Original Research

# Prospective MRI-Based Comparison of Graft Maturation After ACL Reconstruction Using Quadriceps Versus Hamstring Tendon Autograft

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**Background:** Biological graft maturation after anterior cruciate ligament (ACL) reconstruction is a prolonged and heterogeneous process that may not directly correlate with clinical recovery. Magnetic resonance imaging (MRI)–based signal intensity ratio (SIR) is widely used as an indirect marker of graft remodeling and early maturation. However, comparative data regarding MRI-based graft maturation between quadriceps tendon (QT) and hamstring tendon (HT) autografts remain limited.

**Purpose:** To compare graft maturation between all–soft tissue QT autografts and HT autografts using quantitative MRI-based SIR at 6 and 12 months after primary all-inside ACL reconstruction in athletes.

**Study Design:** Cohort study; Level of evidence, 2.

**Methods:** A total of 76 athletes undergoing primary all-inside ACL reconstruction were prospectively enrolled. QT autografts were used in 39 patients and HT autografts in 37 patients. All patients followed a standardized postoperative rehabilitation protocol and underwent 3.0-T MRI evaluation at 6 and 12 months. Graft maturation was assessed using SIR measurements obtained from standardized regions of interest along the intra-articular graft, with the posterior cruciate ligament used as reference. Interobserver reliability was evaluated using intraclass correlation coefficients (ICCs).

**Results:** Baseline patient characteristics and associated surgical procedures did not differ between groups (all $P > .05$). At both 6 and 12 months postoperatively, the mean SIR values were similar between QT and HT autografts ($P > .05$). Within-group analysis showed a significant decrease in SIR values from 6 to 12 months in both groups ($P < .05$), indicating progressive graft maturation. The magnitude of SIR change did not differ between groups ($P > .05$). Interobserver reliability was excellent, with ICC(2,1) values of 0.98 at 6 months and 0.98 at 12 months.

**Conclusion:** Quantitative MRI-based assessment using SIR demonstrated no significant difference in graft maturation between all–soft tissue QT and HT autografts at 6 and 12 months after primary all-inside ACL reconstruction. Both graft types showed comparable MRI-based maturation profiles during the early postoperative period, supporting QT autografts as a reliable alternative to HT autografts in athletic populations.

**Registration:** NCT06617559 (ClinicalTrials.gov identifier).

**Keywords:** knee ligaments; ACL; biology of ligaments

Anterior cruciate ligament (ACL) reconstruction is one of the most frequently performed surgical procedures to restore knee stability and enable a safe return to sport (RTS). Although the clinical outcomes after primary ACL reconstruction are generally satisfactory, it has been shown that surgical success does not depend only on mechanical stability, and that the biological healing of the graft plays a critical role in long-term outcomes.[6,15] Therefore, graft selection and the biological behavior of the graft during the postoperative period are of critical importance for functional recovery and RTS after ACL

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reconstruction.[2] Hamstring tendon (HT) and quadriceps tendon (QT) autografts are among the most frequently used graft options today, and both grafts have their own biomechanical and biological advantages.[13,20]

After ACL reconstruction, the graft undergoes a complex and time-dependent remodeling process known as ligamentization. This process includes phases of graft necrosis, revascularization, cellular repopulation, and progressive reorganization of collagen fibrils.[6,15] Experimental and clinical studies have demonstrated that the ligamentization process may continue for months or even years, and that biological maturation of the graft can progress independently from the improvement of clinical symptoms.[6,15,24] For this reason, evaluating the biological status of the graft based only on clinical examination and functional tests may be insufficient, and objective and noninvasive methods for monitoring graft maturation have become more important.

Magnetic resonance imaging (MRI) is the most commonly used imaging method for evaluating graft maturation after ACL reconstruction. Quantitative MRI parameters, particularly signal intensity–based measurements, are considered indirect indicators reflecting the biological status of the graft. Among these, signal intensity ratio (SIR) is one of most frequently used measurement methods in literature, allowing normalization of graft signal intensity relative to reference structures such as the posterior cruciate ligament (PCL) and background signal.[9,17] Lower SIR values are associated with decreased water content and increased collagen organization within the graft, and are therefore interpreted as indicators of more advanced graft maturation.[3,17,27]

Previous studies have demonstrated that graft signal intensity changes dynamically over time after ACL reconstruction. It has been reported that MRI signal intensity generally increases in the early postoperative period, followed by a gradual decrease as the maturation process progresses.[12] Longitudinal studies have suggested that the postoperative sixth month corresponds to the peak graft remodeling phase, whereas the twelfth month represents an early maturation stage.[2,6] However, there are considerable interindividual differences, and the relationship between graft signal changes and clinical or functional outcomes is still not clearly defined.

Studies comparing graft maturation between different autograft types using MRI are limited in number, and existing findings are heterogeneous. While relatively more studies have focused on HT autografts, the biological healing process of QT autografts has been investigated in fewer reports. Because of the larger cross-sectional area, higher collagen content, and different histological structure of the QT, it has been suggested that the remodeling process of this graft may differ from that of HT grafts.[7,22]

The purpose of this prospective cohort study was to compare graft maturation in athletes who underwent primary all-inside ACL reconstruction using all–soft tissue QT autografts or HT autografts, based on quantitative MRI assessment using SIR obtained at 6 and 12 months postoperatively. We hypothesized that QT autografts would demonstrate similar or more advanced graft maturation compared to HT autografts within the first postoperative year.

## METHODS

### Study Design

This was a single-center, prospective cohort study conducted at the Department of Orthopaedics and Traumatology, Acıbadem Fulya Hospital. Consecutive patients evaluated with an ACL injury after March 1, 2024, and undergoing primary ACL reconstruction with either QT autograft or HT autograft were enrolled. Patient enrollment was completed on November 15, 2024, and the study period ended after all patients had completed a minimum follow-up of 12 months. The study was prospectively registered on ClinicalTrials.gov before recruitment (registration date: September 23, 2024; identifier: NCT06617559). Ethical approval was obtained from the Acıbadem Mehmet Ali Aydınlar University Institutional Review Board (approval No. 2024-4/134), and all participants provided written informed consent. The study adhered to the Declaration of Helsinki.

### Patient Population

Athletes >18 years with a primary ACL rupture confirmed by clinical examination and MRI were eligible. Recreational, amateur, and elite-level athletes were included, provided they underwent primary ACL reconstruction using either QT or HT autograft and could comply with standardized postoperative rehabilitation and MRI evaluations at 6 and 12 months. Exclusion criteria included revision ACL reconstruction, multiligamentous knee injuries requiring surgical repair, Outerbridge grade ≥2 chondral

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lesions,[25] previous ipsilateral knee surgery, open physes, peri-articular fractures, or inflammatory arthropathy.

## Group Allocation

Patients were allocated to the QT or HT autograft group using an alternating sequence, a quasi-randomized method commonly applied in prospective surgical cohort studies to maintain balance while preserving clinical workflow feasibility. Consecutive eligible patients received alternating graft types. An a priori sample size calculation was performed based on expected differences in SIR values between groups, informed by previously published MRI-based ACL graft maturation studies.[1,18,23] Given the heterogeneity of the reported findings and the lack of consistently reported effect sizes in the literature, a moderate effect size (Cohen $d = 0.6$) was assumed. Using a 2-sided alpha level of .05 and a statistical power of 80%, a minimum of 25 patients per group was required to detect a statistically significant difference between groups.

## Surgical Techniques

A single senior surgeon (Ö.T.) with substantial experience performed all surgical interventions. Patients were positioned supine in a standard arthroscopy setup with a pneumatic tourniquet applied to the proximal thigh. Each procedure began with a diagnostic knee arthroscopy examination to confirm the ACL tear and to identify and treat any concomitant meniscal or chondral lesions as indicated. In group 1, an all–soft tissue QT autograft was used, whereas in group 2, quadruple-looped HT autografts were utilized. All patients underwent single-bundle, all-inside ACL reconstruction. An anteromedial portal approach was used for femoral tunnel preparation. Using appropriate femoral and tibial guides, we prepared the femoral and tibial sockets at the native ACL footprints with a FlipCutter device (Arthrex). The graft was introduced through the anteromedial portal, seated within the femoral socket, and secured with a TightRope suspensory fixation device, after which the tibial end was passed through the tibial socket and fixed using the same system.

## Postoperative Rehabilitation

A standardized, criterion-based rehabilitation protocol was applied to all patients. Quadriceps isometric activation, ankle pumps, and patellar mobilization began immediately. Full knee extension was encouraged from postoperative day 1, and flexion was advanced as tolerated. Weightbearing with crutches was permitted as tolerated, and the patient progressed to full weightbearing by 2 to 3 weeks. Closed-chain strengthening and neuromuscular exercises were initiated once full extension and adequate quadriceps control were achieved, typically by the third to fourth week. Progressive strengthening focused on hip-core synergy, kinetic chain control, and balance. Light jogging was permitted at 3 to 4 months if full range of motion, minimal effusion, and satisfactory strength symmetry were demonstrated. Plyometrics and sport-specific functional training were introduced after 6 months. RTS was allowed only after postoperative month 9 and required fulfillment of the following criteria: near-symmetric isokinetic strength, stable ligamentous examination, absence of effusion, and satisfactory MRI-based graft maturation.

## Clinical Evaluation

Follow-up evaluations were conducted at standardized intervals of 2 and 6 weeks and 3, 6, and 9 months, as well as at the RTS assessment. Range of motion was evaluated at each follow-up visit, with specific attention to recovery of full extension and gradual improvement in flexion. Knee stability was assessed using Lachman and pivot-shift tests, and anterior tibial translation was quantified with a KT-1000 arthrometer as side-to-side difference under standardized loading conditions.

At approximately 9 months, quadriceps and hamstring isokinetic strength testing was performed using a Cybex dynamometer at angular velocities of 60 and 180 deg/s. RTS clearance was based on combined clinical strength and functional criteria. All data were entered into the institutional electronic medical record system.

## MRI Protocol and Graft Maturation Analysis

MRI (Magnetom Skyra; Siemens Healthineers) was performed at 6 and 12 months after surgery, representing validated time points for evaluating peak graft remodeling (6 months) and early maturation (12 months). Previous histological and MRI-based studies have demonstrated that graft remodeling activity peaks around 6 months after ACL reconstruction, whereas progressive signal normalization consistent with early maturation is typically observed by 12 months.[1,2,12] All studies were performed using a 3.0-T superconducting magnet with a dedicated phased-array knee coil. Sagittal proton-density fast spin-echo images, along with sagittal and coronal T2-weighted sequences, were acquired using a slice thickness of 2.0 to 3.0 mm without interslice gap, a field of view of 14 to 16 cm, a matrix size of 384 × 256, a bandwidth ranging from 15 to 20 kHz, repetition times of 3500 to 5000 milliseconds, and echo times of 20 to 36 milliseconds.

Quantitative graft maturation was assessed using the SIR, a validated radiological marker of ligamentization.[1,18,23] SIR measurements were performed on sagittal T2-weighted fast spin-echo images. On the sagittal image demonstrating the maximal intra-articular portion of the graft, circular regions of interest (ROIs) were positioned at the proximal, midsubstance, and distal segments of the graft. A single reference ROI was placed at the tibial insertion of the PCL (Figure 1). Mean signal intensities (SIs) were recorded, and the mean SI of the 3 graft ROIs was calculated and normalized to the PCL signal intensity to obtain the SIR (SIR = graft SI/PCL SI). When the graft and PCL insertion were not visible on the same slice, measurements were obtained from the closest adjacent sagittal

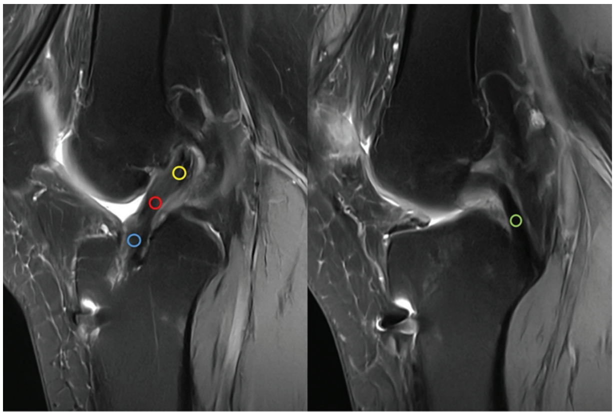

**Figure 1.** Representative sagittal T2-weighted magnetic resonance images demonstrating region of interest (ROI) placement for signal intensity ratio measurements. Circular ROIs were placed at the proximal (yellow), midsubstance (red), and distal (blue) portions of the intra-articular graft. A reference ROI was placed at the tibial insertion of the posterior cruciate ligament (PCL) (green). When the graft and PCL insertion were not visible on the same slice, measurements were obtained from adjacent sagittal slices demonstrating each structure.

slices demonstrating each structure. Lower SIR values were interpreted as more advanced graft maturation.

Using the Sectra IDS7 PACS, 2 musculoskeletal radiologists who were blinded to clinical data independently obtained all measurements. Measurement reliability was analyzed using 2-way mixed-effects intraclass correlation coefficients (ICCs), with an ICC threshold of 0.75 indicating acceptable agreement. For statistical analysis, the mean of the 2 observers' measurements was used as the final SIR value at each time point.

## Statistical Analysis

Continuous variables are expressed as mean ± standard deviation. Between-group comparisons were performed using independent-samples *t* tests, and within-group comparisons using paired-samples *t* tests. Categorical variables were analyzed using chi-square or Fisher exact tests as appropriate. Correlations were assessed using Pearson correlation coefficients. Interobserver reliability was evaluated using ICC(2,1). Statistical significance was set at a *P* value <.05.

## RESULTS

The final analysis included a total of 76 patients. Group 1 (QT) consisted of 39 patients, whereas group 2 (HT) consisted of 37 patients. All participants completed the standardized postoperative rehabilitation program and underwent MRI assessments at both 6 and 12 months after surgery

TABLE 1
Baseline Patient and Clinical Characteristics[a]

| Variable | QTA (n = 39) | HTA (n = 37) | *P* Value |
|---|---|---|---|
| Age, y | 25.8 ± 5.5 | 26.9 ± 5.5 | .38 |
| BMI, kg/m$^2$ | 23.8 ± 1.7 | 23.6 ± 1.8 | .71 |
| Graft diameter, mm | 9.0 ± 0.5 | 8.7 ± 0.5 | .075 |
| 6-mo SSD, mm | 2.27 ± 0.72 | 2.26 ± 0.93 | .95 |
| 12-mo SSD, mm | 1.87 ± 0.78 | 1.97 ± 0.79 | .57 |
| Tegner score | 95.6 ± 3.5 | 94.9 ± 3.4 | .40 |
| IKDC score | 90.7 ± 4.4 | 90.2 ± 3.8 | .62 |
| Medial PTS, deg | 6.44 ± 0.94 | 6.24 ± 1.09 | .41 |
| Lateral PTS, deg | 8.51 ± 1.05 | 8.84 ± 1.07 | .18 |
| Meniscal procedure, n (%) | 13 (33.3) | 13 (35.1) | >.99 |

[a]Data are presented as mean ± SD unless otherwise indicated. Continuous variables were compared using the independent-samples *t* test. BMI, body mass index; HTA, hamstring tendon autograft; IKDC, International Knee Documentation Committee; PTS, posterior tibial slope; QTA, quadriceps tendon autograft; SSD, side-to-side difference.

TABLE 2
MRI-Based Graft Maturation Assessed by SIR[a]

| Time Point | QTA (n = 39) | HTA (n = 37) | *P* Value |
|---|---|---|---|
| 6 mo | 2.86 ± 0.78 | 3.06 ± 0.83 | .296 |
| 12 mo | 2.19 ± 0.66 | 2.24 ± 0.58 | .707 |

[a]Data are presented as mean ± SD. Between-group comparisons were performed using the independent-samples *t* test (Welch correction). HTA, hamstring tendon autograft; MRI, magnetic resonance imaging; QTA, quadriceps tendon autograft; SIR, signal intensity ratio.

Baseline patient and clinical parameters, including age, sex distribution, body mass index, involved side, side-to-side difference, and RTS status, did not differ significantly between the 2 groups (all *P* > .05). The frequency of concomitant meniscal procedures did not differ significantly between the 2 groups (*P* > .05) (Table 1).

Quantitative MRI analysis based on SIR demonstrated a similar temporal pattern of graft signal evolution in both groups. In the QT autograft group, mean SIR values decreased significantly from 6 months (2.86 ± 0.78) to 12 months (2.19 ± 0.66) postoperatively (*P* < .001). Likewise, the HT autograft group showed a significant reduction in mean SIR values between 6 months (3.06 ± 0.83) and 12 months (2.24 ± 0.58) (*P* < .001).

The mean SIR values were comparable between the 2 groups at both the 6-month and 12-month evaluations, with no statistically significant differences observed (*P* = .296 and *P* = .707, respectively) (Table 2). These findings indicate progressive graft maturation over time in both groups, without a detectable difference between graft types within the first postoperative year (Figure 2). Within-

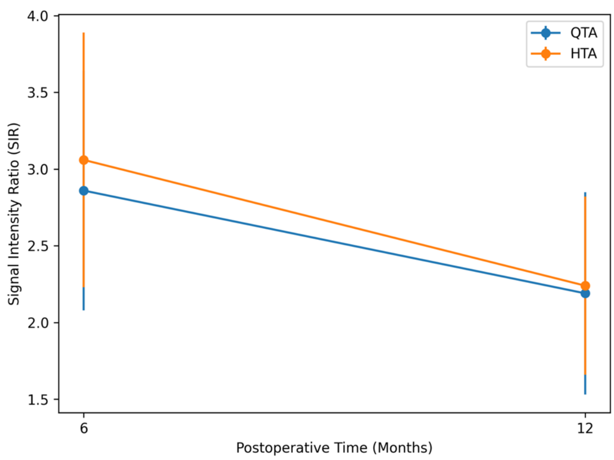


**Figure 2.** Changes in magnetic resonance imaging–based signal intensity ratio (SIR) values at 6 and 12 months after anterior cruciate ligament reconstruction using quadriceps tendon autograft (QTA) and hamstring tendon autograft (HTA).

group analysis demonstrated a significant decrease in SIR values from 6 to 12 months in both the QT and HT autograft groups (both $P < .001$).

Both groups demonstrated a significant decrease in SIR values between 6 and 12 months, indicating progressive graft maturation. No significant differences were observed between graft types at either time point.

Interobserver reliability for SIR measurements was excellent. ICCs demonstrated high measurement reproducibility, with ICC(2,1) values of 0.98 at 6 months and 0.98 at 12 months. In exploratory analyses, no significant association was found between SIR values at 12 months and objective anterior knee laxity measured by side-to-side difference using a KT-1000 arthrometer (Pearson $r = -0.045$; $P = .699$). Similarly, SIR values at 12 months did not differ significantly between patients who returned to sport and those who did not ($P = .297$).

## DISCUSSION

The primary finding of the present study was that graft maturation, assessed using quantitative MRI-based SIR, did not show a significant difference between all–soft tissue QT autografts and HT autografts 6 or 12 months after primary all-inside ACL reconstruction. These results suggest that both graft types demonstrate comparable MRI-based maturation profiles during the first postoperative year when evaluated using a standardized and reproducible imaging metric.

Graft healing after ACL reconstruction, commonly referred to as ligamentization, is a complex and prolonged biological process.[6,15,24] Histological and experimental studies have demonstrated that this process may extend well beyond the first postoperative year, and that graft biological maturation does not necessarily parallel clinical recovery or restoration of mechanical stability.[4,5,11,14] Claes et al[6] emphasized that ligamentization is a gradual and heterogeneous process, with substantial interindividual variability, even under similar surgical and rehabilitation conditions. Our findings are consistent with this concept, as neither graft type demonstrated a clear biological advantage during the early maturation window assessed in this study. The absence of a detectable difference in SIR between QT and HT grafts in the present study suggests that early MRI-based signal changes may follow similar trajectories regardless of autograft type.

MRI is currently the most widely used noninvasive modality for monitoring ACL graft maturation. Among MRI-based parameters, SIR has gained particular relevance because it normalizes graft signal intensity to reference tendon, thereby reducing scanner- and protocol-dependent variability.[1,2,8,9,14] Changes in SIR are believed to reflect alterations in graft water content, vascularity, and collagen organization, with lower SIR values generally indicating more advanced graft maturation.[4,19,28] Lower SNQ and SIR values have been associated with more advanced graft maturation and improved structural properties in both animal models and human studies. Grassi et al[9] highlighted that MRI signal normalization is a gradual phenomenon and that graft signal often remains hyperintense compared with the native ACL for up to 12 months or longer, particularly during periods of active remodeling. The absence of significant differences between quadriceps and hamstring grafts in the present study is consistent with these observations and suggests that early MRI signal characteristics may reflect similar patterns of graft maturation across graft types.

Comparative data on MRI-based graft maturation between different autograft types are still limited, and previously published results have been heterogeneous. Aitchison et al[1] demonstrated lower SIR values for QT autografts compared with HT autografts at 12 months in a pediatric population, suggesting potentially more advanced maturation of QT grafts with time. Similarly, Panos et al[22] reported a significant decrease in MRI signal intensity of QT grafts between 3 and 9 months postoperatively, whereas HT grafts showed relatively stable signal characteristics during the same period. In contrast, our study did not demonstrate a significant intergroup difference at either 6 or 12 months. These differences between studies may be explained by variations in patient populations, surgical approach, graft preparation methods, imaging time points, and MRI analysis protocols. Importantly, our cohort consisted of adult athletes undergoing an all-inside reconstruction technique with standardized rehabilitation, which may have contributed to a more homogeneous biological response between graft types.

Another important consideration is that MRI-based graft maturation metrics, including SIR, do not always correlate with clinical outcomes or knee stability.[16] Lutz et al[18] demonstrated that although ACL graft signal intensity changes significantly over time, these changes are not consistently associated with patient-reported outcome scores or objective laxity measurements. These findings are supported by earlier studies showing that grafts with persistent MRI hyperintensity may still provide satisfactory clinical stability and function.[16,28] Therefore, the absence of a difference in SIR values between graft types in the present study does not imply equivalence or inferiority in clinical performance, but rather highlights the limitations of MRI as a stand-alone surrogate for functional graft integrity, particularly during the early postoperative period. In line with these observations, the present study did not demonstrate a significant association between MRI-based graft maturation assessed by SIR at 12 months and either objective anterior knee laxity or RTS status. This finding suggests that MRI signal characteristics may be more closely related to graft remodeling as reflected by imaging features rather than functional readiness or mechanical stability.

From a clinical perspective, the comparable SIR-based maturation profiles observed in this study suggest that both QT and HT autografts are biologically acceptable options for primary ACL reconstruction in athletic populations. With increasing interest in QT autograft because of its favorable biomechanical properties, larger cross-sectional area, and potentially lower donor site morbidity, our findings provide additional reassurance that early graft biological behavior is not compromised when compared with traditional HT grafts.[10,21,26] This observation is in agreement with previous clinical studies reporting similar graft failure rates, knee stability, and functional outcomes between QT and HT autografts.

Several limitations of this study should be acknowledged. First, although the prospective design and standardized MRI protocol strengthen the validity of our findings, the study sample size may be insufficient to detect subtle differences in SIR values between groups. Second, MRI evaluations were limited to 6 and 12 months postoperatively; longer follow-up may demonstrate different maturation trajectories beyond the first year. Third, while SIR is a widely used and validated parameter, it remains an indirect measure of graft biology and may be influenced by imaging parameters and ROI selection. Finally, clinical outcomes were not directly correlated with MRI findings in the present analysis, which limits interpretation of the functional relevance of imaging findings. However, the absence of major complications such as graft rerupture, arthrofibrosis, or impingement in either group during follow-up may indirectly suggest comparable early mechanical stability between graft types.

## CONCLUSION

This prospective cohort study demonstrated no significant difference in MRI-based graft maturation between all–soft tissue QT autografts and HT autografts at 6 and 12 months after primary all-inside ACL reconstruction. These findings suggest that both graft types demonstrate similar MRI-based maturation profiles during the early postoperative period and support the use of QT autografts as a viable alternative to HT autografts in athletic patients. Future studies with larger cohorts, longer follow-up, and combined clinical-radiological assessment are needed to better understand graft-specific maturation characteristics and their clinical implications.

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