure rates with smaller diameter hamstring grafts.[3,4] Additionally, recent biomechanical testing showed a correlation between tensile strength and the diameter of quadrupled human hamstring grafts.[5]

Concern regarding the potential of a higher failure rate with use of thinner hamstring grafts has led some investigators to the practice of adding allograft tissue to increase the overall graft diameter when thickness of harvested tendons is deemed insufficient.[6] Others prefer to increase the number of times the harvested hamstring tendons are folded to obtain a thicker, albeit shorter, final graft.[5,7-9] But the ability to fold a tendon on itself more than once to increase graft thickness requires the harvested tendon to be long enough to allow that. Indeed, a recent description of the use of a 5-stranded graft for ACL reconstruction by tripling the ST indicated that harvested tendon needed to be at least 21 cm long to yield a graft of sufficient length.[7] Furthermore, some individuals simply have very short tendon lengths of the ST or G due to an abnormally distal musculotendinous junction (MTJ), which can preclude using the too short harvested tendon in the standard fashion, let alone folding it over more than

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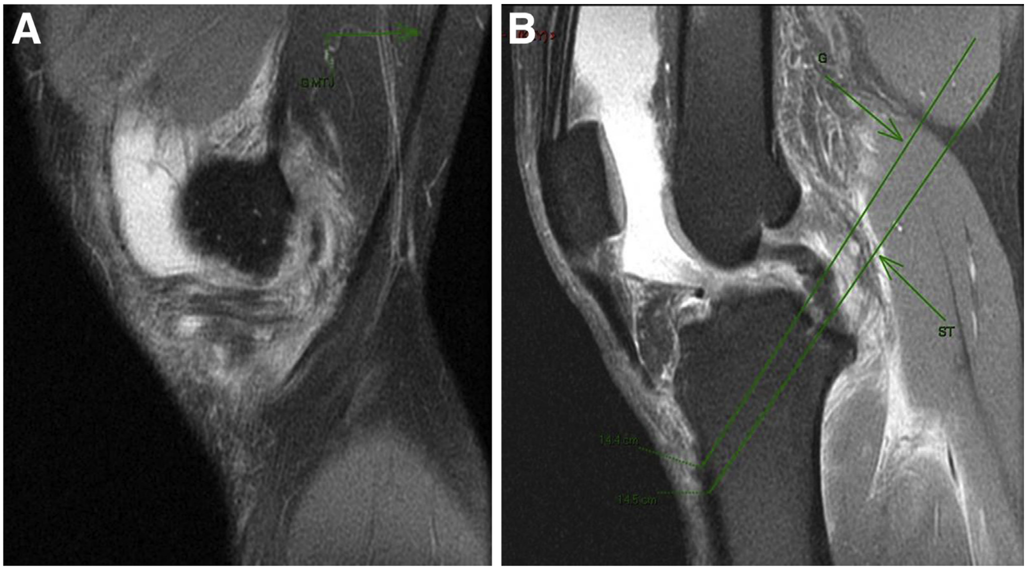

Fig 1. Select magnetic resonance images from the left knee of a 42-year-old male study subject showing (A) the distal-most aspect of the gracilis (G) musculotendinous junction (green arrow) and (B) the tendon-only length measurements for both the gracilis (14.4 cm) and the semitendinosus (ST; 14.5 cm). Upon harvesting, the corresponding lengths measured 14 cm for the G and 15 cm for the ST.

once in order to increase graft diameter.[10] Such information, if known reliably preoperatively, rather than being found only after hamstring harvesting, may influence graft selection decision making.

Although certain anthropometric measurements (especially patient height) have been consistently shown to correlate with the size of harvested hamstring tendons, depending upon these measurements is unreliable as the strengths of such correlations have been repeatedly shown to be moderate, at best.[10-16] Preoperative imaging has also previously been reported to have variable success in predicting adequacy of harvested hamstrings.[17-22] Recent investigation, however, has shown a fairly consistent relationship between the length of the ST and G distal to their respective MTJ and the ultimate harvested length of those tendons.[10] A strong correlation between MRI and surgical measurements would be more reliable than moderate or weaker correlations between various anthropometric measurements and harvested tendon size. The purpose of this study was to determine whether preoperative magnetic resonance imaging (MRI) can help predict the tendon-only length of the ST and the G. The hypothesis of the current investigation was that there would be agreement and strong correlation between the length of both the ST and G from the distal-most aspect of their respective MTJ to insertion (i.e. tendon-only length) measured on preoperative MRI and those same measurements obtained upon surgical harvesting.

Methods

From December of 2011 through December of 2015, all cases of primary, single-bundle ACL reconstructions using hamstring autograft by the senior author (O.A.I.) for which preoperative MRI was ordered by the operating surgeon were included. Patients requiring surgical treatment of ligaments in addition to the ACL were excluded, as those were reconstructed using allograft tendons. Also excluded were those presenting with an MRI obtained previously elsewhere in order to minimize variability of imaging technique/quality. All scans evaluated in this study were performed using a dedicated knee coil, either on a Siemens Magnetom Avanto 1.5 T 18-channel (Siemens, Munich, Germany), a Hitachi Oasis 1.2 T Open (Hitachi, Tokyo, Japan), or a General Electric Signa LX 1.5 T MRI instrument (General Electric, Chicago, IL).

A musculoskeletal-trained radiologist (R.S.S.), blinded to operative findings, performed measurements on the MRIs using a computerized imaging caliper tool (Carestream Vue PACS ver. 12.1.5.1156, Rochester, NY). Because the MTJs and tibial insertions were not visible on the same image slice, for each tendon the distal-most aspect of the MTJ (confirmed in at least 2 planes) was digitally marked and this point translated to a fat-suppressed, PD FSE sequence sagittal image depicting the tibial insertion, which was then also digitally marked. The straight-line distance between these 2 points was reported as the tendon-only length of each hamstring (Fig 1). These measurements were rounded to the nearest centimeter to mirror surgical measurement precision. Patients with MTJs outside the visualized field of the MRI were excluded from final analysis. Prior to measuring the study scans, the senior author and the radiologist together reviewed several MR scans of patients not included in the study to confirm measurement parameters.

At surgery, both the ST and G tendons were harvested through a 2-cm incision over the pes anserinus insertion. Blunt dissection between the pes tendons and the

Fig 2. Intraoperative picture of a patient whose right gracilis tendon (shown fully prepared) was 26 cm long and whose semitendinosus tendon (shown prior to removal of muscle fibers) was 29 cm long. The tendon-only length of this semitendinosus measured 19 cm.

deeper medial collateral ligament was then performed from superior to inferior to establish a plane, after which the tendons were sharply transected at their tibial insertion and reflected to reveal the G and ST tendons on the undersurface of the pes. These were both separated from each other and the overlying sartorial layer by blunt and sharp dissection, after which braided, no. 2 nonabsorbable traction suture was placed in the distal end of each mobilized tendon in modified Krakow fashion. After all adhesions to surrounding fascia were released, each fully mobilized tendon was harvested using a 6-mm diameter, closed-end tendon stripper (Mitek, Andover, MA) for its full length until autoamputation. Following harvesting, the distance from the MTJ, defined in this study as the most distal aspect of visible muscle fibers, to the distal end of each tendon was measured to the nearest centimeter and constituted the tendon-only portion (Fig 2). These data were recorded intraoperatively.

MRI measurements for the tendon-only length of the ST and G were compared to the intraoperative surgical tendon-only measurements. Descriptive statistics including means, 95% confidence intervals, and standard deviations were calculated for tendon-only ST length and G length as measured at surgery and on MRI. Descriptive statistics were also calculated for the difference between surgical and MRI measurements. Spearman correlation analysis, which does not rely on the assumption that the data have a normal distribution pattern, was performed to examine linear relationships between the variables. $P < .05$ was considered statistically significant. Strength of correlation was classified as being strong ($R > .66$), moderate ($0.33 \leq R \leq 0.66$), or weak ($R < 0.33$).[10] Any coefficient value 0.80 or greater was considered indicative of very strong correlation. Additionally, Bland-Altman plots were constructed to evaluate agreement between the MRI and surgical measurements for tendon-only length for the ST and the G and to look for any systematic error between the 2 measuring methods. Institutional Review Board approval was obtained with a priori collection goals being a minimum of 40 study subjects to improve statistical reliability.

Table 1. Demographics of Study Group and Those Excluded for Musculotendinous Junction of Semitendinosus/Gracilis Not Being Included in Magnetic Resonance Imaging Field of View

Patient Characteristic	Study Group ($n = 42$)	Excluded Group ($n = 8$)
Age, yrs	21.1 ± 9.01	24.8 ± 10.5
Height, cm	166.6 ± 8.5	173.5 ± 14.1
Weight, kg	76.9 ± 20.6	78.1 ± 15.2
Male:female	15:27	6:2
Right:left	20:22	3:5

NOTE. Data are mean ± standard deviation unless otherwise indicated.

Results

A total of 50 patients were evaluated. In 8 cases, the MTJ was not included in the visual field of the MRI scan. The tendon-only lengths of these 8 excluded knees were all estimated to be >10 cm for both the ST and G, and the shortest tendon-only length measured at surgery among these was 10 cm for either tendon. Excluding these 8 cases, the analyzed study population therefore consisted of 42 patients. As shown in Table 1, patients included in the study group were similar to those excluded because of the MTJ not being visualized

Table 2. Comparison of Tendon-Only Length Estimated by Magnetic Resonance Imaging (MRI) to That Measured at Surgery, Postharvesting

Tendon-Only Length of:	MRI Estimate	Surgical Measurement	Difference
Semitendinosus (cm)	13.0 (9-17)	13.4 (9-20)	−0.4 (−3 to 2)
Gracilis (cm)	11.9 (9-15)	11.7 (9-16)	0.2 (−3 to 2)

NOTE. Data are mean (range).

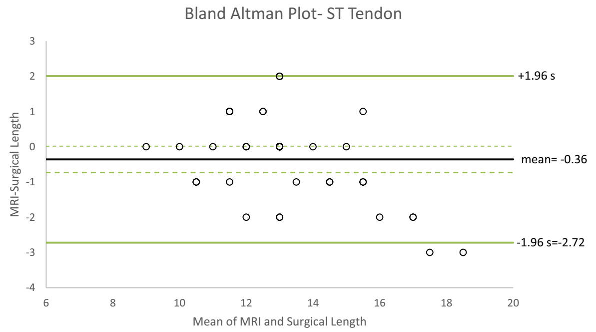

Fig 3. Bland-Altman plot of differences between semitendinosus (ST) tendon-only length measured by magnetic resonance imaging (MRI) and that same length measured at surgery versus average of MRI and surgically measured tendon-only lengths. Dashed gray lines represent the 95% confidence interval around the mean and range from −0.73 to 0.019.

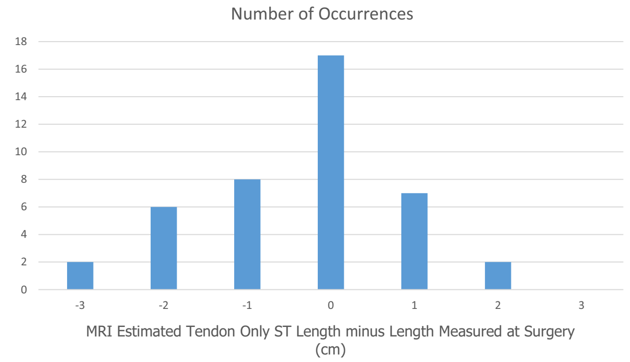

Fig 5. Bar graph of the difference between magnetic resonance imaging estimate of semitendinosus tendon-only length and that measured on the harvested tendon, to the nearest centimeter.

on MRI, with no characteristic differing to a statistically significant degree between these 2 groups.

In no case in this series was there obvious technical harvesting error, and each harvested tendon extended well proximal to its MTJ. The tendon-only length of the ST measured at surgery averaged 13.4 cm (standard deviation = 2.4 cm), whereas the total length of the harvested ST averaged 25.5 cm (standard deviation = 2.9 cm). Similarly, the tendon-only length of the G measured at surgery averaged 11.7 cm (standard deviation = 1.6 cm), whereas the total length of the harvested G averaged 22.7 cm (standard deviation = 2.8 cm).

Overall comparison of MRI estimates with surgical measurement of tendon-only ST and G length is presented in Table 2. The difference between the MRI estimate and surgical measurement averaged −0.4 cm (standard deviation = 1.5 cm) for the ST and 0.2 cm (standard deviation = 1.2 cm) for the G, indicating MRI tended to slightly underestimate ST tendon-only length and slightly overestimate tendon-only G length. Bland-Altman plots show no evidence of statistically significant systematic error, as the line of equality (0) is contained within the 95% confidence interval for the mean difference for both the ST and the G (Figs 3 and 4). Discrepancy between the 2 measurement methods did not exceed 3 cm for any of the 84 tendons harvested in the study population (Figs 5 and 6). Given the standard deviations, harvested tendon-only length is expected to be within 3 cm or less of preoperative MRI estimate with 95% confidence for both the ST and G.

Additionally, very strong correlation between MRI estimates of tendon-only length and surgical measurements is indicated by the Spearman correlation coefficients being 0.83 ($P < .0001$) for the ST and 0.82 ($P < .0001$) for the G. There was also strong correlation between the harvested tendon-only length of the ST and that of the G (Spearman coefficient = 0.68; $P < .0001$).

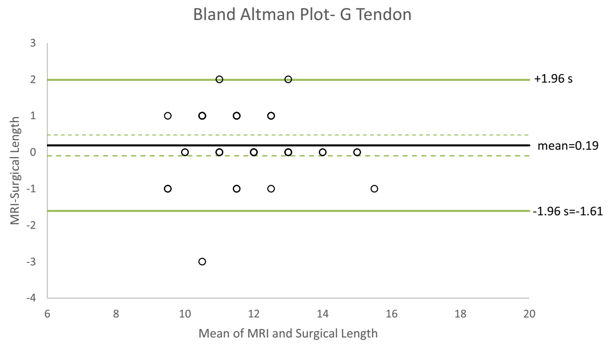

Fig 4. Bland-Altman plot of differences between gracilis (G) tendon-only length measured by magnetic resonance imaging (MRI) and that same length measured at surgery versus average of MRI and surgically measured tendon-only lengths. Dashed gray lines represent the 95% confidence interval around the mean and range from −0.095 to 0.47.

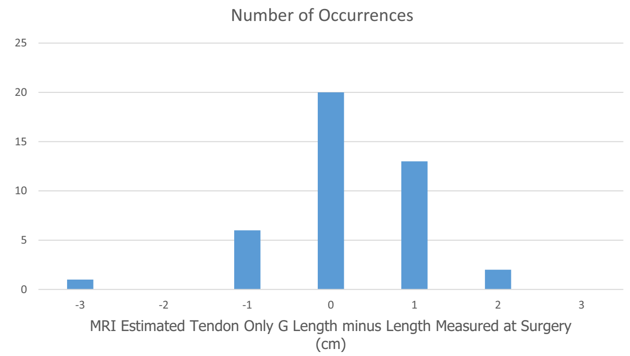

Fig 6. Bar graph of the difference between magnetic resonance imaging estimate of gracilis tendon-only length and that measured on the harvested tendon, to the nearest centimeter.

Discussion

The results of this investigation confirm the study hypothesis that preoperative MRI can estimate tendon-only lengths of the ST and G tendons from the distal-most aspect of their MTJ to tibial insertion, if the MTJ is visualized on the MRI scan. The data suggest the harvested length of this tendon-only portion of the ST and G is expected to be within 3 cm of the length estimated by MRI with 95% confidence. The tendon-only length has been very recently shown to range from 39% to 71% of the total harvested length of the ST and from 43% to 71% of the total harvested length of the G.[10] That investigation further revealed that the chance of harvesting an abnormally short ST (defined in that study as having a total length <15 cm) was <5% if its tendon-only length was >9.5 cm. Similarly, the chance of harvesting a G <15 cm in length was found to be less than 5% if its tendon-only length was 9 cm or greater. With that in mind, given the findings of the current investigation, an MRI estimate of ST tendon-only length being 12.5 cm or greater would make the likelihood of that harvested tendon having a total length <15 cm very unlikely. Similarly, an MRI estimate of G tendon-only length of 12 cm or more would make it highly improbable the total length of that harvested tendon would be <15 cm. Thus, measuring the tendon-only length on preoperative MRI scans might be a reliable method of finding those patients likely to have hamstring tendons too small to fashion into robust grafts for ACL reconstruction without graft augmentation.

Even if the MTJ itself is not included in the MRI scan's imaged field, thereby precluding measuring the exact tendon-only lengths of the ST or G, those harvested tendons are still highly likely to be 15 cm or greater if their tendon-only lengths are estimated to be at least 12.5 cm or 12 cm, respectively, on imaging. Although some clinicians may argue harvested tendons <15 cm in length may still be fashioned into useful grafts for ACL reconstruction, they would appear to be clearly too short to be useful if folded over more than once in order to increase graft diameter.[7] This is concerning as moderate correlation has been shown between harvested total tendon length of the ST or G and the resulting diameter of the quadruple-stranded graft.[10] It would appear, therefore, that thinner tendons, which produce thinner grafts, also tend to be shorter than thicker tendons.

The focus of prior imaging investigations into the adequacy of the size of these tendons for ACL reconstruction has overwhelmingly been on their diameter, not length.[17-19,21] An older study by Hamada et al.[20] did find weak correlation between the MRI measured cross-sectional area of the ST and that tendon's harvested length. Although they also reported better correlation with the diameter of the harvested ST, no imaging evaluation of the G was performed in that investigation. Also focused solely upon the ST is a 3-dimensional computer tomographic study by Yasumoto et al.,[22] which found moderate correlation between tendon length on imaging and at harvesting but no significant correlation between tendon diameter measured on imaging and after surgical harvesting. Attempting to measure the entire length of the ST or G on routine MRI scans of the knees is frustrated by the fact that the imaged region often does not cover the entire length of these tendons. Indeed, in 8 (16%) of the 50 cases originally looked at in the current investigation, even the MTJ of these tendons was not included in the imaged fields.

Limitations

The limitations of this investigation include that it represents the experience of a single surgeon and the MRI estimates of ST and G tendon-only lengths were all performed by a single radiologist perusing scans obtained on high magnetic field strength machines, using particular MRI sequence protocols and specific imaging measuring software. Therefore, selection bias may have been present and inter-rater reliability was not assessed. However, the imaging methods used in this investigation were standard knee MRI sequences and the software used to perform measurements is also standardly in current use by radiologists. Furthermore, having a single surgeon and radiologist involved helps to standardize the techniques of operative harvesting/measurement and MRI estimation. Although a formal power analysis was not performed, this investigation's findings are markedly statistically significant, so the question of the study being underpowered to the point of risking a type 2 statistical error does not arise.

Conclusions

MRI estimates of tendon-only length for both the ST and G very strongly correlate with operative measurements of these lengths; the discrepancy between these 2 measurement methods was found not to exceed 3 cm when the MTJ of these tendons is visible on MRI scans.

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