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Editorial

Return to Sport After ACL Reconstruction: Is It Time to Add Lateral Extra-Articular Tenodesis?

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Anterior cruciate ligament (ACL) reconstruction is a standard surgical procedure in sports traumatology. However, a key question remains unanswered: who truly returns to sport, at what level, and at what cost? In young pivoting athletes, graft re-rupture and failure to return to pre-injury performance levels remain a significant challenge. Over the past decade, the focus has shifted from isolated ACL reconstruction toward combined procedures that also address injuries of the anterolateral complex and incorporate lateral extra-articular tenodesis (LET).[1] Concurrently, the notion of return to sport (RTS) has evolved from a rudimentary milestone to a multifaceted process.[2]

RTS decisions are no longer made based solely on time, such as six months, nine months, or one season. Contemporary clinical protocols encompass a range of assessments, including quadriceps and hamstring strength testing, hop tests, patient-reported outcome measures, clinical examinations, and radiological evaluations.[2, 3] Despite this evolution, real-world practice remains highly variable, and a reexamination of pivot-shift, graft laxity, and rotational control underscores the fact that intra-articular reconstruction alone does not invariably restore the native mechanics of the knee. This discrepancy is most apparent in younger, high-demand pivoting athletes, where the incidence of second ACL injuries within the first two years after RTS can approach unacceptably high rates.[4] In this conceptual framework, the central question shifts from the feasibility of ACL reconstruction to the development of strategies that ensure the safety and sustainability of the reconstruction process, facilitating a secure and feasible return to high-risk sports.

The STABILITY randomized trial provided the first high-quality clinical evidence that adding an LET to a hamstring autograft ACL reconstruction in young, high-risk patients can meaningfully change failure patterns. In 15–25-year-old pivoting athletes with high-grade pivot shift or generalized laxity, combining ACL reconstruction with a modified Lemaire LET reduced graft failure and persistent rotatory laxity from about 40% to roughly 25% at two years, and isolated graft ruptures from around 11% to 4%. Importantly, these mechanical gains did not come at the cost of inferior patient-reported outcomes. Functional scores were broadly similar across groups, although the LET group had slightly more lateral tenderness and hardware-related irritation, which were typically managed with minor secondary procedures.[5] For the high-risk athlete, this is an attractive trade-off: fewer ACL failures and better pivot-shift control, in exchange for a modest rise in lateral-side symptoms.

Outside of STABILITY, several cohort studies in elite and recreational athletes have reported lower revision rates and improved rotational stability when LET is added to ACL reconstruction. Together, these data suggest that for selected high-risk patients, LET is not an experimental embellishment but a rational biomechanical adjunct.[6, 7] More recently, systematic reviews and meta-analyses have allowed us to look beyond pure failure rates and examine what really matters to athletes: returning to their previous level of sport. A large meta-analysis of lateral extra-articular procedures (LEAP) combined with ACL reconstruction, including over 30,000 patients, found that those receiving a LEAP achieved higher postoperative activity levels and were more likely to return to their pre-injury level of sport than those undergoing isolated ACL reconstruction. In a subset of nine studies, 62% of patients in the ACLR+LEAP group returned to their pre-injury level, compared with only 40% in the isolated ACLR group.[6] Another systematic review focusing on LET and anterolateral ligament procedures reported that most patients treated with LEAP returned to their pre-injury level of function after approximately 6 months. Interestingly, LET-augmented ACL reconstructions tended to have slightly better clinical outcomes than ALL-based reconstructions but also a higher reoperation rate, often related to lateral hardware or local irritation.[1] These findings reinforce a key message: adding a lateral extra-articular procedure can improve not only mechanical stability and graft survival, but also the likelihood of regaining pre-injury sporting performance. However, the price may be a modest increase in lateral-side complaints and occasional secondary procedures.

One practical concern is whether LET might delay rehabilitation or make RTS testing "worse" at 6–9 months. Emerging evidence suggests this is not the case. Case–control data indicate that when modern rehabilitation is used, the addition of LEAP to quadriceps or bone–patellar tendon-bone ACL reconstruction is non-inferior to isolated ACLR with respect to RTS test batteries and psychological readiness at 6 and 9 months post-operatively.[8] In other words, LET does not seem to lock the knee, slow down early functional recovery, or prevent athletes from meeting standard strength and hop-test criteria. From a rehabilitation standpoint, this allows clinicians to embed LET within existing, criteria-based RTS frameworks, rather than designing entirely separate protocols.

The temptation, when confronted with strong data in high-risk cohorts, is to extend the indication to everyone. At present, the evidence does not support a universal "LET for all" strategy. The most robust benefits are seen in young athletes (often <25 years) participating in pivoting or contact sports, with high-grade pivot shift or generalized laxity, and frequently with additional risk factors such as meniscal deficiency or revision surgery. In these patients, the combination of lower graft failure, better rotational control, and a higher likelihood of returning to the pre-injury level is compelling. For older, lower-demand patients, or for those in straight-line sports, the incremental benefit of LET is far less clear, and any additional risk or cost is harder to justify.[9]

We must also acknowledge the unknowns. Long-term data beyond 10–15 years remains limited. Concerns about over-constraint, increased lateral compartment loading, and potential acceleration of osteoarthritis are biologically plausible, but not yet fully quantified.[10] Moreover, the heterogeneity of LET techniques (modified Lemaire, MacIntosh variants, fixation methods, graft choices) complicates generalizing outcomes.

Should we accept the hypothesis that LET can reduce graft failure and improve the chances of high-level RTS in selected patients? If so, how should this influence our day-to-day decisions? Firstly, it is imperative to conceptualize LET as biomechanical protection rather than a license for earlier or more aggressive RTS. The fundamental principles of safe RTS remain consistent, emphasizing the temporal aspect of the recovery period following surgery, particularly the avoidance of premature RTS before 9–12 months in young pivoting athletes. The objective strength criteria encompass two fundamental components: limb symmetry and minimum torque/body-weight thresholds. The implementation of functional hop tests and movement-quality assessment further substantiates these criteria. The absence of effusion, pain, or instability, psychological readiness, and realistic risk perception are all factors that must be considered. In cases of elevated baseline risk, the application of LET has been shown to increase the likelihood of achieving sustained, long-term engagement without recurrence of ligament failure.[5, 6]

Second, we should move toward structured risk stratification. Age, sport type, pivot-shift grade, laxity, ligamentous hypermobility, meniscal status, and previous surgery can all be integrated into clinical risk scores to guide the indication for LET.[9] High-risk athletes might routinely be counselled about LET as part of shared decision-making, while low-risk individuals could reasonably undergo isolated ACL reconstruction with standard follow-up.

Adding a lateral extra-articular tenodesis will not, by itself, solve the complex problem of returning athletes safely to sport. But for the young, high-risk pivoting athlete, it may finally align what we see in the operating room and on the pivot-shift test with what the athlete feels on the field. Our challenge now is to define who truly needs this additional protection, how to integrate it into robust, criteria-based RTS algorithms, and whether the short-term gains we observe today will stand the test of time in the decades to come.

DECLARATIONS

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Original Article

Height and Leg Length Can Predict Quadruple Hamstring Tendon Thickness for ACL Reconstruction

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ABSTRACT

Objective: Accurate preoperative estimation of hamstring tendon graft thickness is crucial for improving the success rates of anterior cruciate ligament (ACL) reconstruction surgeries. Although several imaging methods have been proposed, simple anthropometric measurements may provide a practical and cost-effective alternative. This study aimed to investigate the predictive value of leg length, total body height, and the leg length-to-body height ratio for estimating hamstring graft thickness preoperatively.

Materials and Methods: This retrospective cohort study included 120 patients who underwent ACL reconstruction with quadruple hamstring tendon autografts. Anthropometric measurements, including leg length (measured from the anterior superior iliac spine to the medial malleolus) and total body height, were collected prospectively during follow-up. The correlation between these parameters and intraoperative graft thickness was analyzed using Pearson correlation. Simple and multivariate linear regression analyses were performed to determine predictive factors. Receiver operating characteristic (ROC) curve analysis was conducted to evaluate the diagnostic performance of each parameter for predicting graft thickness ≥8 mm.

Results: Total body height demonstrated the strongest correlation with graft thickness ($r=0.52$, $p<0.001$), followed by leg length ($r=0.48$, $p<0.001$). Although the leg length-to-body height ratio showed a weak correlation ($r=0.40$, $p=0.003$), it was not a statistically significant predictor in the multivariate analysis. ROC analysis showed that total body height had the highest diagnostic accuracy (AUC=0.82, 95% CI: 0.70–0.94) for predicting graft thickness ≥8 mm, with 82.4% sensitivity and 75.0% specificity at a cut-off value of ≥174.0 cm.

Conclusion: Total body height and leg length are reliable preoperative predictors of hamstring tendon graft thickness in ACL reconstruction. Simple anthropometric measurements may help optimize graft selection, reduce the risk of graft failure, and improve surgical outcomes.

Keywords: Anthropometry, anterior cruciate ligament, graft diameter, hamstring autograft, height, leg length, predictive model, ROC analysis.

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INTRODUCTION

The anterior cruciate ligament (ACL) is a principal stabilizer of the knee, limiting anterior tibial translation and controlling rotatory laxity relative to the femur. It is intra-articular yet extrasynovial, invested by synovial membrane, and is vascularized predominantly by the middle genicular artery with contributions from inferior genicular branches. Structurally, the ACL comprises two functional bundles (anteromedial and posterolateral bundles) that are tensioned differentially across the knee flexion–extension arc. In addition to its mechanical role, the ligament contains mechanoreceptors that subserve proprioception and contribute to neuromuscular control of the joint [1,2].

ACL injuries are prevalent in athletic participation and after trauma, constituting a frequent orthopedic problem. Although primary repair may be considered for acute, select tear patterns in carefully chosen patients, contemporary management in routine practice predominantly favors reconstruction [3,4]. Multiple graft sources are available for ACLR, including allografts and autografts. Among autografts, the quadrupled hamstring tendon, typically consisting of the semitendinosus and gracilis tendons, is one of the most frequently utilized constructs [5–8]. Additional graft options include bone-patellar tendon-bone, quadriceps tendon, tibialis anterior, tibialis posterior, peroneal tendons, and Achilles tendons. Surgical techniques may involve single-bundle or double-bundle reconstructions [9–14].

Graft diameter is a key determinant of long-term outcomes after ACLR. In hamstring autografts, diameters <8 mm are associated with greater postoperative instability and higher graft failure rates [15,16]. Consequently, accurate preoperative estimation of graft thickness is clinically important for planning tunnel size, potential augmentation, and selecting the appropriate graft. Reported preoperative approaches include MRI-based assessments (13) and ultrasonography [17–19]. In addition, several anthropometric variables, including age, weight, height, body mass index (BMI), and thigh circumference, have been investigated for their predictive value for graft thickness [20–22].

The growing volume of ACLR has heightened the clinical importance of selecting an appropriate graft and ensuring adequate graft diameter. Insufficient graft diameter is a recognized mechanism of failure, predisposing to residual laxity, patient dissatisfaction, revision surgery, and secondary chondral injury with downstream implications for earlier arthroplasty. Consequently, developing reliable methods to estimate graft diameter (thickness) preoperatively remains a priority to optimize graft selection, surgical plan, and improve outcomes.

This study aims to evaluate the clinical applicability and predictive value of previously under-investigated anthropometric parameters, specifically leg length, height, and the ratio of leg length to height, in estimating hamstring tendon autograft thickness preoperatively. We hypothesize that these anthropometric measures will demonstrate acceptable discriminative performance in identifying patients at risk of a graft diameter below 8 mm, supporting their use as simple and cost-effective preoperative screening tools. Ultimately, the study seeks to facilitate improved graft selection, minimize revision surgery rates, and enhance long-term surgical success.

MATERIALS AND METHODS

Patients and Study Design

This retrospective cohort study was approved by the Orthopedics, Hatay Mustafa Kemal University Local Ethics Committee (Approval No: 04/58; date: 19 March 2025) and conducted in accordance with the Declaration of Helsinki. Patients who underwent ACLR with a quadrupled autologous hamstring tendon graft (semitendinosus and gracilis) at the Department of Orthopedics, Hatay Mustafa Kemal University Hospital, between 1 June 2017 and 1 June 2019 were retrospectively identified from institutional medical records and surgical notes.

Eligible patients were those who underwent anterior cruciate ligament reconstruction using a quadrupled hamstring tendon autograft and for whom complete intraoperative documentation and follow-up anthropometric measurements were available; all participants provided informed consent. Patients were excluded if surgical records were incomplete or follow-up data were missing, if reconstruction was performed with any graft other than a quadrupled hamstring tendon autograft, or if prior knee surgery or concurrent knee pathology was present that could plausibly influence anthropometric measurements.

Data Collection

Data on intraoperative hamstring tendon graft thickness were abstracted from operative records for each eligible patient, reflecting the final diameter of the quadrupled construct as documented by the operating surgeon. The graft thickness was determined intraoperatively using a standard ACL graft sizing set with measurement holes in 0.5-mm increments (e.g., 8.0, 8.5, 9.0, 9.5 mm), and the final graft diameter was recorded as the largest size through which the quadrupled tendon could pass smoothly without resistance.

Thereafter, patients were prospectively invited to a standardized follow-up visit for anthropometric assessment. At this visit, leg length was measured on the operated limb using a predefined protocol from the anterior superior iliac spine to the medial malleolus with the patient supine and the lower extremities in neutral rotation. Total height was measured using a stadiometer, with patients standing barefoot and upright. For each patient, the ratio of leg length to height was then calculated. All variables, including graft diameter, leg length, height, and the leg length-to-height ratio, were entered into a data sheet, subjected to basic range and consistency checks, and reconciled against the source records when discrepancies were identified.

Statistical Analysis

All statistical analyses were performed using SPSS software (Statistical Package for the Social Sciences) version 27.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were presented as median (min -max) for normally distributed continuous variables and as median (minimum–maximum) for non-normally distributed variables. Categorical variables were summarized as frequencies (n) and percentages (%). The normality of continuous variables was assessed using the Shapiro-Wilk test. Correlation between anthropometric parameters (leg length, total body height, and leg length/body height ratio) and hamstring tendon graft thickness was evaluated using Pearson correlation coefficients. Simple linear regression analysis was conducted to determine the individual predictive strength of each anthropometric parameter for graft thickness. Multivariate linear regression analysis was then performed to assess the combined effect of all anthropometric parameters on graft thickness. Receiver operating characteristic (ROC) curve analysis was used to evaluate the diagnostic performance of each anthropometric parameter in predicting a hamstring graft thickness of 8 mm or greater. The area under the curve (AUC), optimal cut-off values, sensitivity, and specificity were calculated. The optimal cut-off point was determined based on the Youden index. A p-value of less than 0.05 was considered statistically significant in all analyses.

A post-hoc sensitivity analysis for the Pearson correlation was performed using Fisher's z-transformation (two-sided α=0.05). For the observed correlation between total body height and graft thickness (r=0.52), the achieved power exceeded 99.9%. With N=120, the study had ≥80% power to detect correlations. These calculations support the adequacy of the sample to detect clinically relevant effect sizes.

RESULTS

A total of 120 patients who met the inclusion criteria were included in the final analysis. The mean age of patients was 28.4±6.3 years, ranging from 18 to 42 years. Among these, 90 patients (75%) were male and 30 patients (25%) were female.

The mean intraoperative quadruple hamstring tendon graft thickness was 8.2±0.8 mm, with a range of 6.5 mm to 9.5 mm. The mean leg length measurement was 90.3±4.8 cm, while the average height was 175.5±7.6 cm. The mean leg length-to-height ratio was calculated as 0.51±0.02 (Table 1).

Correlation of anthropometric measurements with hamstring tendon graft thickness was shown in Table 2. Statistical analysis demonstrated a significant positive correlation between hamstring tendon graft thickness and leg length (r=0.48, p<0.001), height (r=0.52, p<0.001), and leg length-to-height ratio (r=0.40, p<0.05).

Linear regression analysis for predicting hamstring graft thickness is shown in Table 3. Height emerged as the strongest individual predictor of graft thickness (β=0.52, 95% CI: 0.35–0.69, R^2=0.27, p< 0.001), followed by leg length (β=0.48, 95% CI: 0.30–0.66, R^2=0.23, p< 0.001) and leg length/height ratio (β=0.40, 95% CI: 0.15–0.65, R^2 0.16, p=0.003).

Multivariate regression analysis for predicting hamstring graft thickness is shown in Table 4. According to the multivariate regression analysis, height remained the strongest independent predictor of hamstring graft thickness when all three anthropometric variables were included in the model (β=0.37, 95% CI: 0.20–0.54, p<0.001). Leg length also showed

Table 1. Demographic and anthropometric characteristics of the study population

Characteristics	Patients (n=120), n (%) or median (min-max)
Age (years)	28.5 (18-42)
Gender	
Male	90 (75%)
Female	30 (25%)
Height (cm)	175.5 (162-190)
Leg length (cm)	90.3 (82-98)
Leg length/height ratio	0.51 (0.47-0.55)
Hamstring tendon Thickness (mm)	8.2 (6.5-9.5)

Table 2. Correlation of anthropometric measurements with hamstring tendon graft thickness

Variables	Correlation coefficient (r)	p
Leg length (cm)	0.48	<0.001
Height (cm)	0.52	<0.001
Leg length/height ratio	0.40	<0.05

Table 3. Linear regression analysis for predicting hamstring graft thickness

Anthropometric parameter	β	95% CI	R^2	p
Leg length (cm)	0.48	0.30 - 0.66	0.23	<0.001
Height (cm)	0.52	0.35 - 0.69	0.27	<0.001
Leg length/body height ratio	0.40	0.15 - 0.65	0.16	0.003

CI: Confidence interval.

Table 4. Multivariate regression analysis for predicting hamstring graft thickness

Anthropometric parameter	β	95% CI	Standard error	p
Leg length (cm)	0.19	0.05 - 0.33	0.07	0.008
Height (cm)	0.37	0.20 - 0.54	0.09	<0.001
Leg length/height ratio	0.09	-0.12 - 0.30	0.10	0.350
Model R^2	0.32			<0.001

CI: Confidence interval.

Table 5. ROC analysis of anthropometric parameters predicting hamstring graft thickness ≥8 mm.

Anthropometric parameter	AUC (95% CI)	Cut-off	Sensitivity (%)	Specificity (%)	p
Leg length	0.78 (0.66-0.90)	≥ 89.5 cm	76.5	70.2	<0.001
Height	0.82 (0.70-0.94)	≥ 174.0 cm	82.4	75.0	<0.001
Leg length/body height ratio	0.70 (0.56-0.84)	≥ 0.50	68.8	65.4	0.006

ROC: Receiver operating characteristic; AUC: Area under the curve; CI: Confidence interval.

a statistically significant association with graft thickness (β=0.19, 95% CI: 0.05–0.33, p=0.008), while the leg length/height ratio did not reach statistical significance (β=0.09, 95% CI: -0.12 to 0.30, p=0.350). The overall model explained 32% of the variance in graft thickness (Model R^2=0.32, p<0.001).

The ROC analysis demonstrated that height was the most accurate anthropometric predictor for identifying patients with a hamstring graft thickness ≥8 mm, with an AUC of 0.82 (95% CI: 0.70–0.94), a sensitivity of 82.4%, and a specificity of 75.0% at a cut-off value of ≥174.0 cm (p<0.001). Leg length also demonstrated strong predictive performance, with an AUC of 0.78 (95% CI: 0.66–0.90), a sensitivity of 76.5%, and a specificity of 70.2% at a cut-off of ≥89.5 cm (p<0.001). The leg length/height ratio exhibited lower predictive accuracy, with an AUC of 0.70 (95% CI: 0.56–0.84), sensitivity of 68.8%, and specificity of 65.4% at a cut-off value of ≥0.50 (p=0.006) (Table 5, Fig. 1).

DISCUSSION

The present study evaluated the predictive value of selected anthropometric measurements, specifically leg length, total body height, and the leg length-to-height ratio, for preoperative estimation of hamstring tendon graft thickness in ACL reconstruction. Total body height was the strongest independent predictor, showing the greatest linear association and remaining significant in multivariable regression, with superior discriminative performance on receiver operating characteristic analysis.

These results are in agreement with several previous studies that have explored anthropometric predictors for graft sizing. For instance, Albishi et al. reported a significant correlation between graft thickness and anthropometric variables such as height and BMI, emphasizing height as one of the most reliable indicators [15]. Similarly, Bagherifard et al. identified thigh length and body height as consistent predictors of

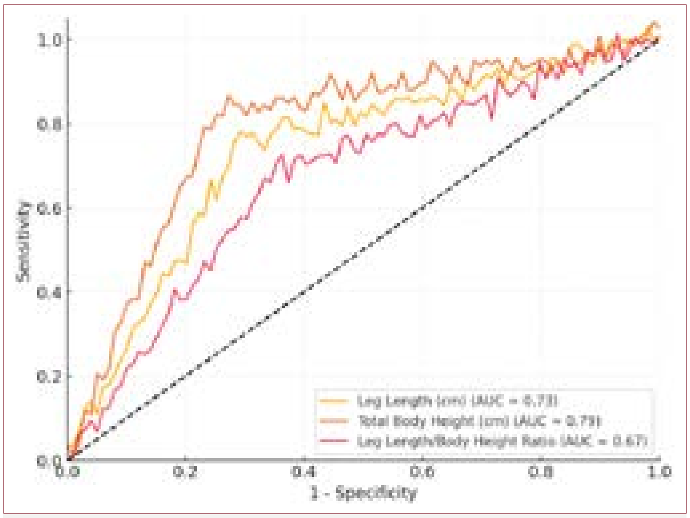

Figure 1. ROC curve for predicting hamstring graft thickness ≥8 mm.

hamstring tendon diameter in Iranian patients undergoing ACLR, further supporting our findings [21].

In this study, linear regression analysis revealed that height (β=0.52, R^2=0.27, p<0.001) outperformed leg length and leg length-to-body height ratio in predicting graft thickness. These results align with the study by Babalola and Akinyemi, which also found a strong correlation between semitendinosus tendon dimensions and patient height [20]. Moreover, Kremen et al. demonstrated that the combination of tendon parameters and anthropometric data, particularly height, improves the preoperative prediction of autograft diameter [22].

In the multivariate model, height remained the strongest predictor (β=0.37, p<0.001), whereas the leg length-to-height ratio did not reach statistical significance (p=0.350). This outcome highlights the limited utility of proportional indices compared to absolute measurements, such as height and leg length. Our ROC analysis further validated these conclusions, with height showing the highest area under the curve (AUC=0.82), sensitivity (82.4%), and specificity (75.0%) for predicting adequate graft thickness (≥8 mm). These diagnostic performance metrics are comparable to those reported in the study by Fucaloro et al., where preoperative ultrasound measurements correlated well with intraoperative tendon dimensions, particularly when combined with patient height [18].

Interestingly, while some authors have promoted the use of preoperative MRI or ultrasound for tendon sizing [17,19], this study demonstrates that simple and inexpensive anthropometric measurements may offer similar predictive capabilities. This is particularly relevant in low-resource settings or when imaging is unavailable or cost-prohibitive.

One strength of our study lies in its focus on a previously underexplored parameter, leg length and its relationship with tendon size. While studies like that of Bagherifard et al. [21] emphasized thigh length, our inclusion of leg length as a predictor provides a broader view of lower limb morphology's contribution to graft size estimation. However, our study is not without limitations. The sample size is modest, which may limit the generalizability of the findings. On the other hand, an a priori sample size calculation was not feasible due to the retrospective design; a post-hoc sensitivity analysis indicated that the study was adequately powered to detect clinically meaningful correlations (≥80% power for r≈0.25). Furthermore, we did not evaluate other potentially influential factors, such as thigh circumference or BMI, which have been shown to correlate with graft thickness in other populations [16,20]. Additionally, information regarding patients' sports activity levels and occupations was not available in the medical records, and these factors may potentially influence tendon morphology and graft thickness. Finally, we analyzed both genders together.

CONCLUSION

In conclusion, our findings support the clinical utility of height and leg length as accessible and reliable predictors for preoperative estimation of hamstring tendon graft thickness. These measurements can help surgeons select the most suitable graft and reduce the risk of using undersized grafts, which are associated with higher failure rates and the need for revision surgeries.

DECLARATIONS

Ethics Committee Approval: The Hatay Mustafa Kemal University Local Ethics Committee approved this study (Date: 19/03/2025, Number: 04/58).

Informed Consent: Informed consent was not required due to the retrospective nature of this study.

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Original Article

Does Trochlear Dysplasia Affect Fluoroscopic Femoral Tunnel Placement During ACL Reconstruction?

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ABSTRACT

Objective: Precise anatomical placement of the femoral tunnel is critical for successful outcomes in anterior cruciate ligament (ACL) reconstruction. Intraoperative fluoroscopic guidance is widely employed to improve tunnel accuracy, particularly using the Bernard–Hertel quadrant method on true lateral views. However, the influence of trochlear dysplasia, commonly seen in patients with patellofemoral instability, on the radiographic identification of the ACL femoral footprint remains unclear. Using the quadrant method, this study evaluated whether trochlear dysplasia affects fluoroscopic localization of the ACL femoral footprint.

Materials and Methods: 43 3D-printed femoral models were created from CT scans of patients with (n=21) and without (n=22) trochlear dysplasia. A consensus panel identified the anatomical ACL femoral footprint and marked it with a radiopaque thumbtack. True lateral fluoroscopic images were obtained under standardized conditions. Two independent observers performed radiographic measurements of the ACL footprint location using the ACL-X mobile application, applying the quadrant method. Intra- and inter-observer reliability was assessed using intraclass correlation coefficients (ICC). Group comparisons were made for the depth and height coordinates of the footprint.

Results: Radiographic measurements demonstrated excellent intra-observer reliability (ICC range: 0.854–0.912) and inter-observer (ICC range: 0.817–0.913). There was no significant difference in ACL footprint location between groups. The mean depth was 22.6±4.1% in the dysplasia group and 21.4±3.8% in the control group (p=0.807). Similarly, the mean height was 37.8±6.3% in the dysplasia group and 39.3±5.4% in controls (p=0.617). These findings indicate that trochlear dysplasia does not significantly affect radiographic footprint localization.

Conclusion: Trochlear dysplasia does not compromise the accuracy of fluoroscopic identification of the ACL femoral footprint using the quadrant method. Intraoperative fluoroscopic guidance remains reliable for anatomical femoral tunnel placement in ACL reconstruction, regardless of underlying trochlear morphology.

Keywords: Anterior cruciate ligament reconstruction, femoral tunnel placement, fluoroscopy, quadrant method, trochlear dysplasia

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INTRODUCTION

Anterior cruciate ligament (ACL) reconstruction is a standard orthopedic procedure to restore knee stability and function after ACL injury. Successful outcomes in ACL reconstruction are highly dependent on precise anatomical placement of the femoral tunnel, as incorrect positioning can lead to graft failure, persistent instability, and impaired knee kinematics [1,2]. During surgery, anatomical landmarks such as the intercondylar ridge and bifurcate ridge, along with remnant fibers, serve as essential guides for identifying the native femoral attachment site of the ACL [3]. In addition to these anatomical references, fluoroscopic techniques, particularly the quadrant method described by Bernard et al., have been widely adopted intraoperatively to guide femoral tunnel placement [4,5]. This method utilizes a true lateral radiographic view, enabling precise localization of the anatomical ACL femoral footprint.

Recent studies comparing femoral tunnel placement techniques have further supported the use of intraoperative fluoroscopy. Dong et al. demonstrated that combining fluoroscopy with anatomical measurements based on the apex of deep cartilage significantly improved the accuracy of femoral tunnel positioning and led to superior postoperative knee function and stability compared to the traditional bony landmark method [6]. Similarly, another study found that fluoroscopic guidance, particularly when using the quadrant method on a true lateral radiographic view, reduced tunnel placement errors and provided better alignment with the native ACL footprint [7]. These findings underscore the clinical value of fluoroscopy-assisted techniques, especially for ensuring consistent and anatomically accurate tunnel positioning during ACL reconstruction.

Although ACL injuries and patellofemoral instability (PFI) are traditionally viewed as separate conditions, recent evidence indicates that they may coexist, particularly in young and active individuals. Both injuries often result from similar non-contact mechanisms, suggesting a shared biomechanical predisposition [8–10]. Epidemiological studies have reported notable rates of simultaneous occurrence, reinforcing the importance of recognizing coexisting PFI during ACL injury assessment [11,12].

Importantly, the morphology of the distal femur—especially the trochlear region—can affect how anatomical landmarks appear on lateral fluoroscopic images [13]. Trochlear dysplasia, which is common in patients with PFI, may distort these landmarks and complicate accurate femoral tunnel placement [14]. Despite its relevance, the influence of trochlear morphology on fluoroscopic localization of the ACL femoral footprint remains underexplored.

The quadrant method is widely used; however, its reliability may be compromised in patients with abnormal distal femoral anatomy. Variations such as trochlear dysplasia can lead to misinterpretation of fluoroscopic landmarks, potentially resulting in femoral tunnel malposition. This study investigates whether trochlear morphology affects the accuracy of ACL femoral footprint localization using fluoroscopy.

Using three-dimensional (3D) printed femur models from patients with and without trochlear dysplasia, we evaluated how trochlear shape influences fluoroscopic localization of the ACL footprint via the quadrant method.

We hypothesized that trochlear dysplasia may significantly influence fluoroscopic interpretation, potentially causing deviations from the true anatomical position of the ACL femoral footprint.

MATERIALS AND METHODS

Patient Selection and Study Protocol

This experimental research utilized 3D-printed femoral models to evaluate the accuracy of the fluoroscopic identification of the ACL femoral footprint using the Bernard–Hertel quadrant method in knees with and without trochlear dysplasia. A retrospective review of radiological data was carried out using our institutional digital archive, encompassing patients treated for patellar instability between 2015 and 2024. From the identified 204 cases, a random sample was selected from those who had undergone CT imaging. For the control group, patients who presented to the emergency department with acute knee trauma and received CT imaging due to suspected fractures were screened. Individuals showing radiological features of trochlear dysplasia were excluded. Subjects with a prior history of knee surgery, fractures, congenital anomalies, or deformities, as well as those with suboptimal CT quality unsuitable for 3D reconstruction, were not included in the final analysis for either group. Institutional Review Board approval was secured before initiating the study (Approval Date/ID: 2025/9-4). The study adhered to the ethical standards outlined in the Declaration of Helsinki and its later revisions.

Sample Size Calculation

The sample size for this study was determined using G*Power software (version 3.1.9.7), assuming equal group allocation [15]. The calculation was based on a two-tailed independent t-test with an effect size (Cohen's d) of 1.0, derived from prior data reporting a standard deviation of 2.5% in the radiographic localization of the ACL femoral footprint using the Bernard–Hertel quadrant method [4,5]. To detect a clinically relevant difference of 2.5% between knees with and without trochlear dysplasia, with 80% power ($1 - \beta = 0.80$) and a significance level of $\alpha = 0.05$, the analysis indicated that a minimum of 34 knees (17 per group) would be required. To account for potential exclusions due to poor image quality, inadequate lateral fluoroscopic projections, or technically unusable CT data for

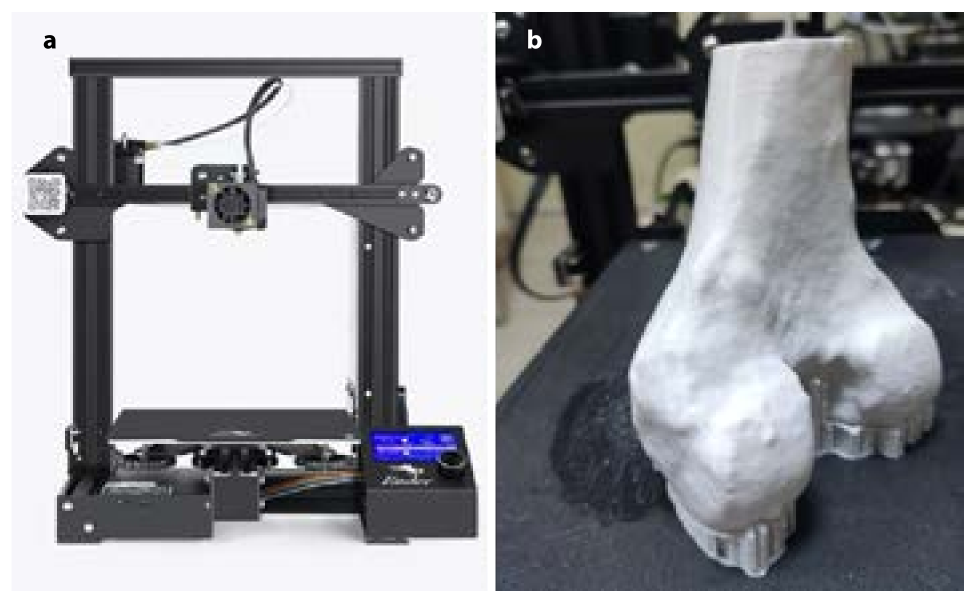

Figure 1. (a) The Creality Ender-3 Pro 3D printer manufacturing the femoral models. **(b)** A representative 3D-printed distal femur model generated from CT data demonstrates anatomical accuracy suitable for fluoroscopic ACL femoral footprint localization evaluation.

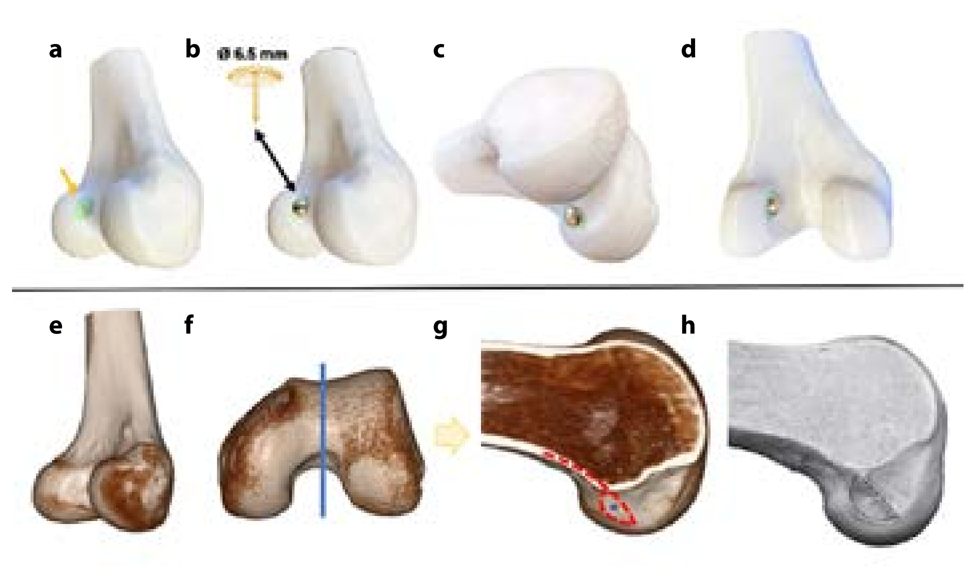

Figure 2. (a-d) Placement of a 6.5 mm diameter radiopaque metallic marker on the anatomically defined center of the ACL femoral footprint on 3D-printed distal femur models, as determined by expert consensus using CT data and anatomical landmarks (yellow arrow indicates the footprint region). **(e-g)** Digital visualization of the ACL footprint using multiplanar CT reconstruction. **(f)** Coronal plane reference line; **(g)** sagittal cross-section showing the anatomical location of the ACL footprint (dashed red outline) on the posteromedial surface of the lateral femoral condyle. **(h)** Comparative anatomical reference image illustrating the native femoral footprint of the ACL in a cadaveric specimen.

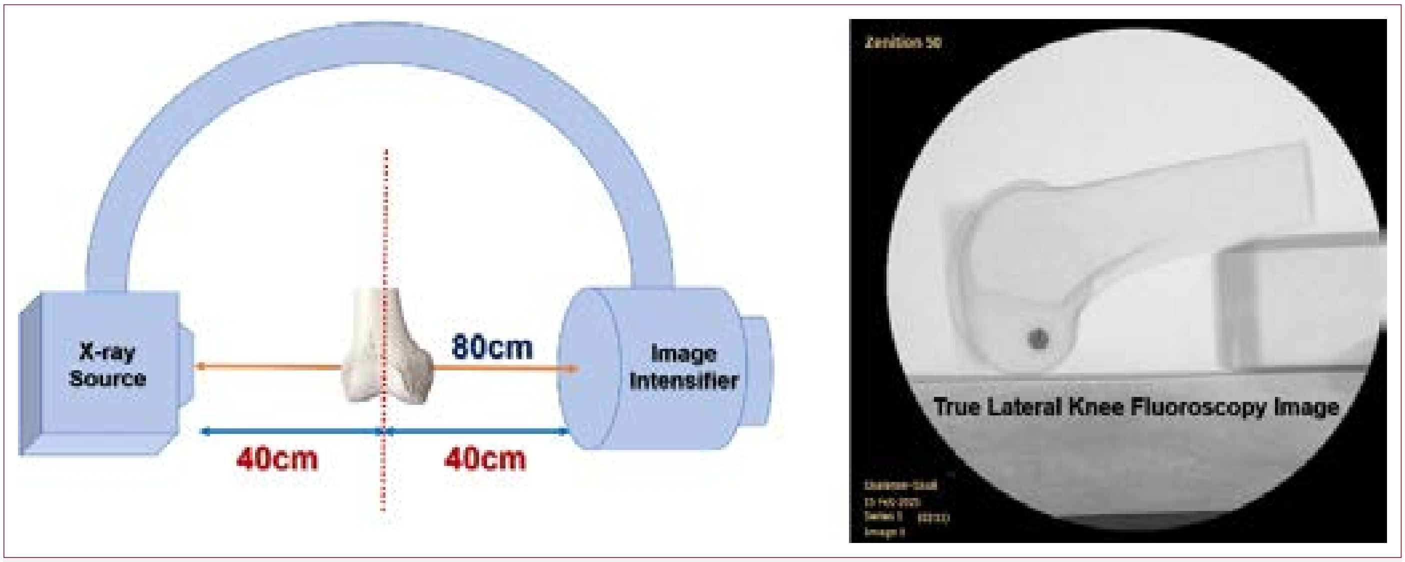

Figure 3. Fluoroscopic imaging setup and representative true lateral radiograph of a 3D-printed femoral model. The model was positioned equidistantly between the X-ray source and image intensifier of a C-arm system, with lateral beam orientation and adjustment to achieve perfect superimposition of the posterior femoral condyles. This positioning ensured an anatomically accurate lateral projection for analysis of ACL femoral footprint localization.

3D reconstruction, additional patients were initially screened to ensure a sufficient number of valid cases could be analyzed.

Three-Dimensional Model Production

CT scans were obtained for all participants using the CT unit (Siemens go. up, Siemens, Munich, Germany) located in either the Radiology or Emergency Department. The imaging protocol included a tube voltage of 121 kV (range: 120–130 kV), a tube current of 143 mA (range: 61–200 mA), a slice thickness of 0.6 mm (range: 0.2–0.8 mm), and a field of view (FoV) of 200 mm (range: 147–269 mm). Using the acquired DICOM data, three-dimensional digital models of the femur were reconstructed using Materialise Mimics and 3-Matic Medical software (Materialise NV, Leuven, Belgium). The STL files were processed using Ultimaker Cura (Ultimaker B.V., Netherlands) and printed with a Creality Ender-3 Pro 3D printer (Shenzhen, China) as shown in Figure 1. The printing settings were configured with an infill density of 3–10% and a layer height of 0.16–0.20 mm to achieve an optimal balance between model durability and anatomical fidelity. Polylactic acid (PLA) filament was selected for its cost-effectiveness and ability to produce dimensionally accurate, robust models suitable for handling and fluoroscopic assessment. Following fabrication, each printed model was visually and digitally compared with the original 3D CT reconstruction to verify the accurate representation of key anatomical landmarks, especially those relevant to identifying the femoral footprint of the ACL. This validation step ensured the reliability of the models for subsequent fluoroscopic analysis.

Determination of the ACL Femoral Footprint on Printed Models

The precise anatomical location of the femoral footprint of the anterior cruciate ligament (ACL) was identified through a consensus by a panel composed of two orthopedic surgeons with over ten years of experience in knee surgery and sports traumatology and one anatomist. To improve accuracy and reduce the risk of localization error, the panel evaluated each case using both the patients' original CT images and their corresponding 3D-printed femoral models simultaneously. Anatomically, the ACL femoral footprint is located on the posteromedial surface of the lateral femoral condyle, situated within the intercondylar notch, posterior to the lateral intercondylar ridge (Resident's ridge), and anterior and superior to the lateral bifurcate ridge, which separates the native insertion sites of the ACL's anteromedial and posterolateral bundles. Once the center of the footprint was identified, a metallic thumbtack with a head diameter of 6.5 mm was securely fixed to this point on each model. This radiopaque marker enabled clear and consistent visualization of the anatomical ACL footprint on fluoroscopic images (Fig. 2)

Fluoroscopy Technique and Image Acquisition

Fluoroscopic evaluations were performed in an operating room environment using a C-arm system (Zenition 50, Philips, The Netherlands). The 3D-printed femoral models were positioned equidistantly between the X-ray source and the image intensifier during image acquisition. Care was taken to align the deepest point of the trochlear groove precisely at the midpoint between

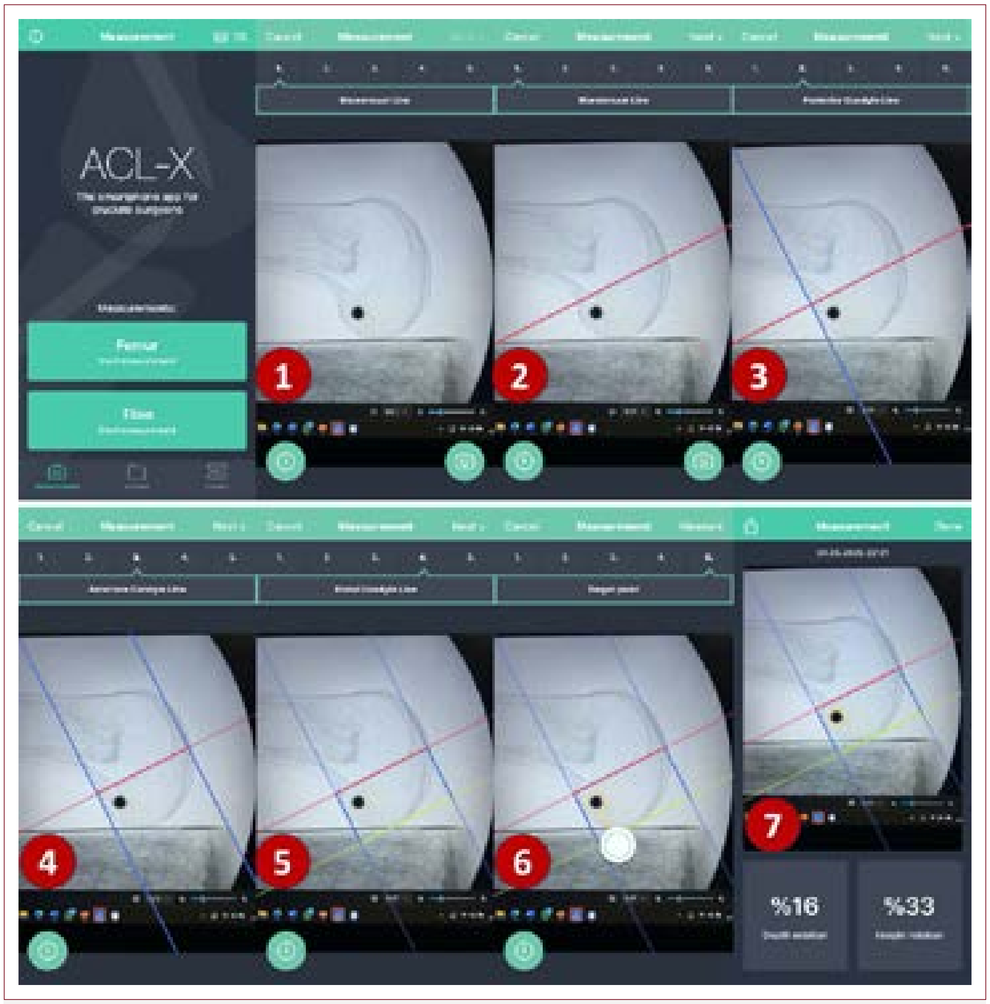

Figure 4. Measurement of the ACL femoral footprint location using the quadrant method on true lateral fluoroscopic imaging via the ACL-X mobile application. (Image 1): A true lateral fluoroscopic image of the femur is obtained with optimal superimposition of the posterior femoral condyles. A radiopaque marker (black circle) represents the center of the anatomically defined ACL femoral footprint. (Image 2): The Blumensaat line (roof of the intercondylar notch) is drawn (red line), forming the horizontal reference axis. (Image 3): A perpendicular line is drawn from the posterior cortical margin of the lateral femoral condyle to the Blumensaat line, representing the posterior border (blue line). (Image 4): The anterior and posterior borders of the lateral femoral condyle are marked to define the sagittal width of the condyle. (Image 5): Superior (Blumensaat) and inferior (distal condyle) borders of the condyle are marked, forming a grid over the lateral condyle. (Image 6): The center of the metal marker (ACL footprint) is selected as the target point. The application calculates its position within the grid. (Image 7): The final screen displays the depth and height ratio of the ACL footprint center within the quadrant, given as percentages: 16% from the posterior cortex (depth) and 33% from the Blumensaat line (height), indicating a typical anatomical location.

the medial and lateral cortical outlines. The X-ray source was placed on the lateral side of the specimen to simulate standard lateral knee imaging. Image acquisition parameters included a tube voltage ranging from 45 to 52 kV and a tube current between 0.4 and 1.8 mA. Each model was carefully rotated until the posterior margins of the medial and lateral femoral condyles

Table 1. Comparison of demographic and clinical characteristics of patients

Variables	Trochlear Dysplasia Group (n=21)	Control Group (n=22)	p
Age (years ±SD)	22.1±7.4	24.8±8.1	0.263[1]
Sex (n, %)			0.219[2]
Male	8 (38.1%)	12 (54.5%)	
Female	13 (61.9%)	10 (45.5%)	
Side (n, %)			0.137[2]
Right	7 (33.3%)	12 (54.5%)	
Left	14 (66.7%)	10 (45.5%)	
Weight (kg ±SD)	70.1±17.5	76.3±13.1	0.593[3]
Height (cm ±SD)	168.3±12.1	173.0±8.6	0.148[3]
BMI (kg/m2±SD)	24.5±4.8	25.3±4.8	0.556[1]
TT-TG Distance (mm ±SD)	22.7±4.1	13.1±3.4	0.001[3]
TT-PCL Distance (mm ±SD)	17.9±4.3	11.4±4.5	0.001[3]
Dejour Classification (n, %)			NA
Type A	5 (23.8%)	-	
Type B	7 (33.3%)	-	
Type C	4 (19.0%)	-	
Type D	5 (23.8%)	-	
Caton-Deschamps Index	1.09±0.15	0.88±0.11	0.001[3]
Patellar Tilt (°±SD)	32.5±11.2	9.5±4.7	0.001[3]
Tibiofemoral rotation (°±SD)	8.9±4.1	5.6±3.6	0.008[1]

were perfectly superimposed to obtain an anatomically accurate true lateral projection. 5 to 10 images were captured for each femur, and the most accurate lateral projection, demonstrating ideal condylar overlap, was selected for analysis. Figure 3 shows the fluoroscopic imaging setup and a representative image

Radiological Measurements on Digital Fluoroscopic Images

Radiological measurements were performed using the ACL-X smartphone application (Linova Software GmbH, v.1.0.2, Munich, Germany), a dedicated mobile software developed to accurately assess cruciate ligament footprint localization on lateral fluoroscopic images [16,17]. The application enables the standardized application of the quadrant method and provides automated calculation of the depth and height ratios of the ACL femoral footprint. Two independent observers, one musculoskeletal radiologist and one orthopedic surgeon specializing in sports traumatology, individually conducted the measurements on the smartphone interface. All images were evaluated in a randomized sequence to prevent order bias. Each observer repeated the entire assessment process on a separate occasion, with a minimum interval of two weeks between the two measurement rounds, allowing for an analysis of intra-observer reliability. To minimize recall bias, the observers were blinded to their prior measurements and those of the other observer. The ACL-X mobile app was used to calculate the final measurements of the ACL femoral footprint location with the quadrant method, as demonstrated in Figure 4.

Inter- and intra-observer reliability of the measurements was tested using an interclass correlation coefficient (ICC). The ICC was above 0.800 (acceptable reliability) for all variables, and the mean of the measurements was employed for the final analysis.

Statistical Analysis

Continuous variables were described using the mean, standard deviation, and range, while categorical data were expressed as frequencies and percentages. The Kolmogorov-Smirnov test was used to determine whether continuous variables conformed to a normal distribution. For data that follows a normal distribution, parametric tests were applied; non-parametric tests were used for data that does not adhere to this distribution. The

Table 2. Inter- and intra-observer reliability results

Variables	Intra-observer Reliability (ICC, 95% CI)		Interobserver Reliability (ICC, 95% CI)	
	A t1 vs. A t2	**B t1 vs. B t2**	**A t1 vs. B t1**	**A t2 vs. B t2**
ACL Depth	0.910 (0.841-0.950)	0.912 (0.844-0.952)	0.913 (0.846-0.952)	0.908 (0.836-0.949)
ACL Height	0.854 (0.747-0.918)	0.817 (0.814-0.945)	0.817 (0.661-0.901)	0.901 (0.816-0.946)

Table 3. Comparison of the center of the ACL femoral footprint between groups

Variables	Trochlear Dysplasia Group	Control Group	Total	p
ACL Depth (%)	22.6±4.14	21.4±3.83	22.0±3.98	0.807
ACL Height (%)	37.8±6.30	39.3±5.40	38.6±5.83	0.617

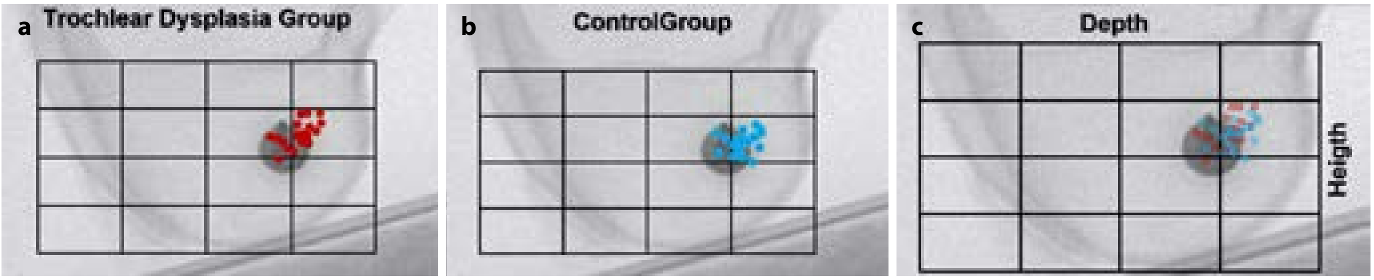

Figure 5. Distribution of ACL femoral footprint coordinates according to the quadrant method. **(a)** Scatterplot of depth and height coordinates in the Trochlear Dysplasia group (red dots), **(b)** Scatterplot of coordinates in the Control group (blue dots), **(c)** Superimposed view showing both groups for comparison (red = dysplasia, blue = control). All measurements were mapped on standardized quadrant reference images derived from true lateral fluoroscopic views. The center of each plotted point represents the radiologically determined ACL footprint location as a percentage of the lateral femoral condyle's total depth (horizontal axis) and height (vertical axis).

independent sample t-test or the Mann-Whitney U test was used to compare continuous variables, while the chi-squared test was employed to compare categorical data. Intra-observer and inter-observer reliability were evaluated using Intraclass Correlation Coefficients (ICC) with 95% confidence intervals (CIs). A two-way random-effects model was used to assess interobserver reliability, considering both absolute agreement and consistency. ICC values were interpreted as poor (<0.50), moderate (0.50–0.75), good (0.75–0.90), or excellent (>0.90) [18]. A p-value of less than 0.05 was deemed statistically significant.

RESULTS

Demographic and Radiological Characteristics

A total of 43 femoral models were evaluated, including 21 models in the trochlear dysplasia group and 22 in the control group. The mean age was 22.1±7.4 years in the dysplasia group and 24.8±8.1 years in the control group, with no statistically significant difference (p=0.263). The distribution of sex and laterality was similar between groups (p=0.219 and p=0.137, respectively). Anthropometric parameters such as body weight, height, and BMI were also comparable (p>0.05 for all). Radiological comparisons revealed significantly greater mean TT-TG (22.7±4.1 mm vs. 13.1±3.4 mm, p=0.001), TT-PCL (17.9±4.3 mm vs. 11.4±4.5 mm, p=0.001), and Caton-Deschamps index values (1.09±0.15 vs. 0.88±0.11, p=0.001) in the dysplasia group compared to controls. Additionally, the dysplasia group demonstrated significantly higher patellar tilt angles (32.5°±11.2° vs. 9.5°±4.7°, p=0.001) and tibiofemoral rotation (8.9°±4.1° vs. 5.6°±3.6°, p=0.008) (Table 1).

Reliability of Measurements

Intra-observer reliability for ACL footprint depth and height measurements showed excellent consistency, with intraclass correlation coefficients (ICC) ranging from 0.854 to 0.912. Interobserver agreement was also high, with ICC values ranging from 0.817 to 0.913 (Table 2).

Comparison of ACL Footprint Location Between Groups

The position of the ACL femoral footprint, expressed as a percentage relative to the quadrant method, did not differ significantly between groups. The mean depth was 22.6±4.1% in the dysplasia group and 21.4±3.8% in the control group (p=0.807), while the mean height was 37.8±6.3% and 39.3±5.4%, respectively (p=0.617) (Table 3). These results suggest that the anatomical ACL footprint location remains consistent, independent of trochlear morphology (Fig. 5).

DISCUSSION

The principal finding of this study is that trochlear dysplasia does not significantly alter the radiographic localization of the ACL femoral footprint when using the quadrant method on true lateral fluoroscopic images. Despite marked anatomical differences in distal femoral morphology and radiographic parameters between the dysplasia and control groups, the depth and height coordinates of the femoral footprint remained statistically comparable. This suggests that the quadrant method provides a reliable reference for femoral tunnel placement during ACL reconstruction, even in the presence of trochlear morphological variations, often associated with patellofemoral instability. These findings support the continued use of fluoroscopic guidance as a reproducible intraoperative tool, highlighting that trochlear dysplasia alone may not necessitate deviation from standard anatomical tunnel placement techniques.

Numerous cadaveric and radiologic studies have sought to define the center of this footprint using the Bernard-Hertel quadrant method. Still, reported coordinates have shown considerable variability, raising concerns about the method's generalizability and reproducibility across populations and imaging modalities [19,20]. In the current study, the mean location of the ACL femoral footprint was measured at 22.6% (depth) and 37.8% (height) in the trochlear dysplasia group, and at 21.4% and 39.3%, respectively, in the control group. These findings are consistent with—but slightly more anterior than—the original values proposed by Bernard et al., who described the anatomical center of the ACL footprint at 24.8% (deep–shallow) and 28.5% (high–low) using the quadrant method on lateral radiographs of cadaveric knees [4,5]. In the extensive cadaveric review by Parkar et al., the weighted mean center of the ACL femoral footprint was 29% (depth) and 35% (height), with a 5th–95th percentile range of 24–37% and 28–43%, respectively [19]. The control group's footprint location fell slightly anterior to this range, particularly in depth, suggesting population-specific variation or methodological differences in 3D model positioning and fluoroscopic imaging. Xu et al. synthesized results from 13 studies and reported a pooled footprint location at 28.4% ± 5.1% (depth) and 35.7% ± 6.9% (height), defining a "standard area" centered at 27.53% and 35.85% [21]. In our study, some values, particularly from the trochlear dysplasia group, fell outside this standard area, although the differences were not statistically significant. These findings suggest that while the Bernard quadrant method remains valid, trochlear morphology may introduce subtle variation in radiographic footprint interpretation, reinforcing the need for careful intraoperative assessment in dysplastic knees.

While this study primarily focused on the impact of trochlear morphology, previous literature has also emphasized the clinical relevance of addressing concurrent patellofemoral instability (PFI) in ACL-injured patients. Several studies have suggested that untreated PFI may negatively affect surgical outcomes, particularly when MPFL injury is present. Our findings complement these reports by demonstrating that, even in the presence of dysplastic trochlear anatomy, reliable femoral tunnel placement can still be achieved using fluoroscopic guidance.

The strengths of the current study include the use of standardized 3D-printed femoral models derived from high-resolution CT scans, precise control of fluoroscopic conditions, and a validated digital measurement application (ACL-X) that enhances reproducibility. Observer blinding, repeated measurements, and excellent inter/intra-observer reliability further strengthen the methodological rigor. However, several limitations should be acknowledged. First, static bone models may not fully replicate intraoperative variables such as soft tissue interference, surgical positioning, or fluoroscopic limitations in live patients. Second, although true lateral projections were carefully selected, slight deviations from ideal positioning in clinical practice could affect measurement accuracy. Finally, this was a cadaveric model-based study with a relatively limited sample size, and larger clinical validation is warranted before generalizing the results to all surgical scenarios

In conclusion, this experimental study demonstrates that trochlear dysplasia does not significantly affect the fluoroscopic localization of the ACL femoral footprint when using the Bernard–Hertel quadrant method. Despite anatomical variations associated with dysplasia, the depth and height coordinates of the ACL footprint remained consistent between dysplastic and non-dysplastic femurs. These findings confirm the reliability of intraoperative fluoroscopic guidance for femoral tunnel placement, even in the presence of altered distal femoral morphology. From a surgical perspective, this supports the continued use of the quadrant method as a standardized approach for anatomic ACL reconstruction without the need for significant adjustments in patients with trochlear dysplasia. Clinically, the routine application of this method may improve tunnel accuracy and reduce the risk of graft malposition, especially when traditional bony landmarks are obscured or distorted. Future clinical studies involving intraoperative data and postoperative outcomes are warranted to validate these findings in real-world surgical scenarios and to explore whether subtle radiographic deviations may influence long-term graft function or failure rates.

DECLARATIONS

Ethics Committee Approval: Antalya Training and Research Hospital Ethics Committee approved this study (Date: 29/05/2025, Number: 9-4).

Informed Consent: Informed consent was not deemed necessary for this study.

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ABBREVIATIONS

ACL – Anterior Cruciate Ligament

ACL-X – ACL Localization Mobile Application

BMI – Body Mass Index

CI – Confidence Interval

CT – Computed Tomography

DICOM – Digital Imaging and Communications in Medicine

FoV – Field of View

ICC – Intraclass Correlation Coefficient

kVp – Kilovolt Peak

mA – Milliampere

MPFL – Medial patellofemoral ligament

PFI – Patellofemoral Instability

PLA – Polylactic Acid

TT-PCL – Tibial Tubercle–Posterior Cruciate Ligament distance

TT-TG – Tibial Tubercle–Trochlear Groove distance

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Original Article

Significant Muscle Strength Deficits Persist One Year After ACL Reconstruction with Hamstring Tendon Autografts

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ABSTRACT

Objective: Hamstring tendon (HT) autografts are frequently used in anterior cruciate ligament (ACL) reconstruction, but their impact on muscle strength recovery and knee functionality remains a concern.

Materials and Methods: This study aimed to evaluate the changes in muscle strength and recovery dynamics in patients undergoing anterior cruciate ligament (ACL) reconstruction using hamstring tendon autografts. The primary focus was on assessing quadriceps and hamstring strength, hamstring-to-quadriceps (H/Q) ratios, and Limb Symmetry Index (LSI) before and one year post-surgery. Additionally, the study examined clinical outcomes using the International Knee Documentation Committee (IKDC) and Lysholm Knee Scores. Seventeen male patients (mean age 25.1±7.1 years) who underwent ACL reconstruction with hamstring autografts were included. Isokinetic testing assessed muscle strength preoperatively and at 12 months postoperatively. Outcome measures included concentric and eccentric peak torque values for quadriceps and hamstrings, H/Q ratios, LSI, and functional outcomes measured by the International Knee Documentation Committee (IKDC) Score and the Lysholm Knee Score. Statistical analysis compared preoperative and postoperative data. Study Design: Prospective cohort study; Level of evidence; 2.

Results: Significant preoperative disparities were observed in concentric quadriceps strength between injured and uninjured sides, with persistent deficits postoperatively. Eccentric quadriceps strength showed stability, but hamstring strength significantly decreased post-surgery. Conventional and functional H/Q ratios worsened postoperatively, failing to meet normal benchmarks. LSI for both quadriceps and hamstrings remained below the 90% threshold postoperatively, indicating persistent strength deficits. Despite these muscle imbalances, significant improvements were observed in knee function, with increased IKDC and Lysholm scores.

Conclusion: One year after ACL reconstruction with hamstring tendon autografts, patients exhibit substantial deficits in quadriceps and hamstring strength, reflected in lowered H/Q ratios and LSI values. Despite these deficits, significant improvements in knee function and stability are observed. Extended and targeted rehabilitation focusing on concentric and eccentric muscle strengthening may be necessary for optimal recovery.

Keywords: ACL reconstruction, hamstring tendon autografts, H/Q ratio, Limb Symmetry Index, muscle strength recovery

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INTRODUCTION

Anterior cruciate ligament (ACL) rupture is a prevalent injury, particularly in young individuals engaged in contact sports.[1] This debilitating injury can have significant consequences for athletes, potentially leading to the end of their sporting careers. ACL reconstruction (ACLR) is essential for restoring knee stability and function, and is often necessary for returning to sports.[2-4] Early surgery, combined with postoperative rehabilitation, is crucial for restoring knee joint stability and function, effectively preventing further complications.[5, 6] There is a wide variety of graft options available for ACLR, including allografts, synthetic grafts, hamstring tendons (HT), quadriceps tendon (QT), bone-patellar tendon-bone (BPTB), and peroneus longus tendon autografts. Each of these graft options has its own advantages and disadvantages. Moreover, graft selection may influence surgical outcomes and the postoperative rehabilitation processes.

The BPTB graft was historically favored for its initial strength and reliable healing properties.[7, 8] However, the BPTB grafts are associated with several complications, including anterior knee pain, patellar tendon rupture, patellar fracture, and knee extensor dysfunction.[9] Among other alternative graft options, HT autografts have gained considerable popularity and have emerged as the most commonly used autograft.[10] HT grafts have several advantages, including ease of harvest, minimal invasiveness, low risk of donor site morbidity, and lack of extensor mechanism dysfunction.[11] Despite the advantages of HTAs, they are not without downsides. One significant concern is their association with hamstring muscle strength deficits.[12] This weakness can significantly impact rehabilitation and increase re-injury risk, as these muscles play a protective role for the ACL and compensate for stability loss in ACL-deficient knees.[8] Furthermore, hamstrings provide a stabilizing effect against valgus stress in MCL injuries, and hamstring weakness is directly associated with decreased knee function following ACL injury.[13] Consequently, this weakness affects the recovery process and raises significant questions about the optimal timing for a safe return to sports.

Given the potential impact of hamstring weakness, it's essential to investigate the muscle strength recovery process after ACLR using HT grafts. The primary aim of this study focuses on evaluating the changes in muscle strength and the dynamics of recovery in patients undergoing ACL reconstruction using HT autografts. The objective is to provide a comprehensive assessment of muscle function, specifically looking at the quadriceps and hamstring strength, hamstring-to-quadriceps (H/Q) ratios and the Limb Symmetry Index (LSI), before and one year after the surgery. This period allows for a substantial phase of rehabilitation, offering insights into the long-term effects of the surgical technique on muscle strength and knee functionality. The secondary aim of the study examines the correlation between these muscle strength measures and clinical outcomes, as assessed by the International Knee Documentation Committee (IKDC) Score and the Lysholm Knee Score, to understand the broader implications of hamstring tendon harvesting on post-surgical recovery. By evaluating these parameters, the study seeks to elucidate the real-world implications of ACLR with HT grafts on an individual's return to sports, ensuring that the surgical advances continue to align with optimal long-term health outcomes.

MATERIALS AND METHODS

Patients and Study Design

This prospective study was conducted on patients who underwent isolated ACLR using quadruple HT autograft. Patients with concurrent meniscal tears, cartilage injuries, and additional ligament injuries were excluded from the study since they would significantly alter postoperative rehabilitation. In addition, patients with a previous history of injury or surgical procedure in the contralateral knee were also excluded from the study. Finally, patients who underwent ACLR more than three months after the initial ACL injury were excluded. All patients scheduled for ACLR between 2020 and 2021 were prospectively evaluated. Seventeen males aged between 18 and 42 who met the specified criteria were included in the study. This study was conducted according to the ethical standards of the 1964 Helsinki Declaration and its subsequent amendments, and the institutional review board (IRB) approved the study protocol (IRB approval date/no: 2019/138.12/2).

Surgical Technique and Postoperative Rehabilitation

All patients underwent anatomic single-bundle arthroscopic ACLR under spinal anesthesia. The hamstring tendons (gracilis and semitendinosus) were harvested using an anteromedial oblique incision and prepared in a quadruple fashion. The femoral tunnel was drilled using the anteromedial portal technique to target the native ACL femoral footprint. The tibial tunnel was placed in line with the posterior border of the anterior horn of the lateral meniscus using a 55-degree tibial guide. An endobutton suspension system was utilized for femoral fixation, while a bioabsorbable interference screw and post-fixation titanium U-staple were employed for tibial fixation. A suction drain was placed within the joint and was removed at 24 hours postoperatively.

ACL postoperative rehabilitation is an extensive process intended to ease pain, reduce swelling, and minimize inflammation following surgery. The main objectives are to regain full range of motion, reestablish neuromuscular function, and eventually ensure a safe return to previous levels of physical activity or sports performance.[14] To achieve these goals more efficiently, accelerated rehabilitation following anterior cruciate ligament (ACL) reconstruction has been introduced as a modern approach. This method aims to speed up recovery and facilitate an early return to functional activities.[15] In line with this approach, an accelerated rehabilitation program was implemented for all patients in this study undergoing ACL reconstruction. Early mobilization and progressive exercises were focused on, starting immediately post-surgery with pain management, edema reduction and knee mobility exercises. In weeks 2-4, the protocol emphasized maintaining knee extension, improving knee flexion, and strengthening the thigh, hip, and trunk, while incorporating low-impact aerobic exercises. From weeks 5-12, efforts continued to normalize knee movements and strengthen musculature, with an increase in the complexity and impact of aerobic and proprioceptive exercises. The final phase (weeks 13-24) aimed at restoring symmetrical strength, introducing plyometrics, and advancing aerobic activities based on individual tolerance, concluding with sport-specific drills to ensure a safe return to athletics.

Isokinetic Testing and Outcome Measurements

Isokinetic testing was conducted on patients to assess muscle strength before and 12 months after surgery, at which point all participants had completed the standard rehabilitation regimen. This isokinetic evaluation was performed with a "Cybex Norm" (CSMI Humac Norm, USA). The same sports medicine physician performed all test procedures. Dynamometers were calibrated according to the operating manual. Before strength testing, participants performed a general cardiovascular warm-up on a Monark cycle ergometer for at least 5 min at a moderate pace (50-100 W). Tests were performed in a predefined ROM of 90°–0°. The gravitational correction was performed at 45^0 of knee flexion. At the beginning of the test procedures, participants were allowed three submaximal contractions of the hamstring or quadriceps muscle group to familiarize themselves with the test conditions. Next, they were given three trial contractions to perform four maximal contractions at the angular velocity of 60 °/sec. Then, they performed eccentric knee extension and flexion four times at the same selected angular velocity in three trials. Subjects were encouraged verbally during the test to ensure maximal participation. The tests were first performed on the non-injured side leg. A 30-second rest period was given between trial repetitions and the test, and a 2-minute rest interval after each test. The best concentric (Con) and eccentric (Ecc) muscle peak torque values were recorded for the hamstring and quadriceps muscle groups. Additionally, limb symmetry index (LSI), conventional hamstring-to-quadriceps ratio (conH/conQ), and functional hamstring-to-quadriceps ratio (eccH/conQ) were calculated and utilized for data analysis (ConQ representing concentric quadriceps, ConH representing concentric hamstring, EccQ representing eccentric quadriceps, and EccH representing eccentric hamstring). The H/Q ratio is calculated in two primary ways, each offering insights into different aspects of muscle function. The conventional H/Q ratio measures the peak concentric forces between the hamstrings and quadriceps, whereas the functional H/Q ratio (formerly known as the Dynamic Control Ratio) evaluates the relationship between the eccentric strength of the hamstrings and the concentric strength of the quadriceps, expressed as a percentage.[16] Traditional guidelines and most recent systematic reviews have benchmarked the conventional hamstring-to-quadriceps (H/Q) ratio at 60% and the functional H/Q ratio at 80%.[16,17]

The Limb Symmetry Index (LSI), expressed as the percentage ratio of the operated limb's strength or performance to that of the unaffected limb (LSI: operated limb/unaffected limb x 100), serves as a quantifiable indicator of functional restoration and bilateral symmetry following anterior cruciate ligament (ACL) reconstruction.[18] Achieving an LSI of ≥90% indicates successful rehabilitation, with strength in the injured limb approaching that of the uninjured side.[19]

The functional outcomes of the patients were assessed using two established scoring systems: the International Knee Documentation Committee (IKDC) Score and the Lysholm Knee Score.[20, 21] Preoperative scores were recorded for each patient before surgery, and postoperative scores were collected 12 months after surgery; at this point, all participants had completed the standard rehabilitation regimen.

Statistical Analysis

Continuous variables were reported as mean, median, and standard deviation, while categorical variables were expressed in terms of percentages and frequency distribution. Continuous variables were compared between independent groups using either the Student's t-test or the Mann-Whitney U test, depending on the results of normality testing. Categorical data were compared using the chi-square test. A p-value of less than 0.05 was considered statistically significant.

RESULTS

The study included seventeen male patients with a mean age of 25.1±7.1 years (range, 18.0 - 42.0). A summary of the patient characteristics is presented in Table 1. In the preoperative assessment, the injured leg demonstrated significantly weaker concentric strength in both the quadriceps (156.6±40.8 Nm vs. 185.0±37.1 Nm, p=0.011) and the hamstrings (75.7±26.5 Nm vs. 87.5±25.8 Nm, p=0.012) compared to the uninjured leg. This discrepancy persisted postoperatively, with the injured leg failing to demonstrate a significant improvement in either muscle group over the study period (p=0.006 for quadriceps; p=0.012 for hamstrings). Notably, the hamstrings of the injured leg demonstrated a further decline in strength postoperatively (75.7±26.5 Nm vs. 87.5±25.8 Nm, p=0.012), while the

Table 1. Demographics and clinical characteristics of patients

Variables	Values
Age, years±SD (min-max)	25.1±7.1 (18.0 - 42.0)
Height, cm±SD (min-max)	176.4±6.4 (168.0 – 189.0)
Weight, kg±SD (min-max)	79.9±14.1 (62.0 – 112.0)
BMI, kg/m^2±SD (min-max)	25.5±3.1 (21.8 – 33.8)
Side, n (%)	
Right	7 (41.2)
Left	10 (58.8)
The time between rupture and ACLR, months±SD (min-max)	2.2±0.6 (1-3)

SD: Standart deviation; min: minimum; max: maximum.

quadriceps exhibited a minor, non-significant improvement (160.4±41.4 Nm vs. 156.6±40). There was no significant difference in the strength of the quadriceps muscles when performing eccentric contractions before surgery (p=0.906). However, following surgery, the strength of the injured side decreased, while the strength of the uninjured side increased significantly (p=0.000). Similarly, there was no significant difference in eccentric contractions of the hamstrings between the injured and uninjured sides before surgery (p=0.660). However, following surgery, the injured side demonstrated a significant decrease in strength (p=0.000), while the uninjured side exhibited an increase (p=0.024), resulting in a significant difference between the two sides (p=0.001).

With regard to the H/Q ratios, both conventional and functional, there were discernible changes over time, with the most remarkable alterations observed on the injured side. The conventional H/Q ratio exhibited a significant decline following surgery on the injured side (p=0.004), while the functional H/Q ratio, initially demonstrating a notable difference in values between the injured and uninjured sides (p=0.042), also demonstrated a significant decline post-surgery (p=0.000). This resulted in a persistent difference between the injured and uninjured sides (p=0.019), with the uninjured side exhibiting a higher ratio postoperatively. However, neither ratio reached the recommended typical values (60% for conventional and 80% for functional) on either side. Regarding Limb Symmetry Indices (LSIs), all indices for both concentric and eccentric contractions failed to reach the 90% threshold considered normal postoperatively. Notably, the eccentric LSI for both the quadriceps and hamstrings demonstrated a significant decline following surgery (p=0.010 and p=0.000, respectively), indicating persistent deficits in muscle function. (For a detailed account of these results, please refer to Table 2).

Table 2. Results of the comparison between injured and uninjured sides in the preoperative and postoperative period

		Con Q	
	Injured	Uninjured	p
Preoperative	156.6±40.8	185.0±37.1	0.011[2]
Postoperative	160.4±41.4	185.7±44.7	0.006[2]
p-value	n.s[2]	n.s[2]	
		Con H	
	Injured	**Uninjured**	**p**
Preoperative	88.2±25.5	96.4±25.7	0.047[2]
Postoperative	75.7±26.5	87.5±25.8	0.012[2]
p-value	0.042[2]	n.s[2]	
		Ecc Q	
	Injured	**Uninjured**	**p**
Preoperative	177.1±58.9	175.5±53.9	n.s[1]
Postoperative	172.7±67.6	186.3±60.6	n.s[1]
p-value	n.s[1]	0.000[1]	
		Ecc H	
	Injured	**Uninjured**	**p**
Preoperative	111.8±35.1	115.9±39.3	n.s[2]
Postoperative	82.1±37.4	120.2±42.5	0.001[2]
p-value	0.000[2]	0.024[2]	
		ConH/ConQ Ratio	
	Injured	**Uninjured**	**p**
Preoperative	0.57±0.11	0.51±0.11	n.s[1]
Postoperative	0.46±0.10	0.47±0.08	n.s[1]
p-value	0.004[1]	n.s[1]	
		EccH/ConQ Ratio	
	Injured	**Uninjured**	**p**
Preoperative	0.71±0.17	0.62±0.17	0.042[2]
Postoperative	0.51±0.20	0.65±0.21	0.019[2]
p-value	0.000[2]	n.s[2]	
		LSI	
	Preoperative	**Postoperative**	**p**
LSI Con Q	0.85±0.17	0.84±0.16	n.s[1]
LSI Con H	0.92±0.16	0.87±0.20	n.s[1]
LSI Ecc Q	1.01±0.18	0.86±0.24	0.010[2]
LSI Ecc H	0.98±0.15	0.70±0.26	0.000[1]

[1]Paired Sample T Test; [2]Wilcoxon Test; SD: Standart deviation.

Table 3. Comparison of preoperative and postoperative knee functional outcome score

	Pre-operative Score	Post-operative Score	p
IKDC Score	61.8±7.6	85.6±5.6	0.000[1]
Lysholm Knee Score	69.4±5.4	85.3±5.1	0.000[1]

[1]Paired Sample T-Test.

Notwithstanding the persistent muscular imbalances, there were notable improvements in knee function postoperatively, as evidenced by increased IKDC and Lysholm scores ($p<0.001$ for both). The IKDC averaged 85.6±5.6, while the Lysholm averaged 85.3±5.1, indicating favorable outcomes. (Functional outcomes are presented in Table 3).

DISCUSSION

This study aimed to elucidate the changes in muscle actions in individuals one year following anterior cruciate ligament (ACL) reconstruction using a hamstring tendon autograft. The results demonstrated that there were persistent challenges in muscle strength recovery. Notably, concentric quadriceps strength was significantly weaker than the uninjured leg, whereas eccentric strength demonstrated greater stability, indicating less impact from the surgery. There was a marked decline in both concentric and eccentric hamstring strength, likely due to harvesting the tendon for the graft. Furthermore, conventional and functional hamstring-to-quadriceps (H/Q) ratios declined following surgery, falling below the recommended normal values. This highlights a significant imbalance that may impact joint stability. Consequently, limb symmetry indices (LSIs) for both muscle contractions remained below the 90% threshold, which is considered normal, thereby underscoring persistent deficits in muscle function. Moreover, the IKDC and Lysholm Knee scores demonstrated substantial improvements from preoperative to postoperative evaluations. These improvements reflected significant enhancements in knee function, stability, pain, and mechanical function, which were statistically significant.

The hypothesis that quadriceps strength is significantly reduced following an ACL injury is supported by the findings of this study. This aligns with the existing literature highlighting atherogenic muscle inhibition as a compensatory mechanism to mitigate the risk of anterior subluxation and subsequent knee damage.[22] Before surgery, there was a notable discrepancy between the strength of the injured and uninjured sides. Following surgery, there was a modest increase in strength on the injured side. Despite a slight increase in strength postoperatively, the injured side did not achieve the strength levels of the uninjured side. This ongoing weakness is primarily attributed to neuromuscular dysfunction and diminished activity levels following ACL injury, further exacerbated by a restricted range of motion during recovery.[20] These findings are consistent with studies that have documented quadriceps muscle strength deficits of 10–27% one-year post-surgery, with deficiencies persisting at 6–10% even beyond five years following the procedure.[8, 20] These persistent deficits can have a negative impact on functional outcomes and increase the risk of re-injury.[20]

Given the potential biomechanical benefits, it is postulated that augmented hamstring strength confers advantages in patients presenting with anterior cruciate ligament (ACL) tears. The hamstrings' contraction can counteract anterior tibial translation, thereby reducing the stress placed upon the injured ligament.[23] Furthermore, it can enhance knee joint compression and provide resistance against external varus/valgus loads, thereby promoting overall stability.[23] It is notable that a decline in hamstring muscle strength on the injured side before surgery was observed in this study, in contrast with the anticipated maintenance or enhancement of hamstring strength due to its compensatory role in ACL deficiency. This may indicate the potential implications of using hamstring tendons for grafting. Moreover, the recovery of hamstring strength appeared less promising. The postoperative strength on the injured side was found to significantly decrease from the preoperative measure, reflecting the substantial impact of HT autografts on knee flexor strength, as previously reported.[24] This evidence supports the hypothesis that HT autografts result in more pronounced deficits in knee flexor strength, which must be addressed more assertively in rehabilitation protocols.

The current study also investigated the effects of ACLR on the H/Q ratios, which are paramount in evaluating the equilibrium between hamstring and quadriceps strength following surgery. The H/Q ratio, a pivotal metric in rehabilitation, indicates the equilibrium between hamstring and quadriceps strength.[25] Two primary assessment methods were employed to evaluate the hamstring-to-quadriceps (H/Q) strength ratio. The conventional H/Q ratio compares peak isokinetic torque values of the hamstrings and quadriceps during concentric contraction. In contrast, the functional H/Q ratio assesses the ratio of peak eccentric hamstring torque to peak concentric quadriceps torque. This functional ratio is designed to reflect how these muscles function more accurately in dynamic activities such as landing and running. Establishing definitive cutoff values for a healthy H/Q ratio remains a challenging task. Studies have reported varying values for the conventional H/Q ratio, ranging from 0.47 to 0.66, and for the functional H/Q ratio, ranging from 0.78 to 1.05, across different speeds. This variability is likely attributable to differences in the methodology employed to determine these cutoff values and variations in the size and characteristics of the populations examined. The conventional H/Q ratio has frequently been established at 60%, originating from the work of Klein and Allman. Subsequently, it gained prominence following Heiser et al.'s[17] demonstration of its efficacy in reducing injuries among American football players.[26, 27] This benchmark has been further supported by a systematic review by Baroni et al.,[16] which concluded that conventional H/Q ratio scores close to the typical reference landmark of 60% are considered suitable. The 100% cutoff has been commonly used to assess agonist-antagonist strength imbalance in athletes, yet there is no support from prospective studies for this normative value.[27] Moreover, findings from the same systematic review conducted by Baroni et al.[16] indicate that H/Q functional ratio scores around 80% should be expected in individuals returning to sports. A low H/Q ratio has been associated with a greater likelihood of experiencing lower limb injuries, such as ACL ruptures and hamstring strains.[24] Understanding these relationships can guide rehabilitation strategies to optimize knee health and reduce reinjury. The findings revealed significant changes in both H/Q ratio types following surgery. These changes highlight the complex and ongoing process of muscle strength recovery after ACL surgery. In line with previous research,[28] it was found that the conventional H/Q ratio, which reflects concentric muscle strength, did not significantly differ between the injured and uninjured sides preoperatively. This suggests a balanced concentric strength profile before ACLR. However, postoperatively, a significant decrease in the conventional H/Q ratio on the injured side was observed. This finding corresponds with the broader literature indicating that ACLR with hamstring tendon autografts can lead to a relative decrease in hamstring strength compared to quadriceps strength.[24] Interestingly, it was found that the functional H/Q ratio was significantly higher in the injured limbs compared to the uninjured limbs preoperatively. This observation resonates with the emerging idea that injuries such as ACL rupture could potentially disrupt the intricate interplay of agonist and antagonist muscles, possibly prompting compensatory changes in eccentric hamstring control to protect the vulnerable joint.[29] Even more striking was the significant reduction in the functional H/Q ratio of the injured limb postoperatively. This suggests a reduction in the relative eccentric strength of the hamstrings compared to the concentric strength of the quadriceps. The specific decrease in the functional H/Q ratio post-surgery is of particular interest. It is plausible that using HT autografts in ACLR contributes to this reduction. This could be due to the harvesting of hamstring tendons, which may affect the eccentric strength capacity of the hamstrings. The postoperative rehabilitation process might also emphasize quadriceps strengthening over hamstring strengthening, further influencing the H/Q ratio.

In the current study, the desired conventional and functional H/Q ratios during the postoperative period could not be achieved. This is likely because these H/Q benchmarks are primarily derived from studies involving professional athletes. The study population consisted of non-professional athletes who likely did not have access to the same intensive and specialized rehabilitation level. Professional athletes often benefit from more frequent rehabilitation sessions, advanced training techniques, and personalized care plans to optimize recovery and performance. Their typically higher baseline conditioning and motivation levels may also contribute to better rehabilitation outcomes. Our rehabilitation protocols, while comprehensive, lacked the same level of personalization and advanced techniques typically afforded to professional athletes, possibly impacting the efficacy of recovery measures. Therefore, the lower H/Q ratios observed in our postoperative patients could reflect these disparities.

Additionally, the Limb Symmetry Index (LSI) was assessed post-ACL reconstruction, highlighting the recovery patterns of muscle strength in concentric and eccentric movements. The literature emphasizes the role of muscle strength restoration in knee extensors and flexors for a successful return to activities that demand significant knee function.[16] Achieving an LSI of ≥90% indicates successful rehabilitation, with strength in the injured limb approaching that of the uninjured side.[19] Grindem et al.[30] highlighted the increased risk of further knee injury when returning to sport with reduced quadriceps strength (LSI<90%). The results indicate that while concentric muscle strength in both quadriceps and hamstrings neared the 90% threshold, displaying relative stability, the eccentric strength remained significantly lower, especially in the hamstrings. This discrepancy highlights a challenge in achieving full recovery in eccentric muscle strength, which is critical given the hamstrings' role in limiting excessive anterior translation of the tibia and preserving rotational stability within the knee.[31, 32]

Furthermore, the choice of autograft significantly influences rehabilitation outcome. The study, focusing on HT autografts, aligns with existing literature that reports greater deficits in knee flexor strength with HT autografts compared to patellar or quadriceps tendon autografts.[33] This information is critical as it suggests that each autograft type may necessitate tailored rehabilitation strategies.

Significantly, a systematic review and meta-analysis by Högberg et al.[34] revealed that while knee flexor strength deficits, defined as less than 90% LSI, are common at one year postoperatively, there is potential for recovery beyond the first year following ACL reconstruction with HT autografts. Moreover, patients following an accelerated rehabilitation protocol showed promising results, achieving ≥90% LSI in knee flexor strength as early as six months postoperatively without adverse events.[35, 36] These findings suggest that earlier and more intensive rehabilitation, particularly of the knee flexors, might be essential for optimal recovery.

Given these insights, the recommendations for future rehabilitation protocols are twofold. First, considering the significant deficits in eccentric hamstring strength observed at the one-year mark, rehabilitation programs should not only continue beyond the first year but also incorporate specific exercises to enhance eccentric strength. Second, the evidence supports the implementation of accelerated rehabilitation protocols emphasizing early and intensive strength training of the knee flexors. This approach could expedite recovery times and improve long-term functional outcomes for patients undergoing ACL reconstruction with HT autografts.

Finally, the study highlights the correlation between muscle strength and knee function outcomes. Notably, a significant decline in hamstring strength, involving both concentric and eccentric contractions, was observed, contrasting with earlier studies that indicated a correlation between IKDC scores and maintained hamstring strength.[37] Similarly, existing research emphasizes the importance of preoperative quadriceps strength as a pivotal factor influencing postoperative outcomes.[38, 39] Studies consistently show a strong correlation between robust preoperative quadriceps strength and improved postoperative results, underscoring that the condition of this muscle before surgery significantly impacts the recovery trajectory and the ultimate restoration of knee function.[20, 40] However, the findings add a new dimension to this narrative, revealing that patients can still achieve favorable functional outcomes post-ACL reconstruction even without marked improvements in muscle strength. The results suggest that a comprehensive rehabilitation program that addresses proprioception, coordination, overall knee stability, and psychological factors can achieve good results, even without dramatic increases in muscle strength.

The study on ACL reconstruction with hamstring tendon autografts has several strengths. It uses a prospective cohort design, tracking patients over time to observe changes in muscle strength and knee function. The focus on hamstring tendon autografts provides specific insights into this popular graft choice. Comprehensive outcome measures, including isokinetic muscle testing, hamstring-to-quadriceps ratios, Limb Symmetry Index, and clinical scores (IKDC and Lysholm), offer a thorough evaluation of recovery. The detailed rehabilitation protocol ensures consistent postoperative care, and rigorous statistical analysis strengthens the reliability of the findings. However, the study also has several limitations that could affect the interpretation and broader applicability of its findings. First, the small sample size of only 17 participants, all of whom were male, may not provide a comprehensive view of the diverse populations affected by ACL injuries. This homogeneity limits the ability to apply the results to broader, more varied populations, including women or individuals from different athletic backgrounds or with different health conditions. Additionally, while prospective studies offer a robust framework for observing changes and outcomes over time, the specific follow-up period of one year in this study might not be sufficient to understand the long-term recovery processes and outcomes fully. Long-term effects, such as sustained muscle strength, rehabilitation successes, or potential chronic complications post-reconstruction, require a more extended observation period to be adequately assessed. Lastly, the absence of a control group makes it difficult to definitively attribute observed outcomes to the specific surgical technique used, limiting the ability to compare it effectively with other interventions. Future research with larger, more diverse samples, longer follow-up periods, and prospective designs could provide a more comprehensive understanding of the long-term effects of ACL reconstruction with hamstring tendon autografts and inform the development of optimized rehabilitation protocols.

The study concludes that one year after ACR using a hamstring tendon autograft, patients still struggle with muscle strength recovery, particularly in the quadriceps and hamstrings. Despite modest improvements in strength, deficits remain compared to the uninjured leg. However, there are significant postoperative improvements in knee function and stability, as indicated by higher knee scores. The findings emphasize the need for targeted rehabilitation to address these ongoing deficits effectively.

DECLARATIONS

Ethics Committee Approval: The Antalya Training and Research Hospital Scientific Research Ethics Committee approved this study (2019/138.12/2).

Informed Consent: Participants provided informed consent for inclusion.

Conflict of Interest: The authors declare that there is no conflict of interest.

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Peer-review: Externally peer-reviewed.

ABBREVIATIONS

ACL - Anterior Cruciate Ligament

H/Q ratio - Hamstring-to-Quadriceps (H/Q) ratio

LSI - Limb Symmetry Index

IKDC - International Knee Documentation Committee

ACLR - Anterior Cruciate Ligament Reconstruction

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Case Report

Concurrent Medial Ramp and Lateral Zip Lesions in ACL-Deficient Knees: A Rare Case Report Highlighting Diagnostic and Surgical Challenges

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ABSTRACT

Anterior cruciate ligament (ACL) injuries are often seen in conjunction with meniscus tears; some of these tears are critical for knee stability, although they can make diagnosis difficult. Ramp lesions of the medial meniscus and zip lesions of the lateral meniscus are examples of this type of injury that require careful arthroscopic evaluation. A 27-year-old male patient presented with pain and instability in his right knee following an injury sustained during football one year prior. Magnetic resonance imaging revealed an ACL tear and a suspected tear in the medial meniscus; however, the lateral meniscus lesion could not be clearly defined preoperatively.

During arthroscopy, the ACL tear, ramp lesion in the medial meniscus, and zip lesion in the lateral meniscus were confirmed. ACL reconstruction was performed using a hamstring autograft. The ramp lesion was repaired with all-inside sutures. A partial meniscectomy was performed on the peripheral zip lesion, and an all-inside repair was applied to the menisco-capsular tear. Ramp and zip lesions are difficult to diagnose both before and during surgery and they may coexist. Adequate repair of these lesions is integral for long-term results, thus the surgeon should approach these lesions carefully and patiently.

Keywords: Knee ınstability, lateral meniscus zip lesion, meniscocapsular tear, meniscal ramp lesion

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INTRODUCTION

Anterior cruciate ligament (ACL) tears are one of the most common sports-related knee injuries and meniscal damage, which often accompanies ACL injuries, has an important place in clinical practice. [1,2,3] Meniscal tears commonly associated with ACL injuries include bucket handle tears, ramp lesions, lateral meniscal posterior root tears (LMPRTs) and lateral meniscal oblique radial tears (LMORTs), some of which are difficult to diagnose and may contribute to knee instability. Several treatment options are available, including meniscal repair, meniscectomy, leave-in-place or meniscal allotransplantation.

Meniscal tears in the presence of ACL injury can affect postoperative functional outcomes and stability if not treated properly. Medial meniscal ramp lesions, which are characterised by tears at the meniscocapsular junction of the posterior horn, are often underdiagnosed but are critical for maintaining knee stability, especially in situations involving rotational instability.[4] Zip lesions (Wrisberg tear, zip tear) are longitudinal vertical/oblique meniscal tears at the junction of the Wrisberg ligament and the posterior horn of the lateral meniscus.[5] Zip lesion has been reported as the equivalent of medial sided ramp lesion.[5] Failure to diagnose or inadequate repair of the posterior lateral meniscal zip lesion may cause instability and ACL graft failure thereafter.[6]

These combined injuries pose a significant challenge in diagnosis and treatment due to their subtle clinical presentation and complex biomechanical effects. Since untreated meniscal injuries may jeopardise the long-term outcome of ACL surgery, proper identification and treatment of these lesions during anterior cruciate ligament reconstruction (ACLR) is essential to restore knee stability and function. We report a rare case of ACL rupture with both a medial meniscal ramp lesion and a lateral meniscal zip lesion.

CASE REPORT

A 27-year-old male patient presented to our clinic in August 2023 with complaints of right knee pain and instability for one year after a rotational injury during a football match. On physical examination, tenderness was noted in both the lateral and medial joint lines of the right knee. Knee stability tests including anterior drawer, Lachman and pivot shift tests were positive. Medial and lateral McMurray tests were also positive. Plain radiographs showed no bone pathology, while magnetic resonance imaging (MRI) showed femoral avulsion of the ACL. In addition, a longitudinal tear of the posterior horn of the medial meniscus and a suspicious tear of the posterior horn of the lateral

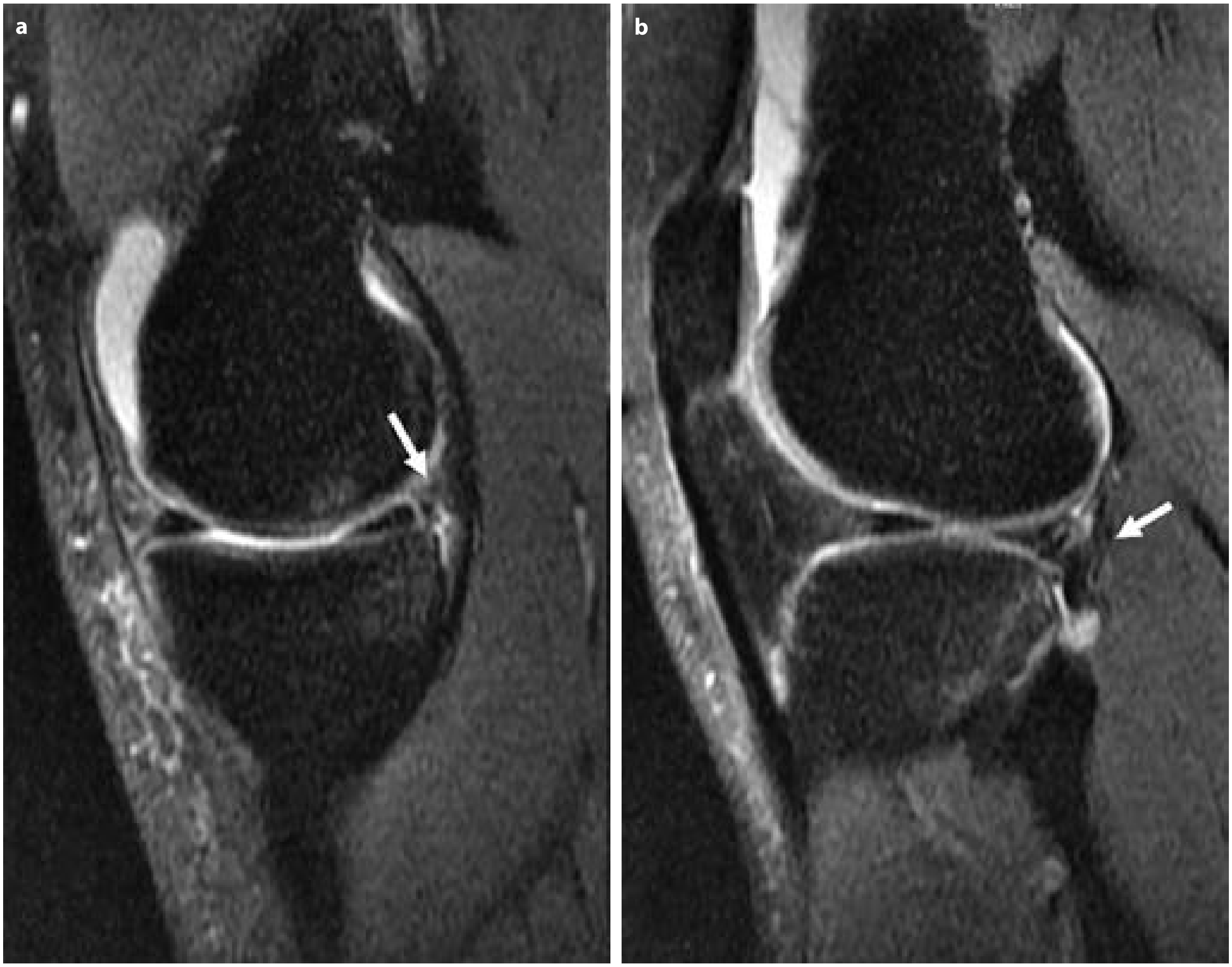

Figure 1. (a) Sagittal T2-weighted MRI showing a longitudinal tear in the posterior horn of the medial meniscus (white arrow) consistent with a ramp lesion. **(b)** Sagittal T2-weighted MRI showing a suspicious tear in the posterior horn of the lateral meniscus (white arrow) suggestive of a possible zipper lesion.

meniscus were observed (Fig. 1). The preoperative diagnosis of the lateral meniscal tear could not be definitively established.

Surgical Management

Following informed consent, arthroscopic surgery was performed under spinal anaesthesia in the supine position using a tourniquet. Intraoperative arthroscopic evaluation revealed a longitudinal tear (ramp lesion) [7] in the meniscocapsular region of the posterior medial meniscus and two longitudinal tears (zip lesions) [8] in the meniscocapsular region and periphery of the posterior lateral meniscus (Fig. 2).

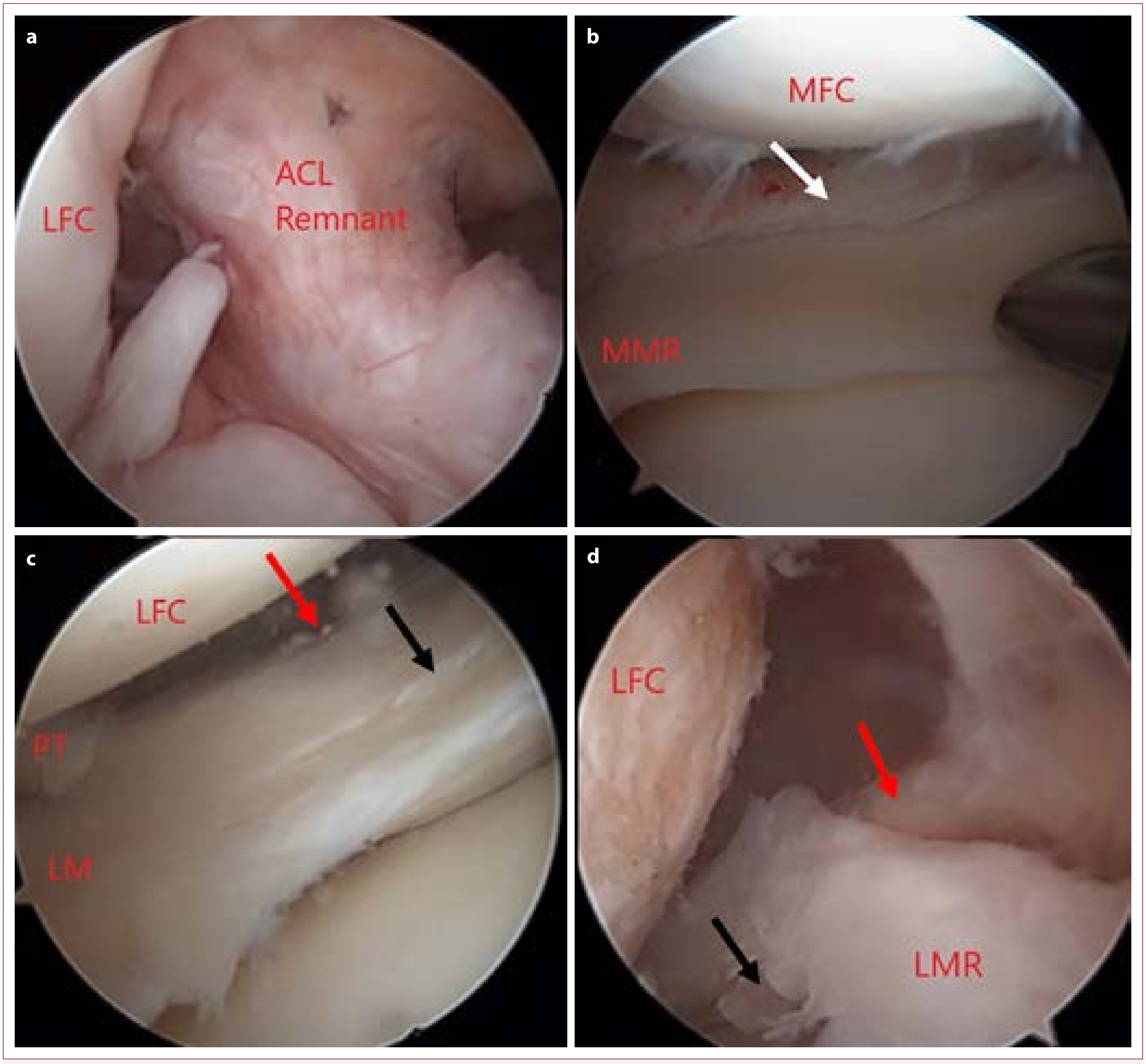

Figure 2. (a): Ruptured anterior cruciate ligament. **(b)**: Arthroscopic view showing a longitudinal tear (ramp lesion) in the meniscocapsular region of the posterior medial meniscus (white arrow). **(c)**: Lateral portal view of two longitudinal tears (zip lesions) of the posterior lateral meniscus in and around the meniscocapsular region. The proximal tear is indicated by the red arrow and the peripheral tear by the black arrow. **(d)**: Medial portal view of the zip lesion.

We performed all inside ACLR using hamstring autograft. For the ramp lesion, all-inside meniscal sutures were used for fixation. For the zip lesion, a partial meniscectomy was performed on the peripheral tear and the meniscocapsular tear was repaired using all-inside meniscal sutures (Fig. 3).

Postoperative Rehabilitation

The rehabilitation programme focused on progressive weight-bearing and strengthening exercises. Early weight bearing was started cautiously, followed by gradual strengthening of the knee musculature to restore functionality.

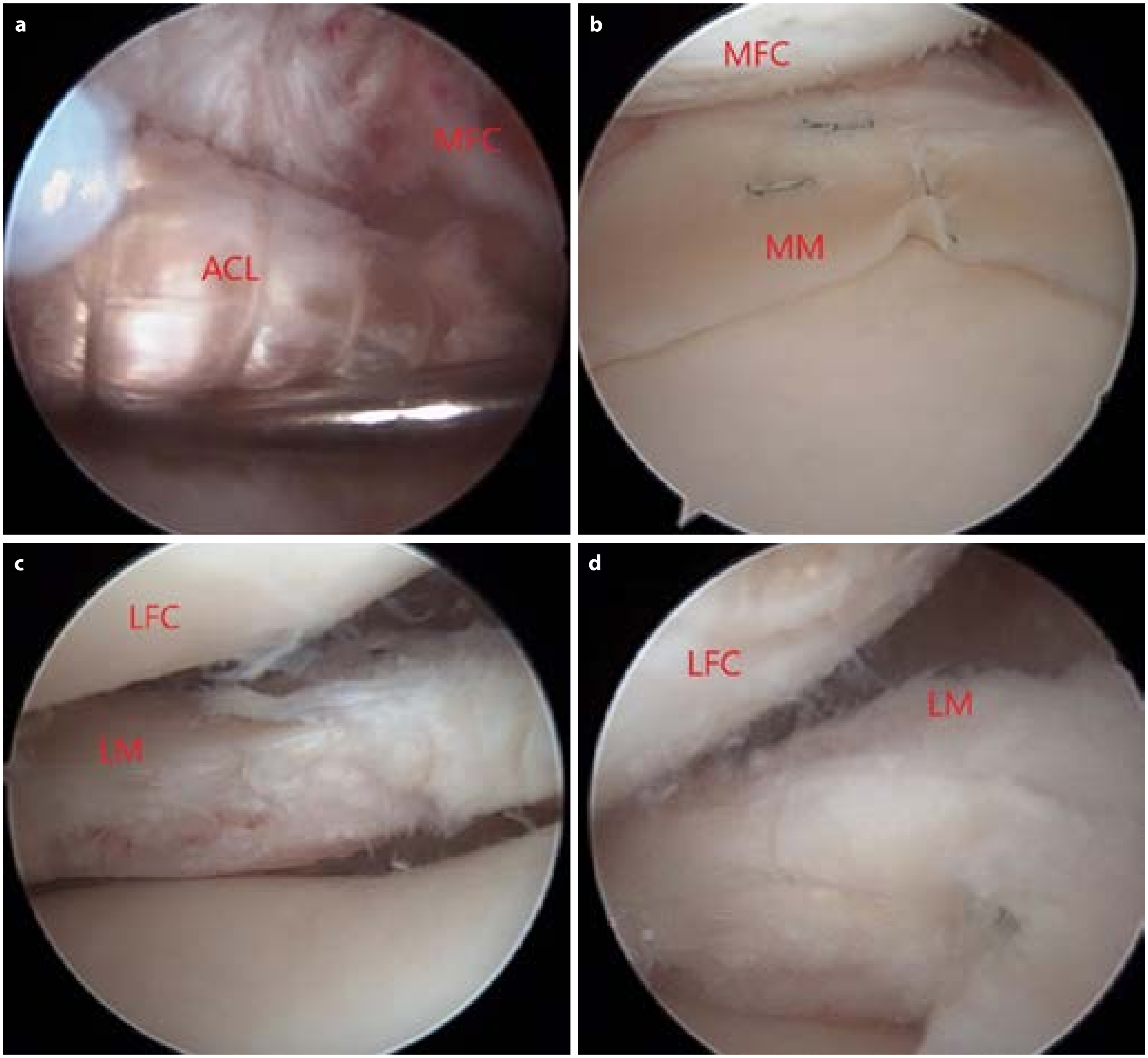

Figure 3. (a): Reconstruction of the anterior cruciate ligament ACL with hamstring autograft using a all inside technique. **(b)**: Repair of the medial meniscal ramp lesion with all inside sutures. **(c)**: View of the peripheral tear of the lateral meniscus after meniscectomy. **(d)**: All inside suture repair of the central tear of the lateral meniscus.

DISCUSSION

This case highlights the importance of comprehensive arthroscopic evaluation in ACL-deficient knees, as concomitant meniscal lesions significantly affect stability and outcomes. Ramp and zip lesions, although difficult to detect preoperatively, should be carefully addressed to optimise the success of ACLR.

Meniscal ramp lesions are increasingly recognised as an important comorbidity in ACL injuries, with reported prevalence rates ranging from 9.3% to 42% among ACLR patients.[9,11] Despite their clinical importance, these lesions are often underdiagnosed preoperatively and are missed up to 50% of the time (cases) on MRI scans.[9] Posteromedial tibial bone bruising has emerged as a useful indirect indicator to suspect ramp lesions in such cases, as studies report that up to 72% of ACLR patients with this MRI finding exhibit ramp lesions during arthroscopy.[9] Ramp lesions are particularly difficult to identify and repair during standard arthroscopic evaluations due to limited visualisation of the posterior horn and medial meniscocapsular junction through the anterior portals.[12] This limitation often results in inadequate assessment and surgical repair, potentially compromising the stability and long-term outcome of ACLR. The necessity of advanced arthroscopic posteromedial exploration to detect and repair these lesions cannot be overstated.

Similar to ramp lesions, zip lesions are difficult meniscal injuries to diagnose.[8] Clinical examination of the knee and MRI have limited accuracy in detecting these lesions.[8,13] These diagnostic difficulties and limited data in the literature lead to uncertainties regarding the classification and management of zip lesions. Therefore, a systematic evaluation of the posterolateral region is important during ACLR. It has been reported that detailed examination of the meniscal surfaces during arthroscopy and use of the anteromedial portal may increase surgical success by enabling the recognition and appropriate treatment of zip lesions.[8]

Untreated ramp lesions may lead to residual anteroposterior laxity [5], while zip lesions contribute to rotational instability [6] and they can both jeopardise ACLR results.

CONCLUSION

Ramp and zip lesions are difficult to diagnose both before and during surgery and they may coexist. Adequate repair of these lesions are integral for long term results thus the surgeon should approach these lesions carefully and patiently.

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Review

Meniscus Root Tears: Current Concepts in Anatomy, Diagnosis, and Treatment Strategies

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ABSTRACT

Meniscal root tears are defined as radial tears or avulsions of the meniscal attachment within 1cm of its insertion on the tibial plateau. These injuries disrupt the meniscus' ability to convert axial loads into circumferantial hoop stresses, resulting in increased tibiofemoral contact pressure and accelerated osteoarthritis. Medial meniscus posterior root tears are the most commonly encountered type, generally associated with degenerative diseases. Lateral meniscus root tears (MRT), on the other hand, are mostly associated with acute injuries of younger patients. Diagnosis can be challenging due to nonspecific clinical symptoms, necessitating a combination of thorough physical examination, patient history, and high-resolution imaging. Treatment strategies have evolved from partial meniscectomy to MRT repair, which is now considered the gold standard. Techniques such as transtibial pullout and suture anchor repair aim to restore the native anatomy and function of the meniscus. Postoperative protocols are evolving, but typically involve restricted weight-bearing and range of motion for the initial weeks. As understanding of meniscal root pathology continues to grow, further research is needed to refine surgical techniques and establish evidence-based rehabilitation protocols.

Keywords: Hoop stress disruption, meniscal root tear, osteoarthritis progression, transtibial pullout repair

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INTRODUCTION

MRTs are radial tears or avulsions occurring within 1 cm of the meniscal attachment to the tibial plateau, where the meniscus anchors to bone and transmits axial loads into circumferential hoop stresses to stabilize the joint structure.[1,2] The meniscal roots have an essential role for proper functioning of the menisci and, in turn, knee biomechanics.[3,4] A tear in meniscal roots leads to an increased tibiofemoral pressure and contact area.[5,6]

Failure of MRTs accordingly leads to progressive joint degeneration, as hoop stress dissipation becomes ineffective. It has been accepted in the literature that meniscal root tears are equivalent to meniscectomy biomechanically.[7] Long-term follow-up studies have demonstrated a significantly increased rate of osteoarthritis and need for total knee arthroplasty in patients with untreated root tears compared to those who underwent anatomical repair.[8] Furthermore, non-anatomic repair of meniscal roots induces similar results.[9] Therefore, treatment modalities for meniscal root pathologies have shifted focus towards preserving and repairing to return the menisci to their native origin.[10]

Anatomy of the Meniscus Root Attachments

The fan-shaped anterior horn of medial meniscus has been reported to have the largest and strongest footprint of any meniscus root attachments.[1,11] It inserts in line with medial tibial eminence roughly 7 mm anterior to the anterior cruciate ligament (ACL) tibial insertion.[11] Berlet and Fowler described 4 different insertion types in this area, describing a potential link with the ACL.[12]

The posterior root attachment of the medial meniscus inserts anteromedial to the tibial attachment of the posterior cruciate ligament(PCL).[13] "Shiny white fibers", first reported by Anderson et al.[14], are supplemental posterior based fibers named after their brilliant appearance on arthroscopy. Early approximations of the attachment of the posterior root were 47.2 mm^2 and 80 mm^2, while recent studies reported areas of 30.4 mm^2 and 68 mm^2, a reduction caused by exclusion of the shiny white fibers from the root attachment.[8,11]

The anterior root of the lateral meniscus is smaller compared to that of medial meniscus. The attachment is found anterior to the lateral tibial eminence and laterally to the tibial insertion of the ACL.[8,15] An attachment between the anterior horn of the lateral meniscus with the bundles of the ACL was reported in previous studies.[11]

The attachment of the lateral meniscus posterior root is found directly anterior to that of medial meniscus posterior root.[8,11,16] The posterior root of the lateral meniscus was reported to be the smallest among all root atachments; however, with the exclusion of the shiny white fibers from the medial meniscus posterior root attachment, some studies suggested that the medial meniscus posterior root may have the smallest area.[8]

Epidemiology

MRTs hold particular clinical significance among all meniscal injuries, accounting for approximately 20% of all meniscal tears.[17] However, with growing interest in the diagnosis and treatment of meniscal root tears, it is increasingly believed that their true prevalence is significantly higher than what is currently reported in the literature.[1]

The anterior attachments of both roots are shown to be more mobile and therefore less susceptible to injury compared to the posterior attachments. Degenerative posterior root tears of the medial meniscus have been reported as the most common type of meniscal root tears, likely due to the limited mobility of the medial meniscal posterior root compared to other root attachments.[8] Studies have shown that individuals with certain risk factors—such as sedentary patients over the age of 50 and those with lifestyles involving prolonged sitting or frequent squatting with legs in a flexed position—are more prone to developing medial MRT.[1,8]

The lateral meniscus is nearly twice as mobile as the medial meniscus, resulting in a reduced role in knee stabilization and making it less susceptible to stress-related injuries.[18] However, participation in sports activities—particularly pivoting and contact sports—has been identified as a significant risk factor for lateral MRT.[19]

Clinical Features

Diagnosing MRTs requires a comprehensive evaluation that combines clinical signs and symptoms with a detailed patient history, as the presentation is often nonspecific and lacks high sensitivity.[20]

Clinical Presentation

MRTs often present with vague and nonspecific symptoms, making clinical diagnosis challenging. Patients typically report posterior knee pain exacerbated by deep flexion, squatting, or climbing stairs.[21] In degenerative cases, symptoms may have an insidious onset, whereas acute root tears may be associated with a sudden "pop" or giving-way episode.[22]

Physical Examinaton

Physical examination findings include tenderness along the joint line, a positive McMurray and Apley test, and pain during deep flexion. Effusion may be present but is often minimal in chronic tears. It is essential to perform a comprehensive physical examination, as meniscal root tears may be associated with other knee injuries.[8,21,22]

Radiological Imaging

X-Ray

The first recorded MRT in the literature dates back to 1935, when Weaver described ossification of the semilunar cartilage.[17] Despite advancements in radiology and the growing interest in advanced imaging techniques such as MRI, plain radiographs—including anteroposterior, lateral, Merchant view, and orthoroentgenograms—remain essential in the evaluation and preoprative planning of MRT.

Orthoroentgenograms are a fundamental component of preoperative evaluation in patients with suspected MRT for through assesment of the limb alignment, joint space, and intraarticular deformity.

The Kellgren-Lawrence (KL) grading system is commonly used to assess the severity of osteoarthritis, ranging from grade 0 (normal) to grade 4 (severe joint space narrowing and osteophyte formation).[23] Studies showed positive correlation between the KL grade and severity of the meniscus extrusion in the MRI.[23]

Mechanical tibiofemoral angle is the angle between mechanical axes of the femur and tibia. It is known that varus deformity increases load distribution to the medial meniscus.

Mikulicz line, a term used for the mechanical axis of the lower limb, is drawn from the center of the femoral head to the center of the ankle. Physiologically, this line runs 4±2mm medial to the center of the knee. Medial deviation indicates varus and lateral deviation indicates valgus of the knee.[24]

In knees exhibiting varus or valgus malalignment, several radiographic measurements are available to help determine the origin of the deformity, which is critical for accurate surgical planning.

Joint line convergence angle (JLCA) is the angle between the lines drawn between femoral condyles and tibial plateaus. It runs almost parallel in physiological condition. JLCA deviations indicate intra-articular origin of the malalignment, especially lateral laxity.[25] JLCA increases progressively with osteoartrhitis progression.[26]

The mechanical medial proximal tibial angle (mMPTA) and the lateral distal femoral angle (mLDFA) help determine whether the malalignment originates from the tibia or the femur. These angles are defined as the intersection between the respective joint line and the corresponding mechanical axis.[27] Normal values for these angles are 85°-90°. An increased mMPTA indicates that the varus deformity originates from the tibia and may suggest the need for a high tibial osteotomy(HTO).[24]

Precise preoperative calculation of these values is essential to avoid overcorrection or undercorrection and to optimize outcomes following meniscal root repair, especially when combined with alignment correction procedures.

Magnetic Resonance Imaging (MRI)

MRI remains the gold standard imaging technique for diagnosing MRTs, having the highest sensitivity and specifity.[8] The diagnosis is affected by the skill level of the radiologist as well as the quality of the MRI. There are direct and indirect signs that can guide specialists for the diagnosis. T2-weighted sections are considered to be the best section to detect a meniscal tear.[1]

Direct MRI signs of meniscal root tears include high signal intensity replacing the normally dark meniscal tissue in the root region on axial, the cleft sign on coronal (Fig. 1), and the ghost sign, which is the absence of an identibiable meniscus on sagittal T2-weighted images.[17,22]

Indirect signs include parameniscal cysts, subchondral bone marrow edema and meniscal extrusion of >3mm.[28] Meniscus extrusion is defined as a complete or incomplete detachment of meniscus from the tibial attachment site.[1]

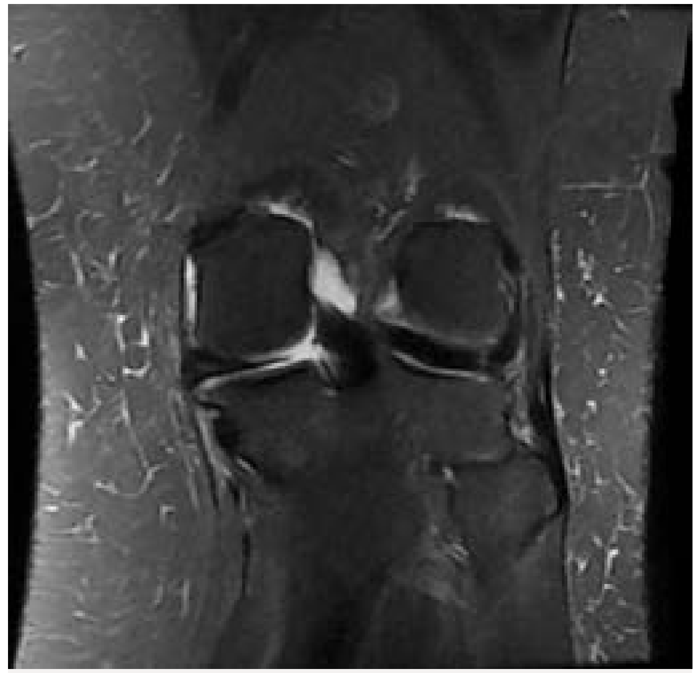

Figure 1. A coronal T2-weighted MRI section of a 50 year old female patient with a degenerative medial menicus posterior root tear (Optima MR450 GE, Matrix 512*512)

(Fig. 2) Although being a significant sign of a MRT, it could also indicate articular cartilage degeneration, severe meniscal degeneration and a complex meniscal tear.[29] That is why, not all cases with meniscal extrusion should be attributed to a MRT.

Although MRI is the most sensitive and specific imaging modality for diagnosing meniscal tears, some MRTs may still be missed during interpretation. Thus, arthroscopic visualization still remains as the gold standart for diagnosis.[17]

Ultrasound (US)

Ultrasound is a non-invasive, dynamic imaging modality that may assist in detecting meniscal extrusion or joint effusion, particularly in follow-up assessments or resource-limited settings. However, moderate to significant heterogeneity exists among studies evaluating the use of ultrasound, likely due to variations in equipment, scanning techniques, and radiologist experience.[30] "Dynamic extrusion" can be assessed by measuring the change in meniscal extrusion from the supine to the standing position; minimal change in this measurement, often referred to as the "dead meniscus sign," is suggestive of an MRT.[31] While ultrasound may be considered a complementary diagnostic tool for meniscal root tears, it currently lacks the resolution to visualize deep intra-articular structures as clearly as MRI.

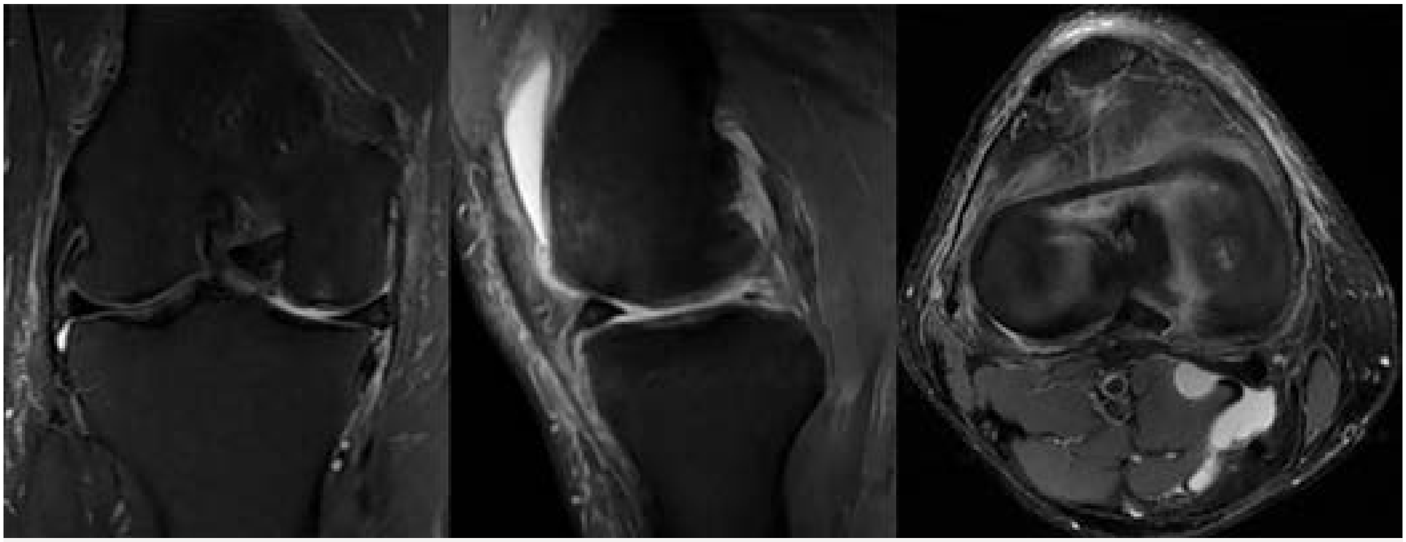

Figure 2. MRI sections of a 55 year old male patient with a degenerative medial menicus posterior root tear (Optima MR450 GE, Matrix 512*512). a) meniscal extrusion at the level of medial collateral ligament in the T2-weighted coronal section, b) 'ghost sign' showing the loss of meniscal structure in the T2-weighted sagital section, c) high signal intensity at the posterior root replacing the dark meniscal tissue in Proton Density (PD)-weighted axial section.

Treatment Algorithm

The management of MRTs depends on patient-specific factors including age, activity level, degree of cartilage degeneration, mechanical alignment, and the chronicity of the tear. While non-operative options may be appropriate in select cases, root repair remains the gold standard for restoring native biomechanics and preventing progression of osteoarthritis in suitable candidates. Two main techniques used to fix the roots are transtibial pullout and suture anchor techniques.[8] Centralization is a newer technique aiming to reduce the extrusion of the meniscus.[32] Combining the repair with high tibial osteotomy is indicated for suitable patients with concomitant varus malalignment. The treatment modalities are detailed in the subsequent section, and a comparative summary of the advantages and disadvantages associated with each surgical technique is presented in Table 1.

Table 1. Comparison of Surgical Techniques for Meniscal Root Tears

Surgical Technique	Advantages	Disadvantages
Transtibial Pullout Repair	• Provides anatomic reduction • Well-established technique • Good long-term outcomes	• Technically demanding • Risk of tunnel widening • Requires implants
Suture Anchor Repair	• No tibial tunnel needed • Reproducible technique • Shorter surgical time	• Posteromedial portal access can be challenging • Higher implant cost
Centralization	• Reduces meniscal extrusion • Restores biomechanics • Promising outcomes	• Technically complex • Steep learning curve • Limited long-term data
Root Repair with HTO	• Corrects varus malalignment • Reduces medial compartment overload	• Two-stage procedure • Prolonged rehabilitation • Higher complication risk
Partial Meniscectomy	• Shorter operative time • Rapid symptom relief	• Accelerates osteoarthritis progression • Loss of meniscal function

Non-Operative Treatment

Non-operative management may be considered in patients with advanced articular cartilage damage and for those who are not medically fit for surgery such as obese and elderly with comorbidites.[1] The management includes activity modification, nonsteroidal anti-inflammatory drugs (NSAIDs), weight loss, physical therapy, and intra-articular injections. However, several longitudinal studies have demonstrated that untreated root tears significantly increase the risk of joint space narrowing and conversion to total knee arthroplasty within 5 years.[33,34]

Operative Treatment

Partial Meniscectomy

Partial meniscectomy no longer remains as the gold standart treatment protocol for MRTs as it is now known that anatomical repair of the meniscus is mandatory to preserve its function to delay osteoarthritis. However, advanced osteoarthritis and chondral damage, severe malalignment and instability are contraindiciations for repairing meniscal roots.[17,33] In these patients who do not benefit from conservative methods, partial meniscectomy could be preferred in order to provide symptom relief. It should be acknowledged that although patients' pain is relieves in short-term, the consequence is development of further osteoarthritis invariably.[17]

Root Repair with Transtibial Pullout Technique

This technique is considered the gold standart treatment for MRTs since it provides a better anatomical reduction, which is shown to be the main indicator for proper functioning of the meniscus and restoration of knee biomechanics.[1,7,8,22] This technique involves drilling a tunnel from anterior proximal tibia to the meniscus root attachment site. Sutures are passed from the meniscal root and pulled through the tunnel and secured on anterior proximal tibia with a suture anchor or a cortical button.[17,32] (Fig. 3)

Root repair with suture anchor

In this technique, sutures are passed through meniscus and secured into the underlying tibia with a suture anchor via posteromedial portal.[32] This method eliminates the need for a guide and tunnel during repair and offers a reproducible technique.[35] Studies showed that both transtibial pullout and suture anchor techniques restore contact pressure and delay further osteoarthritis.[36]

Centralization

This technique has been proposed due to increased attraction towards meniscus extrusion and its role in potential early osteoarthritis.[37] The procedure involves suturing the meniscus-capsule complex to the underlying tibial plateau with the aim of reducing meniscal extrusion.[22] (Fig. 4) Studies showed reduced extrusion in short term postoperative MRIs of these patients.[38] Moreover, it was demonstrated that this technique could restore meniscus biomechanics and reduce further osteoarhritis.[39] However, it still remains as a technically demanding procedure requiring a systemic approach and experience.[40]

Figure 3. Arthroscopic images of a medial meniscus posterior root tear and repair with transtibial pullout technique.

Combining root repair with HTO

MRT repair alone could not be sufficient when there is a varus abnormality and a significant deviation of the mechanicl axis. Such tears are associated with medial femorotibial compartment degenerative changes and extrusion >3mm.[41]

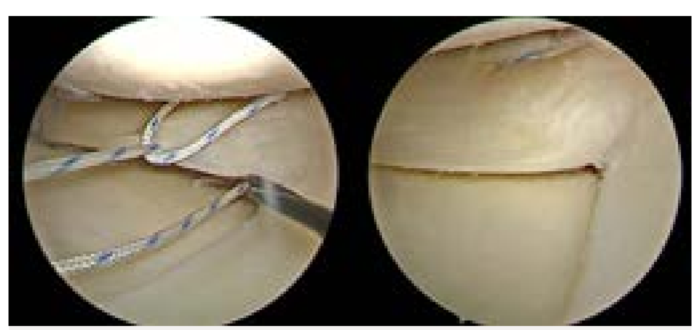

Figure 4. Arthroscopic images of the centralization technique.

HTO can be combined with root repair in such cases in order to reduce the stress distribution on the medial meniscus caused by the deformity thus acellerating the healing process. Patients with varus alignment less than 5° were confirmed to have better results with HTO compared to the ones with higher varus degrees.[42] However, studies have reported varying outcomes regarding whether to perform isolated root repair or to combine it with HTO, and the optimal approach remains a subject of ongoing debate.[43] Several studies have also evaluated the outcomes of isolated HTO versus combined HTO and MRT repair. While short-term results were similar between the two groups, the addition of MRT repair was shown to favor improved meniscal healing and cartilage scores, supporting a combined approach.[44]

Postoperative Rehabilitation

The optimal postoperative rehabilitation protocol following MRT repair remains a subject of ongoing debate among surgeons. Some studies recommend maintaining full knee extension for the first two weeks, followed by a gradual increase in passive flexion, with active flexion permitted starting in the fourth week up to 90°.[1] It is widely accepted that flexion beyond 90° places additional stress on the repaired root.[45] Majority of the protocols doe not recommend full weight bearing until 6 weeks after the surgery.[46]

The International Delphi Consensus published in 2025 emphasized the critical role of postoperative rehabilitation in optimizing outcomes following MRT repair.[47] A structured rehabilitation protocol that began with range of motion exercises and progressive muscle strengthening was deemed essential. In accordance with the current literature, the consensus recommended restricting full weight-bearing during the first 4–6 weeks postoperatively. Furthermore, passive deep knee flexion was advised to be limited during this period, with a gradual increase thereafter.

The postoperative protocol used by the senior author of this study is individualized for each patient, with priority given to restoring range of motion. Full weight bearing is prohibited until the sixth week, in accordance with protocols reported in other studies. However, if the repair demonstrates sufficient stability, active flexion and extension exercises are initiated within a 0–90° range using a knee brace on postoperative day 1. The brace is worn for six weeks. Beginning in the sixth week, range of motion is progressively increased under the guidance of the physiotherapy and rehabilitation department.

CONCLUSION

MRTs have gained particular importance in recent years, as it is now well established that untreated or non-anatomically repaired root tears result in biomechanical consequences equivalent to total meniscectomy.[8]This leads to altered load distribution across the knee joint and accelerates the progression of osteoarthritis. Early diagnosis is critical and relies on a thorough physical examination, careful assessment of patient-specific risk factors, and detailed radiological evaluation, particularly with MRI.

Historically, partial meniscectomy was the preferred treatment method; however, it is now recognized that meniscal preservation offers superior long-term outcomes. Consequently, repair techniques—especially anatomic transtibial pullout or suture anchor methods—are now considered the gold standard for managing meniscal root tears.[22] These techniques aim to restore the native biomechanics of the meniscus and prevent further joint degeneration.

DECLARATIONS

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