MRI Assessment of Tendon Graft After Lateral Ankle Ligament Reconstruction

Does Ligamentization Exist?

Guillaume Cordier,*†‡ MD, PhD(c), Sofiane Boudahmane,§ MD,
Jordan Ovigue,‖ MD, Frederick Michels,‡¶# MD, PhD, Gustavo Araujo Nunes,‡** MD, PhD(c),
and Benjamin Dallaudiere,§†† MD, PhD
Investigation performed at Clinique du Sport, Vivalto Santé, Bordeaux-Merignac, France

Background: No description exists in the literature about the normal evolution of tendon graft after a lateral ankle ligament (LAL) reconstruction.

Purpose: To assess the magnetic resonance imaging (MRI) characteristics and the evolution of the tendon graft during different moments in the follow-up after an endoscopic reconstruction of the LAL.

Study Design: Cohort study; Level of evidence, 3.

Methods: This prospective study included 37 consecutive patients who underwent an endoscopic reconstruction of the LAL with an autograft using the gracilis tendon to treat chronic ankle instability (CAI) resistant to nonoperative treatment (CAI group) and 16 patients without ankle instability (control group). All patients in the CAI group underwent a postoperative assessment at 6, 12, and 24 months using the Karlsson score and MRI examination. Only patients with good and excellent results were included in the study. Graft assessment consisted of qualitative measurements and quantitative evaluations of the reconstructed anterior talofibular ligament (RATFL) and reconstructed calcaneofibular ligament (RCFL), including signal-to-noise quotient (SNQ) and contrast-to-noise quotient (CNQ) measurements in proton density–fat suppressed (PD-FS) and T1-weighted sequences. The analysis of variance test was used to compare the SNQ and the CNQ at different time points for each sequence.

Results: The MRI signal at 6 months was increased compared with that of the control group. Next, a significant signal decrease from 6 to 24 months was noted on PD-FS and T1-weighted images. SNQ measurements on PD-FS weighted images for both the RATFL and the RCFL demonstrated a significantly higher signal ($P < .01$ and $P = .01$, respectively) at 6 months compared with that of the control group. Subsequently, the signal decreased from 6 to 24 months. Similarly, CNQ measurements on PD-FS weighted images for both the RATFL and the RCFL demonstrated a significantly higher signal ($P < .01$ and $P < .01$, respectively) at 6 months compared with that of the control group. Subsequently, the signal decreased from 6 to 24 months.

Conclusion: The present study demonstrated an evolution of the MRI characteristics, suggesting a process of graft maturation toward ligamentization. This is important for clinical practice, as it suggests an evolution in graft properties and supports the possibility of creating a viable ligament.

Keywords: lateral ankle ligament; chronic ankle instability; ligamentization; ligament reconstruction; magnetic resonance imaging; signal-to-noise quotient; tendon graft healing

Chronic ankle instability (CAI) is a common complication after an ankle sprain.[14] Surgical treatment is considered in case of remaining symptoms despite adequate nonsurgical treatment.[28] Anatomic repair and reconstruction are the 2 preferred surgical techniques.[32,36] In recent years, arthroscopic anatomic repair techniques have been increasingly published.[6,34] Although anatomic ligament repair is still the most commonly performed technique, some relative contraindications exist.[7] In those cases, a reconstruction of the lateral ankle ligaments (LAL) should be considered. This involves reconstructing the anterior talofibular ligament (ATFL) and the calcaneofibular ligament (CFL). Recently, an endoscopic technique for ligamentous reconstruction has been developed.[12] The validity of this technique has been confirmed by anatomic[27] and clinical studies.[7,13,25] Although ankle ligament reconstruction using tendon graft has already proved its ability to restore functional properties over time, there is no literature about the normal evolution of tendon graft. It is unknown whether this reconstructed ligament undergoes a maturation process resulting in native ligament

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properties.[19] In anterior cruciate ligament (ACL) reconstruction (ACLR), the postoperative magnetic resonance imaging (MRI) aspect of the tendon graft showed an evolution according to its state of maturation.[15,33] Ligamentization research for reconstructed ACLs showed an evolution of MRI signals comparable with histological changes.[38] The T1-weighted sequence is used to assess the morphological aspect, while the proton density–fat suppressed (PD-FS) sequence is used to assess the tissue's inflammatory level and healing stage. Therefore, in ankle ligament reconstruction, the normal evolution of the MRI aspects of tendon graft may be very useful in assessing the process of graft maturation. This information may be useful to guide the rehabilitation process and return to sports, such as after ACLR in the knee.[2,23,26] These data are also useful for developing MRI criteria that can be used as a reference to assess postoperative imaging after LAL endoscopic reconstruction.

This study aimed to describe the MRI aspects and the evolution of tendon graft after an endoscopically reconstructed ATFL (RATFL) and CFL (RCFL). A group of patients was examined in terms of the short-, mid-, and long-term MRI features and clinical outcomes. This study hypothesized that a postoperative MRI analysis of tendon graft after an LAL reconstruction (LALR) would allow the assessment of graft remodeling and demonstrate ligamentization signs.

METHODS

This study included 37 patients who underwent an endoscopic reconstruction of the LAL. All patients operated in our institution between September 2016 and June 2018 were tested for eligibility. This single-center cross-sectional study was approved by the ethics and research committee of Clinique du Sport, Bordeaux-Merignac, France (No. 09.2017.13), and patients gave informed consent.

The inclusion criteria were persistent reports of ankle instability despite a nonsurgical treatment for ≥6 months. The exclusion criteria were earlier ankle surgery or ankle fractures and additional procedures modifying the postoperative protocol (calcaneal osteotomy for hindfoot varus, gastrocnemius lengthening). The diagnosis of mechanical ankle instability was confirmed via clinical tests, including positive anterior drawer and talar tilt. Diagnosis of ATFL and CFL ruptures was confirmed via ultrasound. All patients were operated on by the same surgeon (G.C.), an experienced foot and ankle surgeon. The surgical procedure involved ligament reconstruction of the ATFL and the CFL using a gracilis tendon autograft. Fixation was provided by a tenodesis screw in the talus, an interference screw in the calcaneus, and an Endobutton (Tight rope ACL RT; Arthrex). in the fibular tunnel.[27] Postoperatively, an ankle brace was indicated for 4 weeks, night and day, and gradually removed over 15 days. Partial weightbearing was permitted. Physical therapy was begun immediately, with a protocol allowing full weightbearing at 2 weeks and nonweightbearing sports at 6 weeks postoperatively (swimming or cycling). Running was introduced progressively from 3 months. The return to competition took place around 5 months.

All included patients underwent a postoperative clinical assessment, including the Karlsson score at 6, 12, and 24 months, by an orthopedic surgeon (J.O.). At the same times, an MRI was performed. As the study focused on the normal evolution of the reconstructed ligaments, only patients with good or excellent clinical scores were included (Karlsson >80). The MRI aspects of the reconstructed ligaments in the study group were compared with the normal ligaments of a control group of 16 patients without a history of instability reports, sprains, or ankle surgery.

MRI Evaluation Protocol

MRI examinations were performed using a 1.5 tesla MRI scanner Optima GEM450 (GE Healthcare) comprising 3 conventional axial, sagittal, and coronal views in PD-FS and T1-weighted sequences (Table 1).

Imaging data were collected once for the control group and 3 times (at 6, 12, and 24 months postoperatively) for the CAI group. MRI images were assessed in consensus by a musculoskeletal radiologist and an independent foot and ankle surgeon (S.B. and J.O.). All measurements were performed in the central part of the ligaments (Figure 1).

The normal ATFL and CFL were assessed in the control group. The RATFL and RCFL were evaluated in the CAI group.

For qualitative analysis, the general impression of the graft signal was given as a "low," "intermediate," or "high" signal.

For quantitative analysis, regions of interest (ROIs) of 6 pixels were placed in the ATFL, CFL, fat, muscle, and talar bone, as well as in the void on axial images at 6, 12, and ≥24 months. For both axial T1 and PD-FS sequences, the

*Address correspondence to Guillaume Cordier, MD, PhD(c), Clinique du Sport, Vivalto Santé, Bordeaux-Merignac, France; MIFAS by GRECMIP (Minimally Invasive Foot and Ankle Society); 2 rue Negrevergne, Merignac, 33700, France (email: docteurcordier@yahoo.fr).
†Clinique du Sport, Vivalto Santé, Bordeaux-Merignac, France.
‡MIFAS by GRECMIP (Minimally Invasive Foot and Ankle Society), Merignac, France.
§Centre d'Imagerie Ostéo-articulaire, Clinique du Sport de Bordeaux-Merignac, Merignac, France.
||Clinique du Sport de Bordeaux-Merignac, Merignac, France.
¶Orthopaedic Department, AZ Groeninge, Kortrijk, Belgium.
#EFAS, ESSKA-AFAS Ankle Instability Group.
**Cote Brasília Clinic, DF, Brasilia, Brazil.
††Centre de Résonance Magnétique des Systèmes Biologiques, Université de Bordeaux, Bordeaux, France.
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TABLE 1
Summary of MRI Sequence Parameters[a]

	TR, ms	TE, ms	Nex	FOV, cm	Thickness, mm	Spacing, mm	Slices, n	Duration
Axial T1	3.130	minimum	3	17	3.5	1	20	1 min 08 s
Axial PD-FS	3.083	45	3	17	3.5	1	20	1 min 57 s
Sagittal PD-FS	2.500	45	2	16	3.5	0.5	17	2 min 35 s
Coronal PD-FS	3.344	45	4	17	3.5	0.5	22	2 min 47 s

[a]FOV, field of view; MRI, magnetic resonance imaging; Nex, number of excitations; PD-FS, proton density–fat suppressed; TE, time to echo; TR, repetition time.

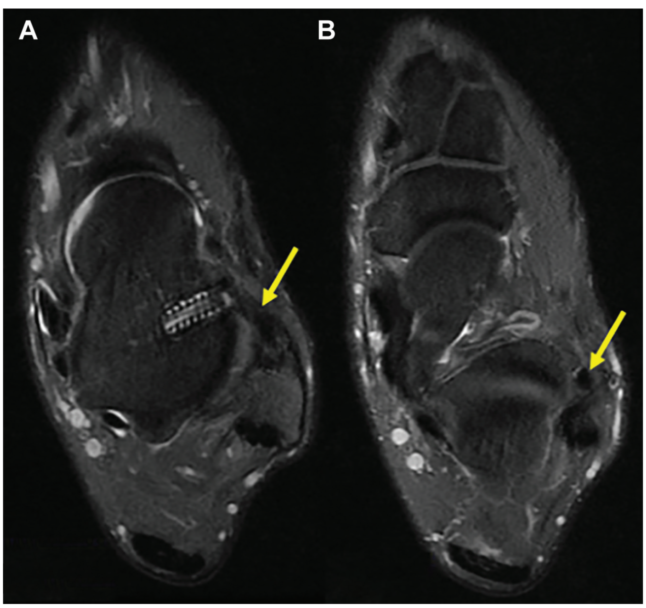

Figure 1. Area of reconstructed anterior talofibular ligament signal measurements (A) and area of reconstructed calcaneofibular ligament signal measurements (B) are indicated by yellow arrows.

signal-to-noise quotient (SNQ) and the contrast-to-noise quotient (CNQ) of the different limbs were evaluated. The SNQ was determined by dividing the mean pixel value over the ROI by the standard deviation of the noise. The Gaussian noise standard deviation was calculated as the standard deviation of the signal measured in a background ROI on the magnitude image divided by 0.695. This value was used to correct the Rayleigh distribution of noise for a 4-element phased-array coil, as shown by Constantinides et al.[5] The CNQ was also determined by subtracting the SNQ of the 2 closer neighboring ROIs (ATFL/fat, CFL/fat).

Statistical Analysis

Statistical analysis was performed using R Software (R Core Team). Categorical data are expressed as fractions (percentages). SNQ and CNQ data were normally distributed. Means were calculated and used for comparison between groups. Therefore, we used an analysis of variance test to compare SNQ and CNQ at different times for each sequence. $P < .05$ was considered significant.

RESULTS

A total of 37 patients were initially enrolled in the CAI group (Table 2). Also, SNQ and CNQ data are presented in Tables 3 and 4, respectively.

MRI assessments were conducted at 6, 12, and 24 months on 36, 30, and 20 patients, respectively (Figure 2). Sixteen patients were also included in the control group.

Image Analysis of Normal and Reconstructed Ligaments

Qualitative Assessment. The normal ATFL and CFL from the control group showed a thin band structure and a low signal in all sequences (Figure 3). The RATFL and RCFL showed a thicker linear band structure than did the normal anatomic ATFL and CFL.

All signal measurements of reconstructed ligaments were compared with those of the control group. The control group demonstrated a low signal for both ligaments in all sequences.

The signal of the RATFL and RCFL was high at 6 months and decreased between 6 months and 24 months postoperatively on PD-FS (Figures 4 and 5, respectively) and T1-weighted images (Figures 6 and 7, respectively).

The qualitative results of the CAI are summarized in Figure 8.

Quantitative Assessment. SNQ and CNQ measurements of RATFL and RCFL were compared with those of the control group corresponding to the qualitative visual analysis assessment.

Analysis of SNQ. Normal ATFL and CFL have SNQ measurements of 16.9 ± 3.4 and 17.8 ± 6.8 in PD-FS, respectively, and 8.2 ± 2 and 11.3 ± 2.9 in T1-weighted images, respectively. All SNQ measurements in the CAI group are summarized in Figure 9.

On PD-FS images, SNQ measurements for RATFL and RCFL demonstrated a significantly higher signal ($P < .01$ and $P = .01$, respectively) at 6 months compared with that of the control group. The SNQ for RATFL decreased significantly between 6 to 24 months postoperatively ($P < .0001$). The SNQ for the RCFL also decreased significantly between 6 and 12 months ($P = .04$) and between 6 and 24 months ($P < .0001$).

TABLE 2
Patient Characteristics of the CAI and Control Groups[a]

Variable	All Patients (N = 37)	6 mo (n = 33)	12 mo (n = 29)	24 mo (n = 20)	Control Group (n = 16)
Age, mean (SD), y	43 (6.7)	43 (6.9)	42 (5.7)	44.5 (5.3)	38.5 (18)
Sex, n (%)					
Male	23 (62.2)	21 (63.6)	17 (58.6)	14 (70)	10 (62.5)
Female	14 (37.8)	12 (36.4)	12 (41.4)	6 (30)	6 (37.5)
Side, n (%)					
Right	24 (64.9)	21 (63.6)	18 (62)	14 (70)	6 (37.5)
Left	13 (35.1)	12 (36.4)	11 (38)	6 (30)	10 (62.5)
Karlsson, mean (SD)	91.5 (8.7)	91.5 (8.7)	90.7 (6.8)	98.2 (3.4)	100 (0)

[a]CAI, chronic ankle instability.

TABLE 3
Data of Signal-to-Noise Quotient[a]

Ligament	MRI	Control Group	6 mo	12 mo	24 mo
ATFL	PD-FS	9 ± 2.7	32.4 ± 7.5	24.1 ± 5.9	22.3 ± 10.8
	T1	8.2 ± 2	38.5 ± 5.9	36.7 ± 4.4	35 ± 8.7
CFL	PD-FS	12.2 ± 5.5	20.1 ± 4.6	17.4 ± 5.2	17 ± 8
	T1	11.3 ± 2.9	33.3 ± 5.5	32.6 ± 5.5	29.7 ± 8.6

[a]Data are presented as mean ± SD. ATFL, anterior talofibular ligament; CFL, calcaneofibular ligament; MRI, magnetic resonance imaging; PD-FS, proton density–fat suppressed.

TABLE 4
Data of Contrast-to-Noise Quotient[a]

Ligament	MRI	Control Group	6 mo	12 mo	24 mo
ATFL	PD-FS	30.1 ± 10	8.2 ± 8.2	–4.7 ± 11.3	–8.4 ± 7.8
	T1	173.1 ± 46.9	–92 ± 26.7	–104.5 ± 22	–118.1 ± 39.8
CFL	PD-FS	26.8 ± 8.2	–4 ± 6.8	–11.3 ± 10.5	–13.6 ± 7.8
	T1	169.8 ± 47.2	–99.4 ± 26.8	–110.5 ± 22.7	–126.5 ± 40.2

[a]Data are presented as mean ± SD. ATFL, anterior talofibular ligament; CFL, calcaneofibular ligament; MRI, magnetic resonance imaging; PD-FS, proton density–fat suppressed.

No significant SNQ variation was found on T1-weighted images.

Analysis of the CNQ. CNQ measurements on PD-FS were −15.9 ± 11.8 and −15.1 ± 8.3, respectively, for the normal ATFL and CFL and 173 ± 46.9 and 169.8 ± 47.2, respectively, for T1-weighted images. All CNQ measurements in the CAI group are summarized in Figure 10.

On PD-FS images, CNQ measurements at 6 months for both the RATFL and the RCFL confirmed a significantly higher signal than that of the control group ($P < .01$ and $P < .01$, respectively). The CNQ for the RATFL decreased significantly from 6 to 24 months ($P = .0001$). The CNQ for the RCFL significantly decreased from 6 to 24 months ($P = .02$).

On T1-weighted images, CNQ measurements for the RATFL and the RCFL demonstrated a significantly higher signal ($P < .01$ and $P < .01$, respectively) at 6 months compared with that of the control group. The CNQ for the RATFL decreased from 6 to 24 months ($P = .03$). The CNQ for the RCFL decreased from 6 to 24 months ($P = .04$).

DISCUSSION

The present prospective study assessed the MRI characteristics of a tendon graft in a cohort of patients with good clinical outcomes. It demonstrated an evolution of the MRI aspects of the tendon graft after an ATFL and CFL reconstruction. Compared with that of the control group, the MRI images showed a high occurrence of high signal at 6 months and a signal decrease from 6 to 24 months. This evolution suggests a process of graft maturation.

The native ATFL and CFL, as well as the normal semitendinosus and normal gracilis tendons (used for grafts), have a low MRI signal in all sequences as described in the literature.[41]

Earlier research assessed the MRI aspects of the ATFL after ligament repair. The repaired ATFL was described as a linear band structure with a low signal and a low SNQ on MRI assessment.[39] Liu et al[24] demonstrated that the ATFL in CAI ankles had a higher SNQ than that of the control

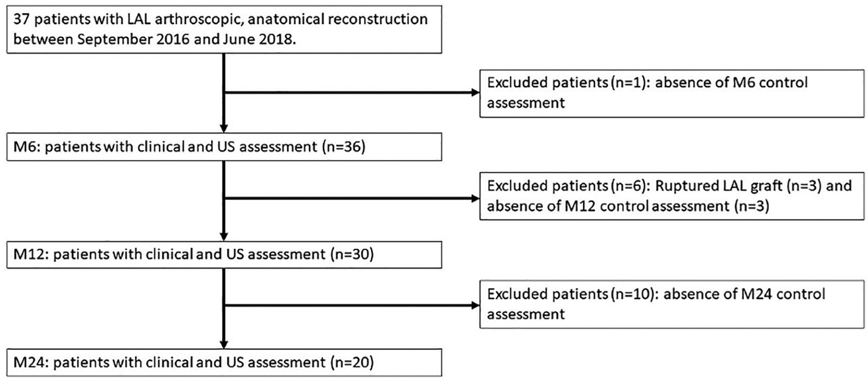

Figure 2. Flowchart of patient inclusion. LAL, lateral ankle ligament; M, month; US, ultrasound.

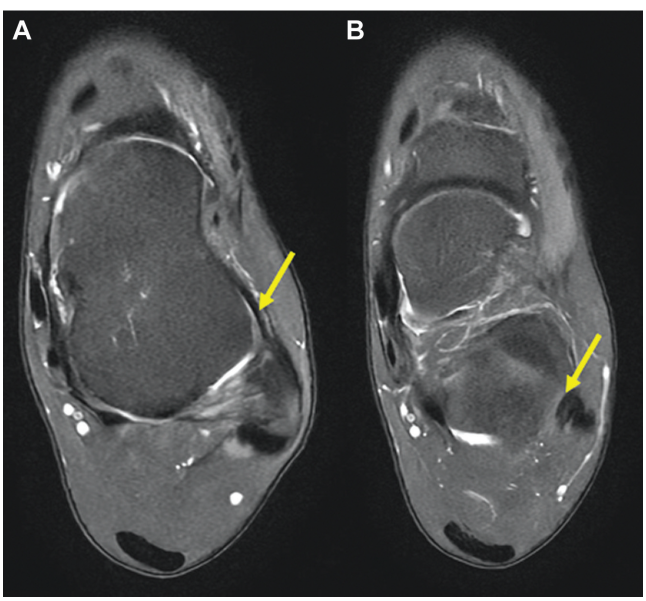

Figure 3. Area of normal reconstructed anterior talofibular ligament signal measurements in the control group (A) and normal calcaneofibular ligament signal measurments in the control group (B) are indicated by yellow arrows.

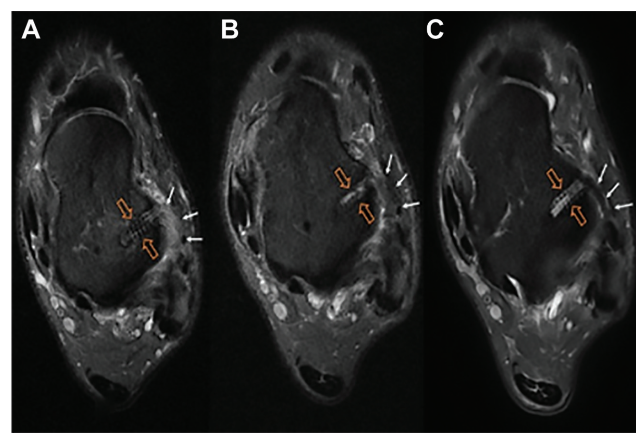

Figure 4. Proton density–fat suppressed weighted sequence with axial ankle view at (A) 6, (B) 12, and (C) 24 months after anatomic lateral ankle ligament reconstruction showing the morphological/signal magnetic resonance imaging evolution of the ATFL graft—ATFL graft (white arrows) and talar tunnel (large open arrows). ATFL, anterior talofibular ligament.

group; after surgical repair, the mean SNQ value of the ATFL decreased, indicating that the repaired ATFL became tight postoperatively. To date, no earlier research has assessed the MRI characteristics after LALR.

In knee surgery, gracilis and semitendinosus tendon grafts are commonly used for ACLR. Several published studies have focused on graft maturation of the reconstructed ACL. In addition to MRI studies, histologic studies have been used to assess the process of graft remodeling after ACLR in animals and humans.[1,4] Three phases are distinguished—(1) an early healing phase with central graft necrosis (0 to 6 months); (2) a proliferative phase with revascularization and remodeling (3-12 months); and (3) a maturation or ligamentization phase (9-48 months).[16,33] The literature has demonstrated that the tendon graft transforms into an ACL-like ligament for ACLR without completely restoring biological properties.[17,31]

The tendon graft maturation has also been demonstrated on MRI scans.[38] Howell et al[15] proposed a classification depending on the signal intensity of the graft (low, intermediate, or high) to evaluate its maturation. A low signal of the graft similar to the native posterior cruciate ligament is considered a sign of graft maturation.[16] A high signal was correlated with hypervascular tissue and corresponded with inferior biomechanical properties.[11,30] The SNQ method, measured using an ROI tool, is currently the reference to evaluate graft maturation.[10,20,21,29,35] A correlation has been described between histologic modifications of the ACL graft and SNQ in an animal study.[37] High SNQ corresponds to poorer graft maturity.[40] In a systematic review, Van Groningen et al[33] found an initial signal increase in the SNQ until 6 months, followed by a signal decrease. It

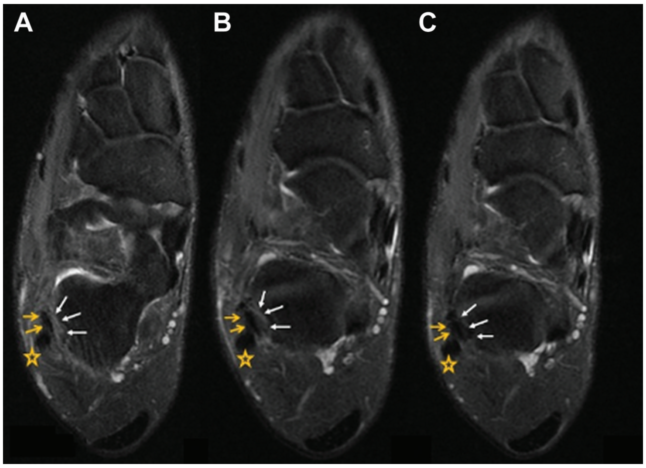

Figure 5. Proton density–fat suppressed weighted sequence with fat-suppressed axial ankle view at (A) 6 months, (B) 12 months, and (C) 24 months after anatomic lateral ankle ligament reconstruction showing the morphological/signal magnetic resonance imaging evolution of the CFL graft—the CFL graft (white arrows), the peroneus brevis tendon (thick arrows), and the peroneus longus tendon (stars). CFL, calcaneofibular ligament.

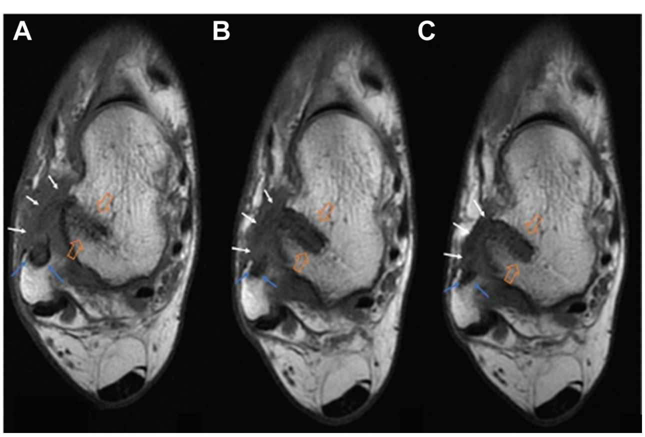

Figure 6. T1-weighted axial view of the ankle at (A) 6 months, (B) 12 months, and (C) 24 months after anatomic lateral ankle ligament reconstruction showing the morphological/signal magnetic resonance imaging evolution of the ATFL graft—the ATFL graft (white arrows), the talar tunnel (large arrows), and the fibular tunnel (gray arrows). ATFL, anterior talofibular ligament.

is commonly accepted that the ACL graft shows a low signal on all sequences immediately postoperatively and after 2 years.[38] However, it has also been demonstrated that a moderate, nonliquid PD-FS hypersignal is present between 3 and 12 months.[18,35] The initial increase of the SNQ in the postoperative period until approximately 6 months corresponds to increased water content and vascularity related to a process of synovialization, which could be seen from 3 months onward.[33]

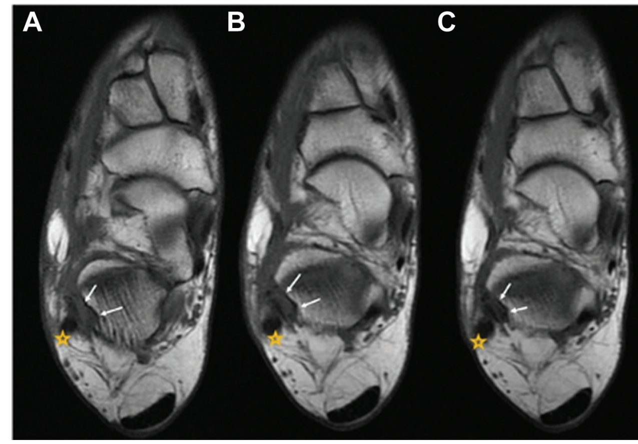

Figure 7. T1-weighted axial view of the ankle at (A) 6 months, (B) 12 months, and (C) 24 months after anatomic lateral ankle ligament reconstruction showing the morphological/signal magnetic resonance imaging evolution of the CFL graft—the CFL graft (white arrows) and the peroneus longus tendon (stars). CFL, calcaneofibular ligament.

Measurement of the different MRI characteristics has been commonly used after ACLR to assess graft maturation.[33] The surgical technique of LALR shows several similarities with that of ACLR. A tendon graft is used in both surgical techniques. During LALR, the tibiotalar joint capsule is partially removed, resulting in tendon grafts becoming in an intra–articular like area. The synovial liquid is beneficial to support the graft pending revascularization. By analogy, it seems reasonable to find similar results about the remodeling of the autograft after LALR.

In the present study, the qualitative view and the SNQ/CNQ of the RATFL and the RCFL demonstrated a high signal at 6 months, and then the signal decreased significantly over 24 months. This process of graft maturation in the ankle is similar to what has been reported for the tendon grafts used for ACL surgery.

The process of graft maturation toward ligamentization is essential for clinical practice. LALR offers the advantage of providing biological tissue at the normal anatomic location of the concerned ligaments. The arguments for ligamentization of the tendon graft confirm the possibility of recreating the LAL.

The current findings are also helpful in postoperative radiographical assessment. Therefore, understanding the normal evolution of the graft tissue is of high importance. The MRI findings of our study can be utilized as a reference for radiologists in particular to determine what a well-functioning LAL graft should look like.

Concerning the schedule of the postoperative rehabilitation, even if the primary stability is excellent, it seems logical to have a progressive loading of the LAL to respect the remodeling of the graft. Although studies concerning ACLR do not demonstrate a correlation between graft maturity and the clinical results,[3,21] understanding periods when the graft is most fragile allows for the modification of

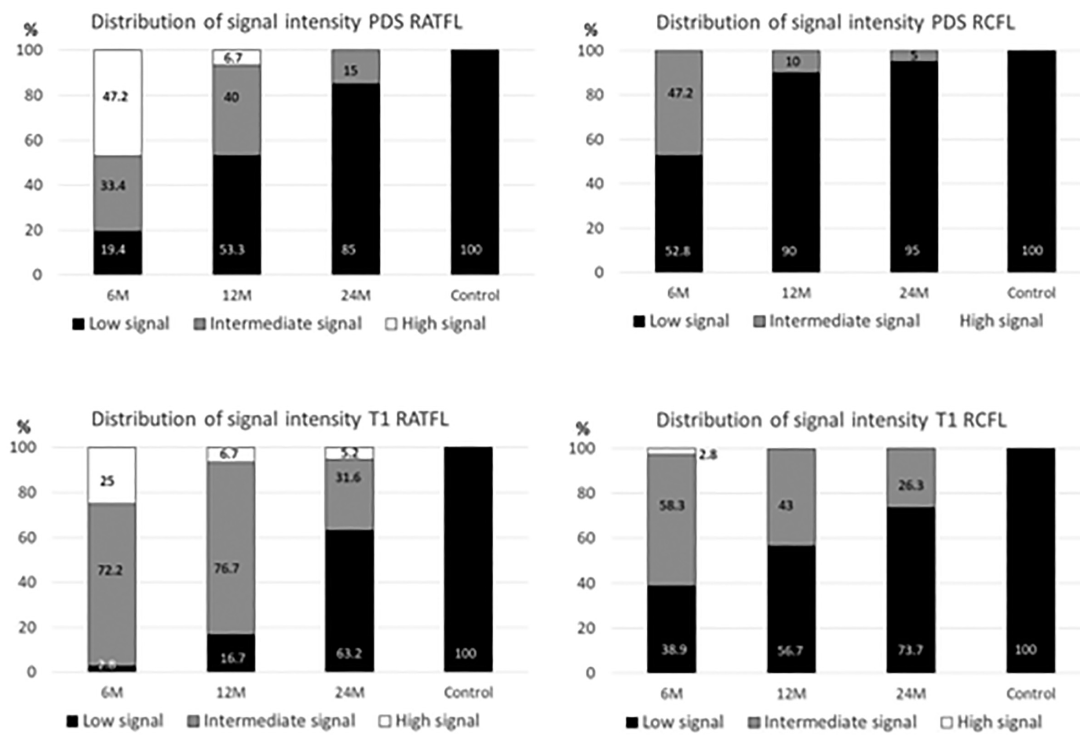

Figure 8. Main qualitative results of visual analysis of the graft from PD-FS and T1 images during the 6 to 24 months of follow-up in the chronic ankle instability group. PD-FS, proton density–fat suppressed; RATFL, reconstructed anterior talofibular ligament; RCFL, reconstructed calcaneofibular ligament.

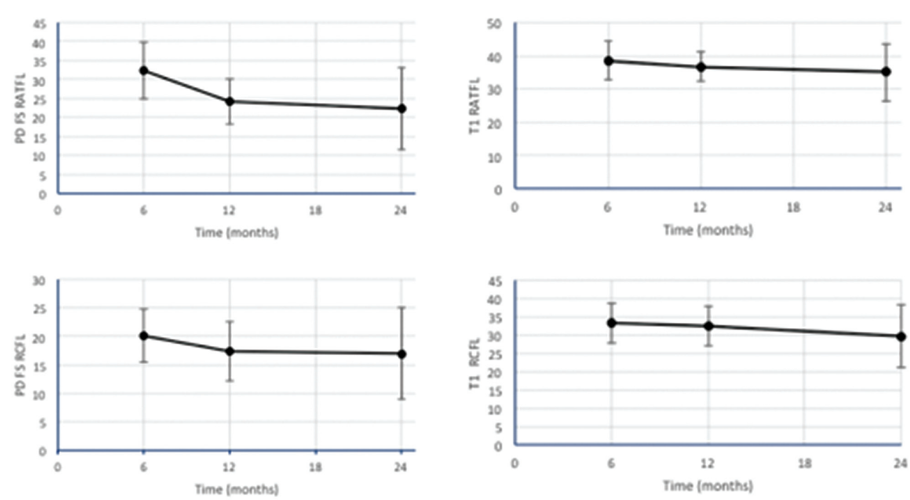

Figure 9. The signal-to-noise quotient of the graft in the chronic ankle instability group was determined using the PD-FS and T1 images. Measurements were performed at 6, 12, and 24 months. PD-FS, proton density–fat suppressed; RATFL, reconstructed anterior talofibular ligament; RCFL, reconstructed calcaneofibular ligament.

rehabilitation exercises. For the same reasons, to prevent reinjury, athletes cannot be allowed to return to the field before the final stage of graft maturation. The literature on animal studies demonstrated that lower graft signal intensity is correlated with higher strength and superior biomechanical properties of the reconstructed ligament.[2,9,37] A similar correlation has been shown after ATFL repair open repair. A lower signal intensity in the ATFL based on preoperative MRI scans is associated with a better clinical outcome—particularly a higher rate of return to sport.[22]

Our results should be interpreted with the following limitations. First, no MRI analysis of the RATFL and

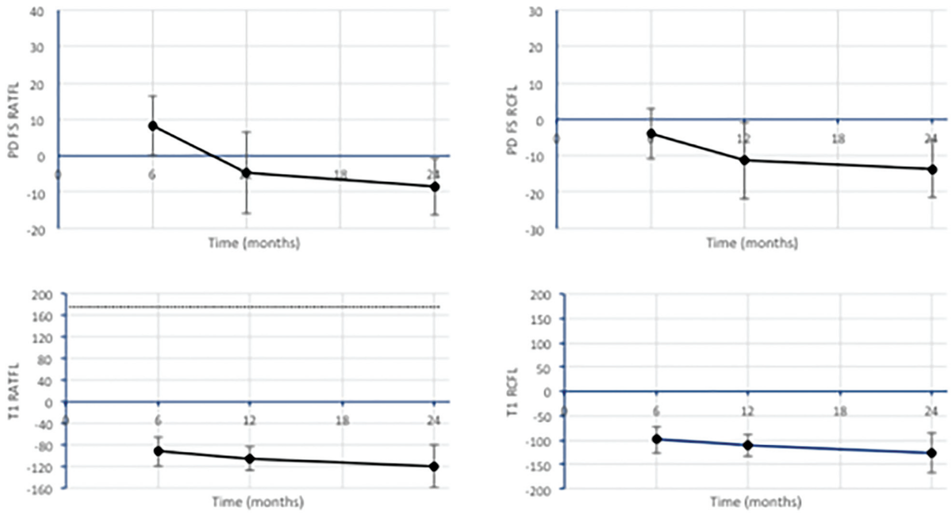

Figure 10. The contrast-to-noise quotient of the graft in the chronic ankle instability group calculated from the PD-FS and T1 images. Measurements were performed at 6, 12, and 24 months. PD-FS, proton density–fat suppressed; RATFL, reconstructed anterior talofibular ligament; RCFL, reconstructed calcaneofibular ligament.

RCFL grafts was performed in the immediate postoperative period. This may complicate the interpretation of the evolution in the first 6 months. However, the qualitative and quantitative measurements of the native ATFL and CFL in the control group correspond with the literature.[8] Second, 17 patients were lost to follow-up between 6 and 24 months follow-ups. However, all patients had good to excellent results during the last MRI. Finally, this study assessed the MRI appearance of intact, well-functioning autografts. This should be taken into account when interpreting the results of this study. The data presented can be compared with future studies assessing allografts or abnormal conditions.

CONCLUSION

This study demonstrated an evolution of the MRI characteristics of the tendon graft after an ATFL and CFL reconstruction. Compared with that of the control group, the MRI scans showed a high signal at 6 months and a signal decrease from 6 to 24 months. A similar evolution was demonstrated by the SNQ and CNQ measurements. The findings of this study suggest a process of graft maturation similar to the graft in ACLR. When SNQ analysis is used as an indirect measure of graft maturation, MRI is the only method available for assessment. MRI scans could be a clinically significant, relevant, and easy-to-obtain assessment of graft maturity when assessing the outcomes of reconstructed LAL and readiness for return to work and sport.

ORCID iD

Guillaume Cordier https://orcid.org/0000-0002-7035-3931

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