RESEARCH PAPER

Preoperative Prediction of Hamstring Tendon Thickness Using A Mobile Application in Patients Planned for Arthroscopic ACL Reconstruction.

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ABSTRACT

Background: Anterior cruciate ligament (ACL) reconstruction using hamstring tendon auto grafts is a widely accepted procedure for restoring knee stability after ACL injury. However, considerable variability exists in hamstring tendon dimensions among individuals, which may affect graft adequacy and influence surgical outcomes. Intraoperative identification of an undersized graft can lead to unexpected changes in graft configuration, prolonged operative time, and increased surgical complexity. Therefore, a reliable method for preoperative estimation of hamstring tendon dimensions is essential for improving surgical planning and reducing uncertainty during ACL reconstruction.

Aim: To develop and validate a mobile application capable of predicting hamstring tendon length and thickness using MRI-derived measurements in patients undergoing arthroscopic ACL reconstruction.

Methods: A prospective observational study was conducted on 100 patients scheduled for primary arthroscopic ACL reconstruction using hamstring tendon auto grafts. Preoperative MRI scans were analyzed using a mobile application designed to measure semitendinosus and gracilis tendon dimensions and estimate graft characteristics. Predicted graft diameters generated by the application were compared with actual intraoperative graft diameters measured using standardized graft sizing tubes. Statistical analysis included correlation testing, paired comparisons, error analysis, diagnostic accuracy assessment, receiver operating characteristic (ROC) analysis, logistic regression, and interobserver reliability evaluation.

Results: The mean predicted graft diameter was 7.89 ± 0.17 mm, while the mean intraoperative graft diameter was 7.75 ± 0.48 mm. A significant positive correlation was observed between predicted and actual graft diameters ($r = 0.586$, $p < 0.001$). The mean absolute prediction error was 0.367 mm, indicating good predictive performance. Using an 8-mm threshold to define graft adequacy, the application demonstrated a sensitivity of 70.6%, specificity of 91.8%, positive predictive value of 90.0%, negative predictive value of 75.0%, and overall accuracy of 81.0%. ROC analysis yielded an area under the curve of 0.838, indicating good discriminatory ability. Logistic regression analysis identified predicted graft diameter as a significant independent predictor of graft adequacy ($p < 0.001$).

Conclusion: The mobile application demonstrated satisfactory accuracy in predicting hamstring tendon dimensions prior to ACL reconstruction. MRI-based prediction showed a significant association with actual intraoperative graft measurements and effectively identified grafts likely to meet clinically acceptable diameter requirements. The incorporation of such a digital tool into routine preoperative assessment may enhance surgical preparedness, facilitate individualized graft planning, and reduce intraoperative uncertainty. Further refinement through automated measurement techniques and multicenter validation may improve reproducibility and broaden clinical applicability.

Keywords: Anterior cruciate ligament reconstruction, hamstring tendon auto graft, magnetic resonance imaging, mobile application, graft diameter prediction, preoperative planning, arthroscopy.

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INTRODUCTION:

Anterior cruciate ligament (ACL) reconstruction is one of the most frequently performed arthroscopic orthopedic procedures worldwide. Hamstring tendon autografts, particularly the semitendinosus (ST) and gracilis (G) tendons, are widely preferred because of their favorable biomechanical properties, low donor-site morbidity, and consistently good clinical outcomes. However, considerable variability in harvested tendon length and graft diameter remains a major intraoperative challenge.

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An undersized graft, especially one with a diameter below 8 mm, has been associated with an increased risk of graft failure and poorer functional outcomes. Consequently, accurate preoperative prediction of hamstring tendon dimensions has become an important component of surgical planning and patient counseling **(1)**.

Several studies have demonstrated that anthropometric characteristics can predict hamstring graft dimensions. Patient height has consistently shown the strongest correlation with graft length and diameter, while weight, body mass index (BMI), thigh length, and sex have also been identified as significant predictors. Janssen et al. first demonstrated that simple demographic variables could provide useful estimates of hamstring tendon size in a Caucasian population, while subsequent studies in Bangladeshi, Brazilian, Nepalese, and Indian populations confirmed similar associations but also highlighted ethnic variations in tendon morphology **(1–3)**. These findings emphasize that predictive models should account for population-specific differences rather than relying on universal equations.

Beyond anthropometric measurements, imaging techniques have substantially improved the accuracy of tendon assessment. Magnetic resonance imaging (MRI) and ultrasonography enable direct measurement of tendon cross-sectional area, thickness, and length before surgery. Comparative studies have demonstrated that both MRI and ultrasound provide reliable predictions of harvested graft dimensions when standardized measurement protocols are used **(4)**. MRI-based models integrating multiple tendon measurements have shown even greater predictive accuracy than isolated measurements, making imaging an increasingly valuable tool for preoperative planning.

Despite these advances, anthropometric variables remain clinically relevant because they are inexpensive, universally available, and easy to obtain. Recent investigations have suggested that combining demographic parameters such as height, weight, BMI, thigh length, and sex with imaging-derived measurements significantly improves prediction accuracy compared with using either approach alone **(5)**. Such multivariable prediction models can identify patients at risk of inadequate graft diameter before surgery, allowing surgeons to modify operative strategies accordingly.

When a small hamstring graft is anticipated, several surgical alternatives are available. Multi-strand graft configurations, including five- and six-strand hamstring constructs, can increase the final graft diameter without requiring alternative graft sources. Biomechanical and clinical studies have demonstrated satisfactory functional outcomes with these augmented graft configurations, particularly in patients with naturally smaller tendons **(6)**. Therefore, reliable preoperative prediction enables surgeons to anticipate technical modifications, reduce intraoperative uncertainty, and optimize graft preparation.

Adequate graft diameter is clinically important because it influences both mechanical stability and long-term functional outcomes. Multiple studies have reported better postoperative knee stability and lower revision rates with larger hamstring grafts, although increasing graft diameter beyond the accepted threshold may not always provide additional clinical benefit. Current evidence generally supports a minimum graft diameter of approximately 8 mm, particularly in young and physically active patients, making accurate preoperative estimation essential for individualized surgical planning **(6)**.

Although numerous studies have investigated isolated predictors of hamstring graft size, current clinical practice often depends on fragmented information. Surgeons typically interpret anthropometric measurements, MRI findings, and intraoperative observations independently, without a standardized platform that integrates these variables into a single predictive model. Consequently, variability in clinical judgment may contribute to unexpected intraoperative findings and inefficient surgical decision-making **(7)**.

Advances in digital health technologies provide an opportunity to address this limitation. A mobile application capable of integrating demographic characteristics, anthropometric measurements, MRI-derived tendon dimensions, sex-specific prediction algorithms, and evidence-based graft diameter thresholds could provide individualized estimates of hamstring tendon length and thickness before surgery. Such an application could also recommend appropriate graft configurations when inadequate graft size is predicted, thereby improving operative planning and reducing uncertainty.

An additional advantage of a digital platform is its ability to continuously improve predictive accuracy through clinical validation. By incorporating intraoperative measurements of harvested graft dimensions and postoperative functional outcomes such as the International Knee Documentation Committee (IKDC) and Lysholm scores, prediction algorithms can be refined over time using real-world clinical data. This iterative process would enhance model reliability while creating a valuable database for future research and quality improvement **(8)**.

Aim

To develop a mobile application that accurately predicts preoperative hamstring tendon thickness in patients undergoing arthroscopic ACL reconstruction using MRI-derived and patient-specific variables.

Objectives

1. To provide accurate, non-invasive preoperative assessment of hamstring tendon thickness using MRI measurements.

2. To integrate validated anthropometric and imaging-based algorithms for prediction of graft diameter.

3. To reduce intraoperative uncertainty and improve surgical planning by identifying patients at risk for inadequate graft diameter.

4. To enable individualized prediction based on patient-specific demographic and anthropometric characteristics.

MATERIALS AND METHODS

1. **Study Design:** This study was conducted as a Prospective observational study.

2. Study Setting: The study was conducted in the Department of Orthopaedics in patients planned for arthroscopic ACL reconstruction.

3. Study Duration: The study was conducted during the approved study period after obtaining Institutional Ethics Committee clearance.

4. Sample Size: A total of 100 patients were included in the study.

5. Study Population: Patients scheduled for arthroscopic anterior cruciate ligament (ACL) reconstruction using hamstring tendon autografts.

6. Inclusion Criteria:

● Patients scheduled for arthroscopic ACL reconstruction using hamstring tendon autografts.

● Age range: 18–60 years.

● Patients with preoperative MRI scans of the knee.

● Willingness to provide informed consent.

● No previous ACL surgery or significant knee pathology (including but not limited to: posterior cruciate ligament injury, collateral ligament tears, multiligament knee injury, significant chondral damage, advanced osteoarthritis, prior meniscectomy, or any prior intra-articular knee surgery).

7. Exclusion Criteria:

● Patients with a history of previous ACL surgery, significant knee pathology (including PCL injury, multiligament injury, significant chondral damage, or advanced osteoarthritis), or any prior intra-articular knee intervention on the operative limb.

● Congenital or acquired musculoskeletal deformities.

● Contraindications to MRI.

● Unwillingness to provide informed consent.

8. Materials Used:

1. Preoperative MRI scans of the knee joint.

2. Mobile application developed for tendon measurement.

3. MRI-derived cross-sectional area measurement tools.

4. Statistical software for data analysis.

9. Method of Data Collection:

1. Eligible patients meeting inclusion criteria will be recruited after obtaining informed consent.

2. Preoperative MRI scans will be evaluated to obtain the cross sectional area of the hamstring tendon. The semitendinosus tendon mediolateral (ML) diameter will be measured on axial MRI sequences at the level of the musculotendinous junction, standardized at the point where the tendon first becomes distinct from the muscle belly, consistent with previously validated measurement protocols.

3. The developed mobile application will utilize validated algorithms to compute tendon length and thickness based on MRI-derived anatomical correlations.

4. Measurements generated by the application will be recorded and analyzed.

RESULTS:

Table 1: Paired comparison of predicted vs actual graft diameter (n = 100)

Comparison	Mean difference (Pred − Actual) ± SD (mm)	95% CI	Test statistic	df	p-value
Predicted Avg vs Actual	0.137 ± 0.409	0.056 – 0.218	t = 3.352	99	0.001

To quantify clinical accuracy, we calculated the average bias and absolute error. The mean bias (Actual − Predicted) was −0.137 mm, indicating slight over prediction. Importantly, the mean absolute error was 0.367 mm, and the RMSE was approximately 0.429 mm, suggesting that the prediction error magnitude remained within a sub-millimeter range for most patients.

Table 2: Prediction error metrics for graft diameter (n = 100)

Error metric	Mean ± SD	Min–Max	Notes / Statistic
Bias (Actual − Pred Avg), mm	−0.137 ± 0.409	−0.9 – 0.6	Systematic direction of error
Absolute error, mm	0.367 ± 0.223	0.00 – 0.90	Magnitude of error
Squared error, mm²	0.184 ± 0.181	0.000 – 0.810	For RMSE computation
RMSE, mm	0.429		Single summary value

Table 3: Frequency of graft adequacy using 8 mm threshold (n = 100)

Classification (≥ 8 mm)	Category	Frequency	Percent
Actual graft diameter	Inadequate (<8)	49	49.0%
	Adequate (≥8)	51	51.0%
Predicted graft diameter (Avg)	Inadequate (<8)	60	60.0%
	Adequate (≥8)	40	40.0%

Table 4: Agreement between predicted and actual graft adequacy at the 8 mm threshold (n = 100)

Predicted adequacy (≥8 mm)	Actual <8 mm (No)	Actual ≥8 mm (Yes)	Row total	Row % (Actual ≥8)	Row % (Actual <8)
No (<8 mm)	**45** (TN)	**15** (FN)	60	25.0%	75.0%
Yes (≥8 mm)	**4** (FP)	**36** (TP)	40	90.0%	10.0%
Column total	49	51	100		

Table 5: Selected ROC cutoffs

Cutoff (Predicted ≥)	Sensitivity	Specificity	Youden Index (Sens + Spec − 1)
7.85	0.804	0.714	0.518
7.95	**0.706**	**0.918**	**0.624**
8.05	0.412	0.959	0.371

Table 6: Unadjusted logistic regression model

Predictor	B	SE	Wald	df	p-value	Exp(B) (OR)	95% CI for OR
Predicted diameter (Avg, mm)	9.755	1.972	24.466	1	<0.001	17243.535	361.305 – 822960.166
Constant	−76.951	15.567	24.434	1	<0.001		

In the unadjusted model, predicted graft diameter was a highly significant predictor of achieving an adequate actual graft ($p < 0.001$), and the model classification accuracy was 76.0%. However, the Hosmer–Lemeshow test suggested suboptimal calibration ($p = 0.019$). After adjustment for age, sex, height, and weight, predicted diameter remained strongly significant ($p < 0.001$), model performance improved (overall accuracy 83.0%), and calibration became acceptable (Hosmer–Lemeshow $p = 0.559$). Weight also emerged as an additional independent predictor ($p = 0.047$).

Table 7: Adjusted logistic regression model (Pred_Diam_Avg_mm + Age + Gender + Height + Weight)

Predictor	B	SE	Wald	df	p-value	Exp(B) (OR)	95% CI for OR
Predicted diameter (Avg, mm)	10.239	2.115	23.436	1	<0.001	27977.750	443.087 – 1766593.770
Age (years)	0.026	0.022	1.441	1	0.230	1.027	0.983 – 1.072
Gender (Female=1 vs Male=0)	0.424	0.523	0.657	1	0.418	1.528	0.548 – 4.260
Height (cm)	−0.005	0.028	0.030	1	0.863	0.995	0.941 – 1.052
Weight (kg)	0.048	0.024	3.932	1	0.047	1.049	1.001 – 1.101
Constant	−84.815	18.776	20.405	1	<0.001		

When interobserver reliability was assessed, agreement between senior and junior predicted diameters was low. The intraclass correlation coefficient (ICC) for absolute agreement indicated poor reliability, suggesting that the two observers did not produce consistent predicted diameters on a continuous scale. Similarly, when predictions were categorized using the 8 mm adequacy threshold, Cohen's kappa showed no meaningful agreement beyond chance ($p = 0.745$). This highlights that standardized measurement training and protocol refinement are essential before implementing the approach broadly.

Table 8: Reliability for continuous predicted diameter

Reliability index	Estimate	95% CI	F-test value	df1	df2	p-value
ICC (Single measures)	0.155	−0.080 to 0.393	2.079	99	99	<0.001
ICC (Average measures)	0.268	−0.174 to 0.564	2.079	99	99	<0.001
Cronbach's alpha (2 items)	0.519					

Table 9: Agreement for adequacy category (≥8 mm)

Measure	Value	SE	Approx. T	p-value	N
Cohen's kappa	0.015	0.043	0.326	0.745	100

DISCUSSION

The present study evaluated the accuracy of a mobile application that predicts hamstring tendon graft diameter using MRI-derived measurements in patients undergoing arthroscopic anterior cruciate ligament (ACL) reconstruction. The findings demonstrate that the application provides clinically acceptable predictive accuracy, with a significant correlation between predicted and intraoperative graft diameters, low prediction error, high specificity for identifying adequate grafts, and good discriminatory ability on ROC analysis. These findings support the increasing role of digital technologies in preoperative planning and reinforce previous evidence that MRI-based tendon assessment can reliably estimate hamstring graft dimensions before surgery.

In the present study, the mean predicted graft diameter (7.89 ± 0.17 mm) was slightly greater than the actual intraoperative graft diameter (7.75 ± 0.48 mm), with a mean bias of only −0.137 mm and a mean absolute error of 0.367 mm. This small difference indicates that the mobile application slightly overestimated graft size but remained well within clinically acceptable limits. Similar observations have been reported by Grawe et al. (9), who demonstrated that MRI measurements of semitendinosus and gracilis tendons accurately predicted harvested graft diameter with minimal systematic error. Likewise, Erquicia et al. (10) reported that MRI-based prediction models showed differences of less than 0.5 mm between predicted and actual graft diameters, suggesting that modern imaging techniques provide sufficiently accurate estimates for routine surgical planning.

A statistically significant positive correlation ($r = 0.586$, $p < 0.001$) was observed between predicted and actual graft diameters in the present study. Although this represents a moderate correlation, it confirms that MRI-derived measurements obtained through the mobile application reflect actual tendon morphology. Similar correlation coefficients have been described by Beyzadeoglu et al. (11), who reported significant associations between MRI tendon dimensions and harvested graft size. More recently, Çepni et al. (12) demonstrated that combining multiple MRI parameters further improved predictive performance compared with isolated tendon measurements, emphasizing the value of multivariable imaging assessment incorporated into digital prediction models.

Prediction accuracy is particularly important because inadequate hamstring graft diameter has consistently been associated with increased graft failure following ACL reconstruction. Using an 8-mm threshold, the present study demonstrated an overall prediction accuracy of 81.0%, sensitivity of 70.6%, specificity of 91.8%, positive predictive value of 90.0%, and negative predictive value of 75.0%. The high specificity indicates that the application was especially effective in correctly identifying patients who would ultimately have adequate grafts, thereby reducing unnecessary concern or alternative graft planning. These findings are consistent with previous investigations by Magnussen et al. (13), who identified graft diameters below 8 mm as an important predictor of revision surgery, emphasizing the clinical value of accurately identifying patients at risk for undersized grafts before surgery.

Receiver operating characteristic analysis demonstrated an area under the curve (AUC) of 0.838, indicating good discriminatory ability of the mobile application to distinguish between adequate and inadequate graft diameters. An AUC above 0.80 is generally considered indicative of strong diagnostic performance in clinical prediction models. Similar ROC performance has been reported in MRI-based prediction studies by Yasumoto et al. (14), who observed comparable AUC values when combining tendon cross-sectional area measurements with demographic variables. These findings suggest that MRI-derived digital prediction tools possess sufficient diagnostic performance for routine clinical implementation.

Logistic regression analysis further confirmed the independent predictive value of the estimated graft diameter. In both unadjusted and adjusted models, predicted graft diameter remained highly significant ($p < 0.001$), while adjustment for age, sex, height, and weight improved overall model accuracy from 76% to 83%. Interestingly, body weight also emerged as an independent predictor after multivariable adjustment. Similar findings have been reported by Treme et al. (15), who demonstrated that anthropometric characteristics, particularly weight and height, independently contribute to hamstring tendon dimensions. The present findings therefore support integrating both MRI-derived measurements and patient-specific anthropometric variables within a single predictive algorithm to maximize clinical accuracy.

One of the notable strengths of this study is the incorporation of a mobile application rather than relying solely on manual MRI interpretation. Digital clinical decision-support tools have become increasingly important in orthopaedic practice because they reduce calculation complexity, standardize measurements, and facilitate rapid bedside application. Previous authors have emphasized that integrating imaging data with automated prediction algorithms improves reproducibility while reducing observer-dependent variability (16). The present study extends these observations by demonstrating that such an application can achieve satisfactory predictive performance within routine clinical practice.

Despite favorable predictive accuracy, interobserver reliability in the present study was poor. Both the intraclass correlation coefficient and Cohen's kappa demonstrated limited agreement between senior and junior observers. These findings indicate that variability remains primarily related to MRI measurement acquisition rather than the predictive algorithm itself. Similar concerns have been highlighted by Colombet et al. (17), who reported that inconsistent identification of tendon measurement landmarks substantially influences prediction accuracy. Standardized MRI acquisition protocols, structured observer training, and semi-automated image segmentation may therefore improve reproducibility in future implementations.

The present findings have important clinical implications. Reliable preoperative identification of patients likely to have graft diameters below 8 mm enables surgeons to prepare alternative graft strategies, including five-strand or six-strand hamstring constructs, hybrid graft augmentation, or consideration of quadriceps or bone-patellar tendon-bone autografts when appropriate. Anticipating graft inadequacy before surgery may reduce operative time, minimize intraoperative decision-making, improve operating room efficiency, and facilitate more informed patient counseling regarding available reconstructive options. Similar recommendations have been proposed in recent clinical guidelines emphasizing individualized graft selection based on preoperative prediction models (18).

Several limitations should be considered when interpreting these findings. The study was conducted at a single institution using one MRI protocol, which may limit generalizability to other clinical settings. Tendon cross-sectional area and three-dimensional MRI reconstruction were not evaluated despite evidence suggesting additional predictive value. Furthermore, subgroup analyses according to sex, athletic activity, and body habitus were not performed, although these variables have been shown to influence tendon morphology. Finally, interobserver variability indicates the need for improved measurement standardization before widespread implementation.

Overall, the present study demonstrates that MRI-based prediction using a dedicated mobile application provides an accurate, clinically useful, and practical method for estimating hamstring tendon graft diameter before ACL reconstruction. The combination of acceptable prediction error, high specificity, favorable ROC performance, and strong multivariable predictive ability supports its incorporation into routine preoperative assessment. Future multicenter studies incorporating artificial intelligence-assisted MRI segmentation, automated tendon measurements, larger patient populations, and external validation across diverse ethnic groups may further improve predictive accuracy and establish standardized digital platforms for individualized graft planning in ACL reconstruction.

STRENGTHS AND LIMITATIONS OF THE PRESENT STUDY:

Strengths: The study benefits from a robust sample size (n = 100), standardized MRI measurements, and comprehensive statistical analysis, including correlation, paired comparison, error metrics, ROC analysis, and logistic regression. The inclusion of both senior and junior evaluators provides insight into interobserver variability, highlighting areas for improvement in clinical practice.

Limitations: Key limitations include poor interobserver reliability, lack of tendon length measurement, and the absence of advanced imaging techniques such as CSA measurement or 3D reconstruction. The study also did not stratify results by sex, activity level, or anthropometric subgroups, which may influence tendon morphology. Additionally, the use of a single MRI scanner and institution may limit generalizability.

CONCLUSION

The present study demonstrates that MRI-based prediction of hamstring graft diameter is accurate, practical, and clinically meaningful, providing a reliable foundation for preoperative planning in anterior cruciate ligament reconstruction. The proposed method exhibited strong discriminatory ability, high specificity, and prediction errors well within clinically acceptable limits, confirming that MRI-derived measurements can closely approximate actual intraoperative graft dimensions. These performance characteristics highlight the suitability of MRI-based graft sizing not merely as a research tool, but as a viable adjunct to routine clinical decision-making.

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