Original Article | Journal of Orthopaedic Case Reports 2026 November:16(11):Page 405-410

Diagnostic Accuracy of an 18.5 mm² Magnetic Resonance Imaging Cross-Sectional Area Threshold for Predicting Graft Adequacy (≥8.0 mm) in Quadrupled Hamstring Anterior Cruciate Ligament Reconstruction

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Learning Point of the Article:

Preoperative axial MRI measurement of semitendinosus (ST) tendon cross-sectional area (CSA) at the joint line provides excellent diagnostic accuracy for graft adequacy. An 18.5 mm² threshold exhibits 100% sensitivity and 94.59% accuracy for predicting an adequate (≥8.0 mm) quadrupled ST graft. All patients below this threshold had an inadequate graft (PPV 100%), although 2 of 13 undersized grafts were missed (sensitivity 84.62%). This enables proactive pre-operative surgical planning for gracilis tendon augmentation or alternative graft selection.

Abstract

Introduction: A quadrupled semitendinosus (ST) graft diameter below 8.0 mm is associated with higher failure and revision rates after anterior cruciate ligament (ACL) reconstruction. Pre-operative identification of patients at risk of an undersized graft may facilitate planning for gracilis augmentation or alternative graft selection.

Objective: To determine the diagnostic accuracy of a pre-operative Magnetic resonance imaging (MRI)-measured ST cross-sectional area (CSA) threshold of 18.5 mm² for predicting an intraoperative quadrupled graft diameter of at least 8.0 mm.

Materials and Methods: Thirty-seven consecutive patients undergoing arthroscopic ACL reconstruction with a quadrupled ST autograft were enrolled in a prospective observational study. Pre-operative ST CSA was measured on axial MRI at the joint line by a single musculoskeletal radiologist blinded to intraoperative findings. Quadrupled ST graft diameter was measured intraoperatively with a standard graft-sizing block before any gracilis augmentation. A CSA cut-off of 18.5 mm², derived by receiver operating characteristic (ROC) analysis within this cohort, was evaluated against the 8.0 mm adequacy threshold using standard 2×2 diagnostic accuracy statistics.

Results: Pre-operative CSA was strongly correlated with graft diameter (Spearman's $\rho = 0.948$, $P < 0.001$). At the 18.5 mm² cut-off (adequate graft as the target condition), sensitivity was 100% (95% confidence interval [CI] 85.75–100%), specificity 84.62% (95% CI 54.55–98.08%), positive predictive value 92.31% (95% CI 77.03–97.72%), negative predictive value 100% (95% CI 71.51–100%), and overall accuracy 94.59% (95% CI 81.81–99.34%), with an area under the ROC curve of 0.986 (95% CI 0.957–1.000). All 11 patients with a pre-operative CSA below 18.5 mm² had an inadequate graft (<8.0 mm); two of the 13 patients with an inadequate graft had CSA ≥18.5 mm² (sensitivity 84.62% for detecting an inadequate graft).

Conclusion: Pre-operative ST CSA below 18.5 mm² was associated with an intraoperative graft diameter <8.0 mm in all 11 patients below the threshold, although 2 of 13 undersized grafts were missed. This threshold may serve as a useful pre-operative screening metric to anticipate the need for graft augmentation, pending external validation.

Keywords: Anterior cruciate ligament reconstruction, cross-sectional area, diagnostic accuracy, graft diameter, magnetic resonance imaging, receiver operating characteristic curve, semitendinosus tendon.

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Access this article online

Website: www.jocr.co.in

DOI: https://doi.org/10.13107/jocr.2026.v16.i11.8510

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Submitted: 17/08/2026; Review: 03/09/2026; Accepted: October 2026; Published: November 2026

DOI: https://doi.org/10.13107/jocr.2026.v16.i11.8510

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Introduction

Reconstruction of the anterior cruciate ligament (ACL) with a quadrupled hamstring autograft is standard practice in many centres worldwide, supported by favourable long-term clinical outcomes and low donor-site morbidity relative to bone-patellar tendon-bone or quadriceps tendon autografts. However, the final diameter of a hamstring construct cannot be directly ascertained pre-operatively and depends heavily on individual tendon dimensions, which exhibit significant anatomical variability and cannot be reliably predicted by external anthropometric measurements alone.

A final quadrupled graft diameter below 8.0 mm has been strongly associated with elevated rates of graft failure and revision surgery in multiple clinical series, establishing 8.0 mm as a widely accepted benchmark for graft adequacy [1,2]. When the isolated semitendinosus (ST) tendon yields a graft diameter below this threshold, ipsilateral gracilis tendon harvesting and co-augmentation are routinely required. In conventional practice, this decision is made intraoperatively only after ST harvest and sizing, creating unforeseen operative delays, altered surgical plans, and additional morbidity.

Magnetic resonance imaging (MRI), routinely performed for diagnostic confirmation of ACL tears, provides high-resolution anatomical cross-sectional area (CSA) measurements of the hamstring tendons [1]. While previous studies have reported positive correlations (r = 0.70 to 0.95) between pre-operative CSA and harvested graft diameter [3,4,5,6], reported cut-off values vary widely (12 to 22 mm^2) depending on the axial slice level, population demographics, and measurement protocols [7,8,9,10,11,12,13,14,15]. Furthermore, few studies present comprehensive diagnostic accuracy parameters – such as sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and receiver operating characteristic (ROC) curves – that directly guide surgical decision-making.

This study evaluates the diagnostic accuracy of an 18.5 mm^2 pre-operative ST CSA threshold derived from a prospective cohort in Southern India to predict whether a harvested quadrupled ST graft reaches the critical 8.0 mm diameter threshold.

Materials and Methods

Study design, setting, and ethics

This prospective observational diagnostic accuracy study was conducted in the Department of Orthopaedics and Traumatology at Pushpagiri Institute of Medical Sciences and Research Centre, Tiruvalla, Kerala, India, over an 18-month period following approval from the Institutional Ethics Committee (EC Reg. No. EC/NEW/INST/2020/1188; Approval ref: PIMSRC/E1/388A/52/2023, granted on June 29, 2023). Written informed consent was obtained from all patients prior to enrolment.

Participant eligibility and flow

Consecutive patients aged 18–50 years presenting with a clinically and radiologically verified complete ACL rupture scheduled for arthroscopic primary ACL reconstruction using a quadrupled ST autograft were screened. Exclusion criteria comprised previous ipsilateral knee surgery, established osteoarthritic changes (Kellgren-Lawrence grade ≥2), multi-ligamentous knee injuries, previous ST injury, active local/systemic infection, and systemic inflammatory diseases. A total of 37 consecutive patients met all eligibility criteria and completed both the index test (preoperative MRI) and reference standard (intraoperative graft measurement), with zero losses to follow-up (Fig. 1).

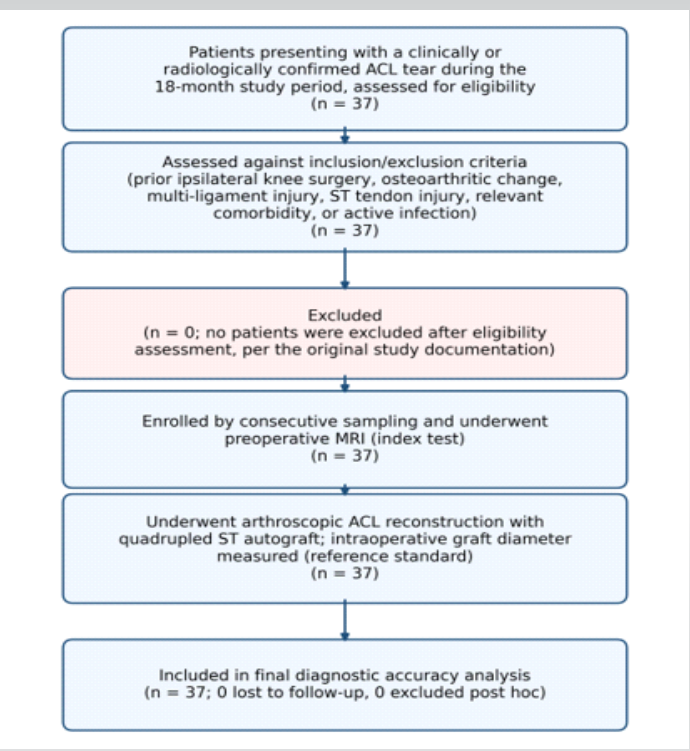


Figure 1: Participant flow through the study. ACL: Anterior cruciate ligament; MRI: Magnetic resonance imaging; ST: Semitendinosus; n: Number of participants.

Sample size calculation

The sample size was determined using Fisher's z-transformation formula for detecting a significant correlation coefficient (Equation 1):

$$N = [(Z1-\alpha/2 + Z1-\beta) / (0.5 \times \ln[(1+r)/(1-r)])]2 + 3$$

where N is the required sample size, $Z1-\alpha/2$ is the standard

Table 1: Demographic and anthropometric characteristics of the study cohort (*n* =37)	
Variable	**Value (*n* =37)**
Age, years, median (IQR; range)	31 (24–38; 18–56)
Sex, *n* (%)	Men: 31 (83.8%); Women: 6 (16.2%)
Weight, kg, mean±SD (range)	74.0±14.0 (45–102)
Height, cm, mean±SD (range)	171.0±8.4 (152–186)
Side of injury, *n* (%)	Right: 20 (54.1%); Left: 17 (45.9%)
IQR: Interquartile range, SD: standard deviation, *n*: Number of participants	

normal deviate for a two-tailed test at the 5% significance level (1.96), Z_1-β is the standard normal deviate corresponding to 80% power (0.84), and r is the anticipated correlation coefficient between CSA and graft diameter (0.45, based on prior literature). Substituting these values yielded a minimum required sample size of approximately 37 participants, which determined the target enrolment for this study.

Index test: Pre-operative MRI protocol

All enrolled participants underwent standard knee MRI prior to surgery. Axial sequences were evaluated by a senior musculoskeletal radiologist blinded to clinical and intraoperative findings. ST CSA was measured at a standardized joint-line level corresponding to the axial slice where the anteroposterior diameter of the medial femoral condyle was maximal, utilizing continuous free-hand region-of-interest tracing.

Reference standard: Intraoperative graft sizing

Arthroscopic ACL reconstruction was performed by a single experienced orthopedic knee surgeon blinded to the pre-operative MRI CSA values. The ST tendon was harvested using an open tendon stripper, prepared, cleaned of muscular tissue, and quadrupled. The quadrupled graft diameter was measured using a calibrated cylindrical graft-sizing block in 0.5 mm increments before any gracilis tendon harvest or augmentation. An adequate graft was defined as diameter ≥8.0 mm; an undersized graft (<8.0 mm) was augmented with the ipsilateral gracilis tendon per institutional protocol.

Statistical analysis

Statistical evaluations were performed using Jamovi (v2.3.28). Normality of continuous data was evaluated using the Shapiro–Wilk test. Continuous variables are reported as mean ± standard deviation (SD), or median with interquartile range (IQR); categorical variables are expressed as frequencies and percentages. The correlation between pre-operative ST CSA and intraoperative graft diameter was assessed through Spearman's rank correlation. ROC analysis was applied to derive the optimal CSA cut-off maximizing the Youden index (J = Sensitivity + Specificity − 1). Diagnostic performance metrics (sensitivity, specificity, PPV, NPV, positive likelihood ratio [LR+], negative likelihood ratio [LR−], and accuracy) were calculated with 95% confidence intervals (CI). Significance was set at $P < 0.05$.

Results

Cohort characteristics

The prospective cohort included 37 patients: 31 males (83.8%) and 6 females (16.2%). The median age was 31 years (IQR: 24–38; range: 18–56). The mean body weight was 74.0 ± 14.0 kg (range: 45–102 kg) and mean height was 171.0 ± 8.4 cm (range: 152–186 cm). Right-sided knee involvement was noted in 20 patients (54.1%) and left-sided in 17 patients (45.9%) (Table 1).

Graft dimensions and correlation analysis

The median pre-operative ST CSA on MRI was 20.7 mm^2 (IQR: 18.1–22.4 mm^2; range: 14.5–23.6 mm^2). Intraoperatively, quadrupled ST graft diameter averaged 8.56 ± 1.14 mm (range: 6.7–10.5 mm) and graft length averaged 30.90 ± 5.05 mm (range: 22–40 mm). Overall, 24 patients (64.9%) had an adequate graft (≥8.0 mm), while 13 patients (35.1%) had an inadequate graft (<8.0 mm) requiring gracilis

Table 2: 2×2 Contingency table for the 18.5 mm^2 CSA threshold against the 8.0 mm graft adequacy standard (*n* =37)			
Preoperative MRI ST CSA	**Graft ≥ 8.0 mm (Adequate)**	**Graft < 8.0 mm (Inadequate)**	**Total**
CSA ≥ 18.5 mm^2 (Test Positive)	24 (True Positive)	2 (False Positive)	26
CSA < 18.5 mm^2 (Test Negative)	0 (False Negative)	11 (True Negative)	11
Total	**24**	**13**	**37**
CSA: Cross-sectional area; ST: Semitendinosus.			

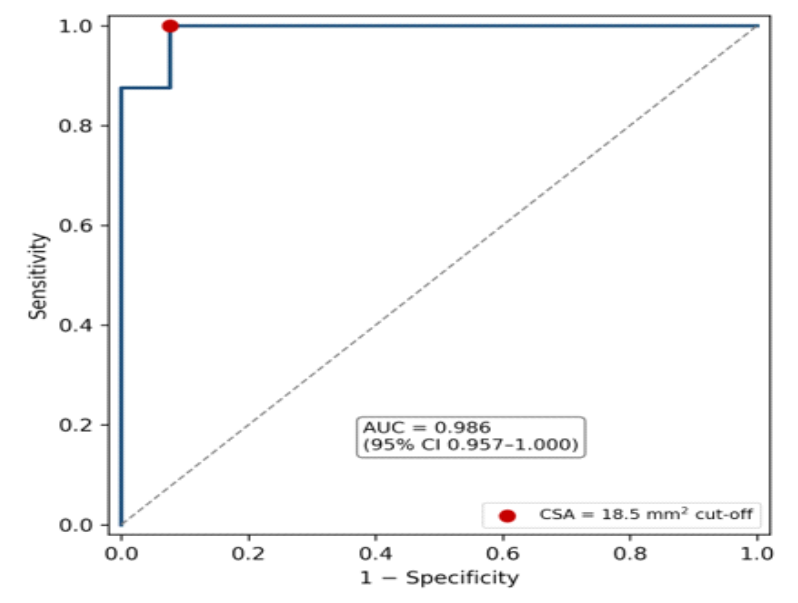


Figure 2: ROC curve for pre-operative ST cross-sectional area predicting an intraoperative graft diameter of at least 8.0 mm (n = 37). ROC: Receiver operating characteristic, ST: Semitendinosus, AUC: Area under the curve, CI: Confidence interval. The red marker denotes the operating point corresponding to the 18.5 mm² cut-off.

augmentation. A very strong positive correlation was identified between pre-operative ST CSA and intraoperative quadrupled graft diameter (Spearman's $\rho = 0.948$, $p^2 = 0.90$, $P < 0.001$).

Diagnostic accuracy of the 18.5 mm² cut-off

ROC curve analysis identified 18.5 mm² as the optimal cut-off for predicting an intraoperative graft diameter ≥8.0 mm, yielding an area under the curve (AUC) of 0.986 (95% CI: 0.957–1.000, P < 0.001) (Fig. 2). The 2 × 2 contingency table (Table 2) showed 24 true positives, 11 true negatives, 2 false positives, and 0 false negatives. At the 18.5 mm² threshold (adequate graft as the target condition), diagnostic sensitivity was 100.0% (95% CI: 85.75–100.0%), specificity was 84.62% (95% CI: 54.55–98.08%), PPV was 92.31% (95% CI: 77.03–97.72%), NPV was 100.0% (95% CI: 71.51–100.0%), LR+ was 6.50 (95% CI: 1.82–23.26), LR− was 0.00 (95% CI: 0.00–0.38), and overall diagnostic accuracy was 94.59% (95% CI: 81.81–99.34%) (Table 3). When the threshold is used to detect an inadequate graft (CSA <18.5 mm² as test-positive: 11 true positives, 2 false negatives, 0 false positives, 24 true negatives), sensitivity was 84.62% (95% CI: 54.55–98.08%), specificity 100.0% (95% CI: 85.75–100.0%), PPV 100.0% (95% CI: 71.51–100.0%), NPV 92.31% (95% CI: 74.87–99.05%), and accuracy 94.59%.

Table 3: Diagnostic accuracy parameters of the 18.5 mm² CSA threshold for predicting graft adequacy (≥8.0 mm)

Diagnostic Parameter	Value (%)	95% confidence interval (CI)
Sensitivity	100	85.75%–100.0%
Specificity	84.62	54.55%–98.08%
Positive predictive value (PPV)	92.31	77.03%–97.72%
Negative predictive value (NPV)	100	71.51%–100.0%
Overall diagnostic accuracy	94.59	81.81%–99.34%
Positive likelihood ratio (LR+)	6.5	1.82–23.26
Negative likelihood ratio (LR−)	0	0.00-0.38
Area Under the ROC curve (AUC)	0.986	0.957–1.000

ROC: Receiver operating characteristic, AUC: Area under the curve, CI confidence interval.
Values are for an adequate graft (≥8.0 mm) as the target condition; the LR− CI was calculated with a 0.5 continuity correction.

Discussion

The primary objective of this study was to evaluate the diagnostic capability of pre-operative MRI-derived ST CSA to predict quadrupled graft adequacy in ACL reconstruction. The most notable finding was that an 18.5 mm² threshold provided 100% sensitivity and 100% NPV for an adequate graft: all 24 patients with an adequate graft had CSA ≥18.5 mm², and all 11 patients with CSA <18.5 mm² had an inadequate graft (PPV 100% for an undersized graft). However, the threshold missed 2 of the 13 patients whose quadrupled ST graft failed to achieve the 8.0 mm benchmark (sensitivity 84.62% for detecting an undersized graft). This strong predictive fidelity is supported by a correlation of $\rho = 0.948$ and an AUC of 0.986.

A quadrupled hamstring graft diameter <8.0 mm has been repeatedly highlighted in the literature as a prominent risk factor for construct failure, with Magnussen et al. demonstrating substantially increased revision rates in younger, active cohorts receiving undersized grafts [16]. Hence, precise pre-operative knowledge of graft thickness is critical for surgical decision-making. If an ST autograft is predicted to be undersized (<18.5 mm²), surgeons can pre-operatively plan gracilis tendon co-harvesting, prepare allograft augmentation, or select an alternative primary autograft (e.g., bone-patellar tendon-bone or quadriceps tendon).

Several prior studies have explored pre-operative MRI and ultrasound measurements for graft diameter estimation [3,4,5,6,7,8,9,10,11,12,13,14,15]. Çeliktaş et al. and Manni et al. observed moderate associations between anthropometric markers and graft dimensions, though anthropometry alone lacked sufficient precision for clinical decision-making [2,3].

Cobanoglu et al. and Movahedinia et al. demonstrated that MRI CSA is a superior predictor compared to height or weight [4,5]. Liau et al. reported an AUC of 0.856 using geometric tendon modeling on MRI [12], while Mayr et al. emphasized that axial slice selection significantly influences cross-sectional thresholds [13]. In the present study, measuring ST CSA at the maximal medial femoral condyle diameter at the joint line offered high diagnostic yield; however, inter- and intra-observer reliability of the CSA measurement was not assessed.

Limitations of the study include the single-center design and a predominantly male cohort (83.8%), reflecting regional athletic presentation patterns. Importantly, the 18.5 mm^2 cut-off was derived and evaluated within the same small cohort (n = 37) without internal or external validation, which likely overestimates its diagnostic accuracy and yields wide confidence intervals; the findings should therefore be considered preliminary. Inter- and intra-observer reliability of the CSA measurement was also not assessed, and external validation across multicentric, diverse cohorts is recommended.

Conclusion

A pre-operative MRI ST tendon CSA threshold of 18.5 mm^2 provides high sensitivity (100%) for an adequate graft and overall accuracy (94.59%) for predicting quadrupled ST graft adequacy (≥8.0 mm). All patients below the threshold had an inadequate graft, although 2 of 13 undersized grafts were missed. Incorporation of this measurement into pre-operative ACL planning may help identify patients requiring gracilis augmentation or alternative graft constructs and reduce unanticipated intraoperative changes, pending external validation.

Clinical Message

Measuring the ST tendon cross-sectional area on routine pre-operative axial MRI at the joint line is a simple method that may help predict quadrupled graft diameter. An ST CSA <18.5 mm^2 alerts the orthopedic surgeon to prepare for gracilis tendon harvest and co-augmentation, optimizing operative readiness and surgical outcomes..

Declaration of patient consent: The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient has given the consent for his/ her images and other clinical information to be reported in the journal. The patient understands that his/ her names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

Conflict of interest: Nil **Source of support:** None

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Conflict of Interest: Nil
Source of Support: Nil

Consent: The authors confirm that informed consent was obtained from the patient for publication of this article

How to Cite this Article

Mathew T, Mathew A, Faris S, Johnson F, Krishna A. Diagnostic Accuracy of an 18.5 mm^2 Magnetic Resonance Imaging Cross-Sectional Area Threshold for Predicting Graft Adequacy (≥8.0 mm) in Quadrupled Hamstring Anterior Cruciate Ligament Reconstruction. J Orthop Case Rep. 2026 November;16(11):405-410. doi: 10.13107/jocr.2026.v16.i11.8510.