More than 200,000 anterior cruciate ligament (ACL) tears occur every year in the United States.1 Hamstring ACL reconstruction using both the semitendinosus and gracilis tendons is commonly performed and may offer advantages compared with bone-patellar tendon-bone grafts by minimizing donor site morbidity, extensor dysfunction, and patellofemoral pathology.2,3 When a hamstring graft is inadequate, typically because the diameter is less than 8 mm, the surgeon must choose a different type of graft or augment the original graft.4-6 In this case, MRI assessment of the semitendinosus tendon can provide a simple and reliable way to help surgeons to prepare for the procedure because MRI is a routine diagnostic tool in ACL injury.1 The ability to anticipate graft diameter based on MRI findings would assist surgeons in graft choice and patient counseling by identifying patients who are at risk for inadequate semitendinosus...
tendon preoperatively. Several studies used MRI to measure the diameter and cross-sectional area of the hamstring tendons to reliably predict graft and tendon diameter. However, to the best of the authors’ knowledge, no studies have used MRI assessment of tendon length to predict graft diameter.

This study evaluated whether MRI measurements of the cross-sectional area and length of the semitendinosus tendon correlated with graft diameter, with the goal of identifying tendons that are likely to require graft augmentation.

**Materials and Methods**

After approval was obtained from the institutional review board, the authors performed a retrospective review of the records of 140 consecutive patients who were scheduled for ACL reconstruction performed by a single surgeon (E.H.A.) between 2013 and 2016. Cases were identified based on the Current Procedural Terminology code for ACL reconstruction, 29888. The study included patients who underwent full ACL reconstruction with a semitendinosus autograft prepared with the Arthrex GraftLink (Arthrex, Naples, Florida) system. Procedures that involved other types of grafts (eg, allografts or bone-patellar tendon-bone grafts) or 3 or more simultaneous ligament (multiligamentous) reconstructions were excluded.

**Magnetic Resonance Imaging**

Routine preoperative MRI scans were reviewed for each patient. Because the scans were performed at various institutions, different MRI machines and methods were used. A T2-weighted axial scan was used to obtain all measurements of the semitendinosus tendon. The cross-sectional area of the tendon was determined according to the method described by Erquicia et al and Wernecke et al. Briefly, the cross-sectional area was measured at the level of the widest point of the medial femoral epicondyle under both 2× and 4× magnification, using the ovoid selection tool in the Amalga MRI software (Amalga Unified Intelligence System; Careggin, Seattle, Washington). Tendinous structures were identified by low signal intensity, and areas with intermediate to high signal intensity were considered surrounding tissue (Figure 1).

Because of the oblique path of the semitendinosus tendon, no single coronal or sagittal slice can be used reliably to measure its entire length. The authors developed a surrogate measure of tendon length in which the number of axial slices containing the semitendinosus tendon, from the beginning of the musculotendinous junction to the lowest point of the pes anserinus insertion, was multiplied by the thickness of each slice. This method measures the vertical distance traveled by the semitendinosus tendon rather than its actual length because it does not account for horizontal distances traveled. The length of the semitendinosus tendon, from the musculotendinous junction to the beginning of the fibular head, also was measured with this method.

**Graft Measurements**

All graft measurements were obtained from the surgeon’s dictated postoperative notes. Either the graft diameter, as measured with a sizing block, was directly dictated or the graft diameter was inferred by the diameter of the femoral or tibial tunnel drilled for graft passage.

**Statistical Analysis**

Simple linear regression was used to calculate Pearson’s product-moment correlation coefficients, comparing the various semitendinosus tendon and graft measurements. A modified version of the statistical method described by Grawe et al was used to determine the cutoff MRI measurements for the semitendinosus tendon cross-sectional area and length for grafts that did not require augmentation (ie, diameter ≥8 mm). Logistic regression of these variables was used to generate receiver operating characteristic curves to determine the minimum semitendinosus tendon cross-sectional area and length on MRI that most closely predicted graft diameter of 8 mm or greater. Statistical analysis was performed with commercially available software (JMP PRO 12; SAS Institute, Cary, North Carolina). Statistical significance was set at P<.05.

**Results**

Of the 140 procedures reviewed, 39 met the inclusion criteria and 101 were excluded. The 2 most frequent criteria for exclusion were allografts (44) and missing information (28). Missing information included MRI records (17) and graft measurements (11). Additionally, 13 bone-patellar tendon-bone grafts, 12 cases of ACL repair, and 4 multiligamen-
tous reconstructions were excluded. A summary of the results is shown in Table 1.

**Semitendinosus Tendon Cross-sectional Area**

Semitendinosus tendon cross-sectional area varied widely, from 7.9 to 21.4 mm² and from 8.5 to 20.7 mm² under 2× and 4× MRI magnification, respectively. On average, 4× magnification produced slightly larger tendon cross-sectional area measurements (14.7±2.8 mm²) compared with 2× magnification (14.5±2.9 mm²). However, the difference was not statistically significant (P=.8). Compared with graft cross-sectional area, Pearson’s coefficients of 0.50 (95% confidence interval [CI], 0.21-0.70) and 0.59 (95% CI, 0.34-0.76) were calculated for semitendinosus tendon cross-sectional area under 2× and 4× magnification, respectively. In both cases, correlations were statistically significant (P<.01) (Table 2).

**Semitendinosus Tendon Length**

The correlation between intraoperative semitendinosus tendon length and MRI measurements of either the total semitendinosus tendon length or the semitendinosus tendon length at the fibular head produced Pearson’s coefficients of 0.75 (95% CI, 0.40-0.91) and 0.74 (95% CI, 0.38-0.90), respectively. Both correlations were statistically significant (P<.01) (Table 2, Figure 2). When graft diameter was compared with tendon length measured with MRI at the fibular head, it yielded a weak Pearson’s correlation coefficient of 0.34 (95% CI, 0.13-0.58) (statistically significant, P=.042). When graft diameter was compared with total tendon length on MRI, it yielded r=0.43 (95% CI, 0.14-0.66) (statistically significant, P=.0058) (Table 3).

**Graft Augmentation**

Augmentation of the semitendinosus tendon with either autologous gracilis tendon or an allograft was required in 6 of the 39 cases that met the inclusion criteria. Average semitendinosus tendon cross-sectional area was 3.10 mm² (95% CI, 0.53-5.67; P=.024) greater in cases that did not require augmentation (Table 3, Figure 3). Similarly, mean total MRI-

### Table 1

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<thead>
<tr>
<th>Variable</th>
<th>No. of Procedures</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
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<td>16.5</td>
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<td>28.3</td>
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*Patient age: mean, 25.6 y; SD, 7.5 y; median, 25 y; minimum, 14 y; maximum, 46 y.

### Table 2

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<td>0.14-0.66</td>
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<td>Graft diameter, mm</td>
<td>Magnetic resonance imaging semitendinosus tendon length at fibula, mm</td>
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<td>0.34-0.76</td>
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*Statistically significant.
measured semitendinosus tendon length was an average of 14.05 mm (95% CI, 1.25-26.85; \( P = .035 \)) greater in cases that did not require augmentation (Table 3, Figure 3). A minimum semitendinosus tendon cross-sectional area of 13.2 mm², measured with 4× magnified MRI, is associated with graft diameter of 8 mm or greater. A minimum semitendinosus tendon length of 81 mm, measured with MRI, is associated with graft diameter of 8 mm or greater (Table 4).

**Discussion**

The most important finding of this study was the development of cutoff MRI measurements that can be used to identify, with reasonable sensitivity and specificity, semitendinosus tendons that are likely to require augmentation. Tendons with cross-sectional area of less than 13.2 mm² or length of less than 81 mm were most closely associated with graft diameter of less than 8 mm, and these tendons were more likely to require augmentation (Table 4). With this method, surgeons may be able to use preoperative MRI findings to assess the need for augmentation rather than relying solely on intraoperative findings. This technique can be especially useful when allografts are not readily available and must be ordered or stocked.

Because graft diameter is related to mechanical resistance, tensile strength, and the revision surgery rate, it is critically important for long-term graft survival. The average diameter of the natural ACL is 11 mm, and increased failure rates are associated with grafts that are less than 8 mm in diameter. Traditionally, anthropometric measures have been used to predict graft diameter. The most commonly studied measure, patient height, significantly correlates with graft diameter (\( r = 0.45 \)), whereas other measures, such as weight and body mass index, weakly correlate with graft dimensions.

Imaging techniques, such as MRI, provide a more reliable and accurate alternative to anthropometric measures in predicting graft size. In this study, MRI assessment of the semitendinosus tendon showed highly variable cross-sectional area measurements, with mean values of 14.5 mm² (range, 7.9-21.4 mm²) and 14.7 mm² (range, 8.5-20.7 mm²) under 2× and 4× magnification, respectively. These values fall within the expected range for mean semitendinosus tendon cross-sectional area based on previous studies, with reported means of 12.4 mm² (range, 9.4-17.5 mm²; 4× magnification) to 16.8 mm² (range, 10.5-24.6 mm²; 2× magnification). Similar to the findings of Erqui et al, cross-sectional area measured under 4× magnification yielded smaller ranges than measurements obtained under 2× magnification, suggesting greater precision under higher magnification. This is likely because higher magnification allows for easier discrimination between low and high signal intensity with the cursor-based measurement tool (ie, Amalga Unified Intelligence System). However, the difference in mean cross-sectional area was an average of 14.05 mm (95% CI, 1.25-26.85; \( P = .035 \)) greater in cases that did not require augmentation (Table 3, Figure 3). A minimum semitendinosus tendon cross-sectional area of 13.2 mm², measured with 4× magnified MRI, is associated with graft diameter of 8 mm or greater. A minimum semitendinosus tendon length of 81 mm, measured with MRI, is associated with graft diameter of 8 mm or greater (Table 4).
area between magnification levels was not statistically significant ($P=.8$). Although both methods of assessing cross-sectional area produced statistically significant correlations compared with graft cross-sectional area, $4\times$ magnification yielded stronger correlation coefficients ($r=0.59; 95\%\ CI, 0.34-0.76$) than $2\times$ magnification ($r=0.50; 95\%\ CI, 0.21-0.70$). Again, these results are in general agreement with those of Erquicia et al, who reported $r$ values of 0.54 and 0.86 under $2\times$ and $4\times$ magnification, respectively.

This study reported a novel method for predicting semitendinosus tendon length with MRI by measuring the vertical distance between the musculotendinous junction and the fibular head or the insertion of the pes anserinus. Figure 2 shows linear regressions comparing these measurements with the intraoperative length of the semitendinosus tendon after harvest. Both correlations were statistically significant ($P<.01$), yielding strong correlation coefficients of 0.75 and 0.74 for the full semitendinosus tendon length and the semitendinosus tendon length at the fibular head, respectively. Therefore, both MRI methods can be used to predict the actual length of the semitendinosus tendon with a reasonable degree of accuracy.

Interestingly, the similarity between MRI methods in predicting semitendinosus tendon length did not remain when compared with graft diameter. Measuring the full length of the semitendinosus tendon on MRI yielded a significantly stronger correlation with graft diameter ($r=0.43, P=.0058$) compared with measurement of the length at the fibular head ($r=0.34, P=.042$). These results are surprising; the limitation of this method is that it measures only the vertical distance traversed by the semitendinosus tendon, whereas its anatomic path is more oblique, becoming significantly more horizontal below the level of the fibular head as it approaches its insertion. The authors hypothesized that measuring the distance to the fibular head would better predict the true length and diameter of the tendon compared with measuring the entire vertical distance to its insertion. However, the converse appears to be true. Measuring the length of the semitendinosus tendon to the fibular head may predict graft diameter less accurately because of the level at which the cuts traverse the fibular head. In addition, this method excludes the important and variable semitendinosus tendon length distal to the fibular head.

Of more clinical significance, MRI assessment of the semitendinosus tendon can be used to predict the need for graft augmentation. The single-tendon GraftLink reconstruction spares the gracilis tendon, which has been associated with increased hamstring strength and better patient-reported outcomes. However, a potential disadvantage of this method is that the graft diameter may be less than 8 mm, increasing the risk of failure.

Preoperative identification of patients with inadequate tendons can allow surgeons to prepare for augmentation or opt for an alternate graft site. In the 6 cases that required graft augmentation, average semitendinosus tendon cross-sectional area was 3.10 mm$^2$ smaller ($P=.024$) and average semitendinosus tendon length was 14.05 mm (95\% confidence interval, 1.25-26.85; $P=.035$) greater in patients who did not require graft augmentation (diameter $\geq 8$ mm).

![Figure 3: Semitendinosus tendon (ST) cross-sectional area (CSA) $4\times$ magnification (A) and magnetic resonance imaging (MRI) ST length (B) in cases that did (Y) and did not (N) require augmentation of the ST graft. The horizontal line represents total mean value. On average, ST CSA was 3.10 mm$^2$ (95\% confidence interval, 0.53-5.67; $P=.024$) greater and ST length was 14.05 mm (95\% confidence interval, 1.25-26.85; $P=.035$) greater in patients who did not require graft augmentation (diameter $\geq 8$ mm).](image)

<table>
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<th>Table 4: Cutoff Values</th>
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<td>Magnetic resonance imaging semitendinosus tendon length, mm$^4$</td>
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*Threshold magnetic resonance imaging measurement associated with adequate graft diameter ($\geq 8$ mm).*

Receiver operating characteristic curves were used to calculate threshold values for semitendinosus tendon cross-sectional area and length that were most predictive of the need for augmentation (Table 4). A minimum semitendinosus tendon cross-sectional area of 13.2 mm$^2$ can predict a graft diameter of 8 mm or greater. Using a similar method, Beyzadeoglu et al found that a minimum semitendinosus tendon...
cross-sectional area of 12 mm$^2$ is required to produce a 2-stranded semitendinosus tendon graft of at least 6 mm in diameter. It is reasonable that a slightly larger cross-sectional area is required to produce a quadrupled graft of at least 8 mm in diameter. Similarly, a minimum MRI-measured semitendinosus tendon length of 81 mm can predict a graft diameter of 8 mm or greater (Table 4). Based on the current findings, it is not surprising that tendon cross-sectional area is a more sensitive and specific measure than tendon length (Table 2). The differences between augmented and non-augmented tendons are more significant for cross-sectional area, and the correlation between graft diameter and tendon cross-sectional area is stronger than that for tendon length (Table 2).

Limitations

Because it was a retrospective chart review, this study had certain limitations. First, the maximum age of subjects was 46 years, potentially limiting extrapolation of the results to older populations. Second, only 15% of patients required graft augmentation, which may limit the reliability of the assessment. Similarly, 72% (101) of cases were excluded, 28 because of missing information. Otherwise, these cases may have met the inclusion criteria, potentially introducing a selection bias. Third, inability to standardize MRI methods and machines resulted in wide variations in resolution, slice thickness, and other parameters that may have contributed to a lack of precision and reproducibility in measurement. Finally, all intraoperative graft measurements relied on the surgeon's dictation, which may have suffered from recall bias.

**CONCLUSION**

This study correlated MRI measurements of the semitendinosus tendon with graft diameter in patients undergoing quadruple, all-inside ACL reconstruction. In this study, tendons with cross-sectional area of less than 13.2 mm$^2$ were most likely to require augmentation with either the autologous gracilis tendon or allogeneic tendons. Measuring the vertical distance traversed by the semitendinosus tendon on MRI correlates not only with the actual semitendinosus tendon length but also with the final graft diameter. Tendons with MRI-measured lengths of less than 81 mm are more likely to require augmentation. The findings showed that MRI assessment of the cross-sectional area of the semitendinosus tendon is more closely related to graft diameter than to tendon length. However, both methods provide a quick, simple, and reliable means to identify patients who are likely to need graft augmentation.

**REFERENCES**