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Predictive Factors for Hamstring Graft Diameter in Anterior Cruciate Ligament Reconstruction

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Purpose: Hamstring graft diameter is a critical factor in anterior cruciate ligament reconstruction (ACLR), with grafts ≥ 8 mm associated with high failure rates. The accurate prediction of graft size before surgery is particularly important in populations with smaller body frames, such as Asian populations. We aimed to identify the anthropometric and magnetic resonance imaging (MRI) -based predictors of hamstring graft diameters ≥ 8 mm in patients undergoing ACLR.

Methods: A retrospective cohort study was conducted in 210 patients (169 men, 41 women) who underwent single-bundle ACLR with quadrupled hamstring autografts at Maharat Nakhon Ratchasima Hospital between 2017 and 2023. Anthropometric data were collected; preoperative MRI measurements of the semitendinosus and gracilis tendons were performed. Graft diameters were recorded intraoperatively following the MRI assessment. All measurements were performed by a single observer. Logistic regression was used to identify predictive factors; a receiver operating characteristic curve was used to evaluate the diagnostic accuracy of the model.

Results: Among the 210 patients, 51 (24.3%) had graft diameters < 8 mm. Those with grafts ≥ 8 mm were predominantly men and had greater height, weight, and MRI-derived tendon dimensions. Multivariate analysis identified the semitendinosus tendon cross-sectional area (CSA-ST) as the sole independent predictor. A CSA-ST ≥ 13.4 mm² predicted graft diameters ≥ 8 mm with 70.4% sensitivity (95% CI, 62.7–77.4%), 80.4% specificity (95% CI, 66.9–90.2%), a positive predictive value of 91.8% (95% CI, 85.4–96.0%), a positive likelihood ratio of 3.6 (95% CI, 2.1–6.3), and an area under the receiver operating characteristic curve of 0.79 (95% CI, 0.69–0.82).

Conclusions: The CSA ST measured on preoperative MRI is a reliable predictor of hamstring graft adequacy in ACLR. A threshold of 13.4 mm² can assist in surgical planning and graft selection, particularly in patients with smaller body sizes. These findings underscore the importance of incorporating MRI-based assessments into routine preoperative evaluations.

Keywords: ACL Reconstruction, Hamstring Graft Size Prediction, Arthropometric, MRI

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Anterior cruciate ligament (ACL) tears are among the most prevalent knee injuries, with an estimated incidence of 85 cases per 100,000 individuals aged 16–39 years [1]. The ACL plays a crucial role in maintaining knee stability by preventing anterior tibial translation and stabilizing the joint during internal rotation. An ACL injury compromises this stability and increases the risk of secondary damage to intra-articular structures, including the meniscus, articular cartilage, and other stabilizing ligaments such as the posterior cruciate ligament and medial and lateral collateral ligaments [2,3].

ACL reconstruction (ACLR) remains the gold standard treatment for patients with ACL injury. This procedure aims to restore joint stability, prevent further degeneration of intra-articular structures, and enable patients to resume sports or other high-demand activities [4]. The hamstring and patellar tendon autografts are the two most commonly used graft options. Evidence indicates that patellar tendon grafts are associated with greater postoperative pain and kneeling discomfort compared with hamstring tendon grafts, leading to an increasing preference for hamstring autografts in recent years [5].

Graft diameter has been identified as a critical factor influencing the success of ACLR. Grafts with diameter smaller than 8 mm are associated with high rates of graft failure and suboptimal functional outcomes [6-8]. Patients in Asian populations, generally have smaller body habitus and are therefore a greater risk of obtaining graft smaller than 8 mm than those in other populations. Consequently, considerable research has focused on identifying reliable predictors of graft size, including anthropometric variables (such as height, weight, body mass index [BMI], and thigh circumference) [9–13] and magnetic resonance imaging (MRI)-derived measurements, such as tendon diameter and cross-sectional area (CSA), to facilitate accurate preoperative graft size estimation[14,15].

Notably, variability in these predictive factors has been observed across different populations and geographical regions. Therefore, the present study aimed to identify factors associated with hamstring graft diameters smaller than 8 mm in patients with ACL tears. These findings are expected to provide valuable evidence to support surgical planning, enhance clinical decision-making, and ultimately improve patient outcomes. We hypothesized that anthropometric parameters and MRI-derived tendon measurements would demonstrate significant associations with hamstring graft diameter, with effect sizes comparable to those reported in previous studies involving Asian populations.

METHODS

This retrospective cohort study included patients who underwent single-bundle ACLR using a quadrupled hamstring autograft tendon. All procedures were performed by a single surgeon at Maharat Nakhon Ratchasima Hospital between January 2017 and December 2023. The inclusion criteria were age greater than 18 years and MRI-confirmed complete ACL tears. The exclusion criteria were a history of ACLR of the ipsilateral limb, multiligamentous knee injuries, ACLR using alternative techniques, and incomplete intraoperative data.

Demographic and anthropometric variables, including height, weight, BMI, age, and sex, were recorded. Height and weight were measured using an automated body measurement device (Saint Med Super Smart Society 5.0) in the Maharat Nakhon Ratchasima hospital's outpatient department.

We used a MRI scanner (Philips model 6A278R8) with a 3.0 T magnet and slice thickness of 3.0 mm in all cases. The hamstring tendon size was assessed using MRI and reviewed on a picture archiving and communication system. Measurements focused on the semitendinosus (ST) and gracilis (GT) tendons, and all evaluations were performed by the authors to ensure measurement consistency. Coronal proton density–weighted images were used to identify the physeal scar, which served as the anatomical reference level according to previously published methods [16]. Corresponding axial proton density images were then used to manually delineate each tendon's border with the picture archiving and communication system area measurement tool, allowing the calculation of the CSA for both the ST and GT in square millimeters. The combined CSA was derived by summing the individual CSA values of the ST and GT. To minimize potential measurement bias, all MRI analyses were completed before intraoperative records were reviewed.

P. Thanomsingh / Journal of Southeast Asian Orthopaedics Vol 50 No 1 (2026) 30-38

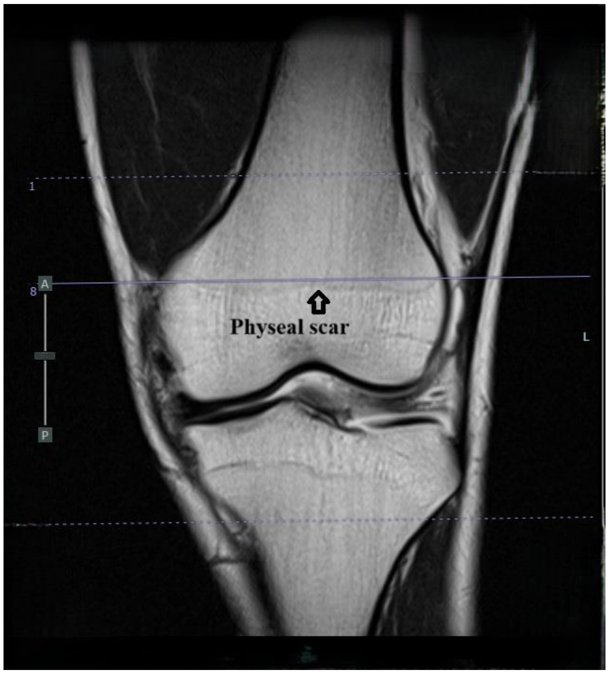


Fig. 1 Identification of tendon locations using the physeal scar as a reference point in the coronal plane.

Fig. 2 Hamstring tendon measurement method from magnetic resonance imaging.

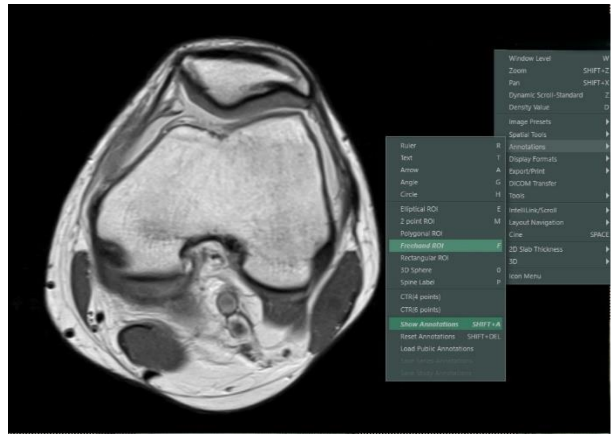


Fig. 3 Picture archiving and communication system area measurement tool used to calculate, by manual tracing, both semitendinosus and gracilis tendons.

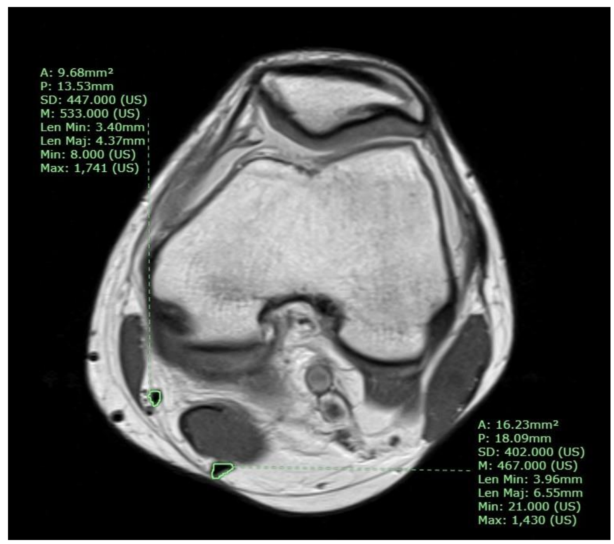


Fig. 4 Axial-plane magnetic resonance imaging showing measurement of the cross-sectional area of the two hamstring tendons. After identifying the semitendinosus and gracilis tendons, magnification was increased by 2× in all cases to improve measurement accuracy. Manual tracing was used for the measurements.

During surgery, graft diameters were recorded following tendon preparation for ACLR using the Smith & Nephew Graft Master Kit II. Measurements, obtained in millimeters by a scrub technician and verified by the operating surgeon (the author), were rounded to the nearest 0.5 mm, with borderline cases documented accordingly. The same fixation devices were used for all patients and graft preparation procedures were consistent across cases.

Statistical Analysis

Based on the study by Thwin et al. [15], the CSA of the GT and ST tendons measured on preoperative MRI demonstrated a sensitivity of 84% and specificity of 100% for predicting hamstring graft diameter. Using these parameters, a minimum sample size of 153 patients undergoing ACLR was estimated to provide 80% statistical power with a two-sided type I error rate of 0.05.

Clinical characteristics and MRI findings were compared between the ≥ 8 mm and < 8 mm graft diameter groups using independent t-tests, Wilcoxon rank-sum tests, or Fisher's exact tests, as appropriate. Univariate and multivariate logistic regression analyses were conducted to identify independent predictors of graft diameters ≥ 8 mm. Receiver operating characteristic curve analysis was performed to determine the optimal MRI-based cutoff value, and diagnostic performance was assessed using sensitivity, specificity, positive and negative predictive values, positive and negative likelihood ratios, and the area under the receiver operating characteristic curve (AUC).

No data imputation was performed and the analyses followed a complete-case approach when applicable. Statistical significance was defined as $p < 0.05$. All analyses were performed using Stata Statistical Software, Release 17 (StataCorp LLC, College Station, TX, USA). The study protocol was approved by the Institutional Review Board (IRB No. 142/2024).

RESULTS

A total of 210 patients (169 men and 41 women) from an initial cohort of 258 individuals were included in the final analysis. Forty-eight patients were excluded because of incomplete imaging data, multiligament knee injuries, or missing intraoperative records. The mean age of the study population was 30.5 ± 9.9 years. The mean height, weight, and BMI were 1.69 ± 0.08 m, 72.0 ± 12.6 kg, and 25.1 ± 3.9 kg/m², respectively (Table 1).

Table 1 Clinical characteristics of the study population (N = 210).

Variable	n (%) or mean ± SD/ median (IQR)
Male	169 (80.5)
Age (years)	30.5 ± 9.9
Diagnosis	
ACL tear alone	37 (17.6)
With one meniscal tear	105 (50)
With both meniscal tear	68 (32.4)
Weight (kg)	72.0 ± 12.6
Height (m)	1.69 ± 0.08
BMI (kg/m²)	25.1 ± 3.9
Time from MRI to surgery (days)	133 (96-175)

Continuous variables are presented as mean (SD) or median (IQR), and categorical variables as numbers (percentages). Statistical analyses were performed using the independent t- test, chi-square test, Fisher's exact test, or Wilcoxon rank-sum test, as appropriate. BMI, body mass index; MRI, magnetic resonance imaging; ACL, anterior cruciate ligament.

Regarding graft diameter, 75 patients (35.7%) had grafts measuring exactly 8 mm, whereas 51 patients (24.3%) had grafts measuring less than 8 mm. The overall distribution of graft diameters was as follows: 7 mm in 34 cases (16.2%), 7.5 mm in 17 cases (8.1%), 8 mm in 75 cases (35.7%), and 8.5–11 mm in 84 cases (40.0%) (Fig. 5). Among the 210 patients, 159 (75.7%) had graft diameters ≥ 8 mm and 51 (24.3%) had grafts < 8 mm. No significant differences in mean age or diagnostic category distribution were observed between the two groups ($p = 0.31$).

Patients with graft diameters ≥ 8 mm were predominantly men and had significantly greater mean weight and height than those of patients with smaller grafts ($p < 0.001$). However, no statistically significant differences were found in BMI or in the median time from MRI to surgery (135 [IQR 96–177] vs. 128 [IQR 93–173] d, $p = 0.42$).

MRI-based measurements revealed that patients with graft diameters ≥ 8 mm had significantly larger mean CSA-ST (15.2 ± 3.8 vs. 11.8 ± 2.3 mm², $p < 0.001$), CSA-GT (9.1 ± 2.5 vs. 7.3 ± 1.9 mm², $p < 0.001$), and combined CSA (24.3 ± 5.4 vs. 19.1 ±

3.6 mm², $p < 0.001$). Similarly, tendon diameters were significantly greater in the ≥ 8 mm group, including ST diameter (4.0 ± 0.6 vs. 3.5 ± 0.5 mm, $p < 0.001$), GT diameter (3.0 ± 0.5 vs. 2.7 ± 0.5 mm, $p < 0.001$), and combined diameter (7.0 ± 0.9 vs. 6.2 ± 0.7 mm, $p < 0.001$) (Table 2).

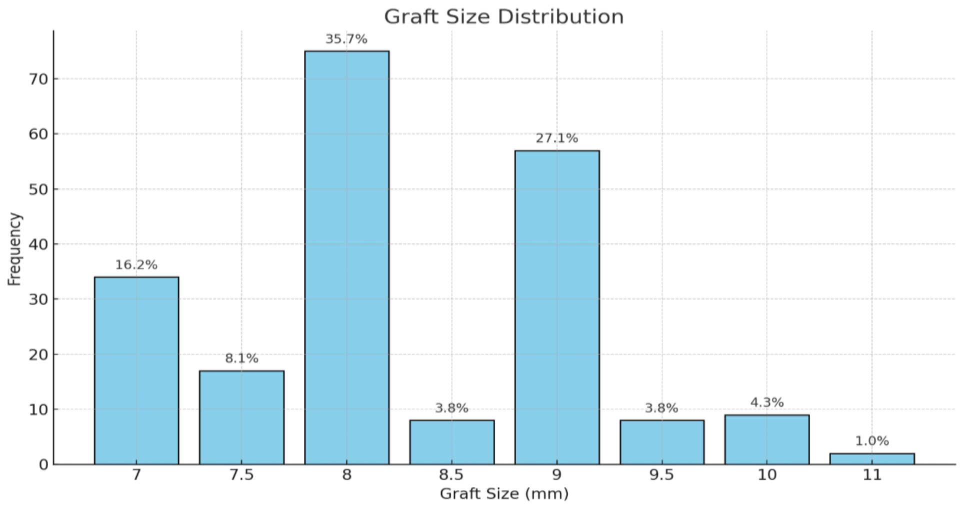


Fig. 5 Graft diameter distribution.

Table 2 Comparison of clinical and MRI variables between patients with graft diameters ≥ 8 mm and < 8 mm.

Variable	**Graft ≥ 8 mm (n = 159)**	**Graft < 8 mm (n = 51)**	**p-value**
Male sex, n (%)	138 (86.8)	31 (60.8)	<0.001
Age (years), mean ± SD	30.1 ± 9.7	31.5 ± 10.5	0.40
Diagnosis, n (%)			0.31
ACL tear alone	25 (15.7)	12 (23.5)	
With one meniscal tear	79 (49.7)	26 (51.0)	
With both meniscal tears	55 (34.6)	13 (25.5)	
Weight (kg), mean ± SD	73.9 ± 12.8	66.2 ± 10.1	0.0001
Height (cm), mean ± SD	170.7 ± 7.4	164.8 ± 7.4	<0.001
BMI (kg/m²), mean ± SD	25.4 ± 3.9	24.4 ± 3.6	0.11
Time from MRI to surgery (days), median (IQR)	135 (96-177)	128 (93-173)	0.42
MRI measurements			
CSA-ST (mm²), mean ± SD	15.2 ± 3.8	11.8 ± 2.3	<0.001
CSA-GT (mm²), mean ± SD	9.1 ± 2.5	7.3 ± 1.9	<0.001
Combined CSA (GT + ST) (mm²), mean ± SD	24.3 ± 5.4	19.1 ± 3.6	<0.001
ST diameter (mm), mean ± SD	4.0 ± 0.6	3.5 ± 0.5	<0.001
GT diameter (mm), mean ± SD	3.0 ± 0.5	2.7 ± 0.5	<0.001
Combined diameter (GT + ST) (mm), mean ± SD	7.0 ± 0.9	6.2 ± 0.7	<0.001

Continuous variables are presented as mean (SD) or median (IQR), and categorical variables as numbers (percentages). Statistical analyses were performed using the independent t- test, chi-square test, Fisher's exact test, or Wilcoxon rank-sum test, as appropriate. BMI, body mass index; MRI, magnetic resonance imaging; ACL, anterior cruciate ligament; CSA, cross-sectional area; ST, semitendinosus; GT, gracilis.

Table 3 Univariable and multivariable logistic regression analyses for predicting graft diameter ≥ 8 mm.

Factors	OR	95% CI	p value	aOR	95% CI	p value
Male sex	4.2	2.1–8.8	<0.001	1.3	0.4–3.9	0.63
Body weight (kg)	1.1	1.0–1.1	<0.001	1.0	1.0–1.1	0.22
Height (cm)	1.1	1.1–1.2	<0.001	1.0	1.0–1.1	0.29
CSA-ST (mm^2)	1.6	1.3–1.8	<0.001	1.3	1.1–1.7	0.012
CSA-GT (mm^2)	1.5	1.3–1.8	<0.001	1.1	0.8–1.4	0.80
Combined CSA (ST + GT) (mm^2)	1.3	1.2–1.5	<0.001	—	*Collinearity*	—
ST diameter (mm)	5.1	2.6–10.0	<0.001	1.5	0.8–1.4	0.43
GT diameter (mm)	4.1	2.0–8.5	<0.001	1.7	0.5–5.5	0.41
Combined diameter (ST + GT) (mm)	3.5	2.2–5.7	<0.001	—	*Collinearity*	—

Variables with $p < 0.05$ in univariable analysis were included in the multivariable model. The combined CSA and diameter were excluded because of collinearity with their components. CSA, cross-sectional area; ST, semitendinosus; GT, gracilis.

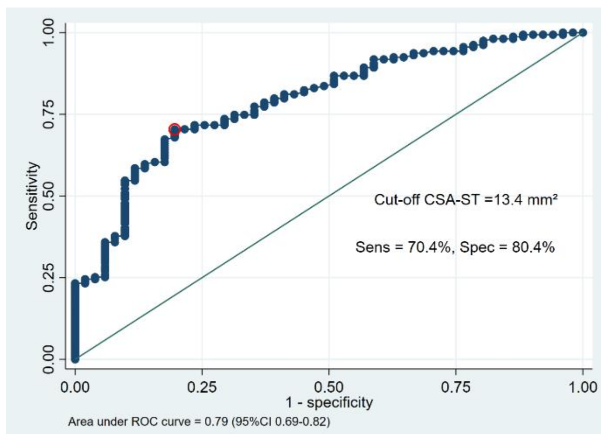
Predictors of Graft Diameter ≥ 8 mm

In univariable analysis, male sex (OR, 4.2; 95% CI, 2.1–8.8; p < 0.001), body weight (OR, 1.1; 95% CI, 1.0–1.1; p < 0.001), height (OR, 1.1; 95% CI, 1.1–1.2; p < 0.001), CSA-ST (OR, 1.6; 95% CI, 1.3–1.8; p < 0.001), CSA-GT (OR, 1.5; 95% CI, 1.3–1.8; p < 0.001), and tendon diameters (ST, GT, and combined; all p < 0.001) were significantly associated with achieving a graft diameter ≥ 8 mm.

In the multivariable model, only CSA-ST remained an independent predictor of graft diameter ≥ 8 mm (adjusted OR, 1.3; 95% CI, 1.1–1.7; p = 0.012). Other variables, including sex, body weight, height, and other MRI-based parameters, were not statistically significant after adjustment for potential confounders. Collinearity was observed among the combined CSA and diameter variables (Table 3).

A cutoff value of CSA-ST ≥ 13.4 mm^2 predicted graft diameter ≥ 8 mm with the following diagnostic performance: (Fig. 6)

- Sensitivity: 70.4% (95% CI, 62.7–77.4%)
- Specificity: 80.4% (95% CI, 66.9–90.2%)
- Positive predictive value: 91.8% (95% CI, 85.4–96.0%)
- Negative predictive value: 46.6% (95% CI, 35.9–57.5%)
- AUC: 0.79 (95% CI, 0.69–0.82)
- Positive likelihood ratio: 3.6 (95% CI, 2.1–6.3)



The red circle represents the optimal Youden cutoff point derived from receiver operating characteristic (ROC) analysis. The diagonal line = represents the reference line (area under the ROC curve = 0.5). CSA, cross-sectional area; ST, semitendinosus.

Fig. 6 ROC curve of CSA-ST predicting graft diameter ≥ 8 mm.

DISCUSSION

This study demonstrated that among patients undergoing ACLR with hamstring autografts, several anthropometric and imaging parameters were significantly associated with final graft diameter. The CSA-ST emerged as the strongest independent predictor of achieving a graft diameter ≥ 8 mm—a threshold widely regarded as clinically meaningful, as previous studies have associated larger grafts with lower failure rates and better postoperative outcomes [6–8].

The findings of the present study are consistent with prior research from both Western and Asian populations showing that MRI-derived tendon morphometric parameters can reliably predict intraoperative graft size [16–18]. These results emphasize the importance of preoperatively identifying patients at risk of obtaining smaller grafts. MRI-based evaluation of tendon CSA, particularly of the ST, offers a practical, noninvasive, and objective method to improve the accuracy of graft size prediction and support individualized surgical planning.

Predictive thresholds reported in previous studies varied across populations. Thwin et al. (Singapore) identified a combined GT and ST CSA cutoff of 17.9 mm², Grawe et al. (United States) reported 21.64 mm², and Hollnagel et al. (United States) reported 18.8 mm². By contrast, the present study found that only CSA-ST remained independently predictive, with an optimal cutoff of 13.4 mm² for anticipating a graft diameter ≥ 8 mm. This threshold achieved a high positive predictive value (91.8%) and balanced diagnostic performance (sensitivity, 70.4%; specificity, 80.4%; AUC, 0.79). Furthermore, the positive likelihood ratio of 3.6 indicates that patients with a CSA-ST ≥ 13.4 mm² are approximately 3.6 times more likely to achieve an adequate graft diameter than those with smaller CSA-ST values.

In this study, CSA-ST remained the only independent predictor in multivariable analysis, whereas CSA-GT and combined CSA (ST + GT) lost significance. This likely reflects both anatomical and methodological factors. Anatomically, the ST tendon contributes the majority of the graft volume and tensile strength in quadrupled hamstring constructs, while the GT tendon shows greater interindividual variability and contributes less to overall graft diameter. Consequently, CSA-ST alone reflects the true graft potential more accurately than the combined or CSA GT.

From a statistical perspective, collinearity among tendon CSA variables (ST, GT, and combined) likely reduced the independent contributions of the latter two variables in the multivariable model. After adjusting for this overlap, CSA-ST retained the strongest and most consistent association with graft size, underscoring its superior discriminatory capacity.

Differences from previous studies may also result from variations in population characteristics, measurement techniques, and surgical protocols. The present cohort, drawn from an Asian population with smaller average anthropometric dimensions, may inherently rely more on the ST contribution to graft composition. Additionally, this study employed a standardized MRI protocol and single-observer measurement at the physeal scar level, minimizing interobserver variation observed in earlier research. Furthermore, because all surgeries were performed using a quadrupled ST graft with optional GT augmentation, the ST tendon served as the principal component of the graft construct—unlike previous studies that included mixed or double-tendon configurations. Together, these anatomical, technical, and population-based differences likely explain why the CSA-ST alone was an independent predictor in this cohort.

Clinical Implications

The identification of a CSA-ST ≥ 13.4 mm² as a predictive marker carries significant practical implications for ACLR planning and patient management.

Preoperative Decision-Making: In patients with smaller anthropometric profiles (such as female sex, shorter stature, or lower body weight), MRI assessment using CSA-ST can assist in anticipating graft adequacy. Values below the established threshold allow surgeons to plan alternative strategies preoperatively.

Graft Strategy Modification: When CSA-ST < 13.4 mm² is identified, alternative graft sources—such as bone–patellar tendon–bone or quadriceps tendon autografts—or adjunctive approaches including allograft augmentation or contralateral tendon harvesting may be considered to ensure optimal graft size and strength.

Patient Counseling: Preoperative identification of patients at risk of graft insufficiency supports informed discussions regarding potential surgical options, fostering shared decision-making and better alignment of expectations.

These findings are particularly relevant in Asian populations, where smaller body size may increase the likelihood of obtaining undersized hamstring grafts. Integrating CSA-ST measurements into routine preoperative MRI evaluations may enhance the accuracy of graft size prediction and promote a more personalized, evidence-based approach to ACLR.

This study has several strengths. It included a well-defined cohort, with all ACLR performed by a single experienced surgeon using a standardized quadrupled hamstring technique, minimizing procedural variability. MRI measurements were obtained using a consistent protocol and analyzed by a single observer to ensure methodological consistency. The use of both univariable and multivariable analyses strengthened statistical validity and confirmed the CSA-ST as an independent predictor of graft adequacy. However, the retrospective, single-center design of the study may limit generalizability and introduce selection bias. The predominantly male cohort (80.5%) may have reduced its applicability to women or more diverse populations. Single-observer measurements improved consistency but prevented the assessment of interobserver reliability and may have introduced observer bias. Future multicenter, prospective studies using automated or AI-assisted tendon measurements are warranted to validate these findings and enhance reproducibility.

CONCLUSION

This study demonstrates that the CSA-ST measured on preoperative MRI is a reliable and independent predictor of achieving a hamstring graft diameter ≥ 8 mm in ACLR among Thai patients. A CSA-ST cutoff value of 13.4 mm^2 showed high predictive accuracy and can serve as a useful tool for identifying patients at risk of graft insufficiency during preoperative planning. These findings support the integration of MRI-based tendon measurements into routine clinical decision-making, particularly in populations with smaller body frames. Early identification of at-risk patients enables surgeons to proactively adjust surgical strategies and provide more effective patient counseling, ultimately improving surgical outcomes and promoting a more personalized approach to ACLR.

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