


MUSCULOSKELETAL



Primary anterior cruciate ligament repair—morphological and quantitative assessment by 7-T MRI and clinical outcome after 1.5 years

Milena L. Pachowsky^{1,2*} , Stefan Söllner³, Kolja Gelse⁴, Jannik Sambale^{1,5}, Armin M. Nagel^{6,7}, Georg Schett¹, Marc Saake⁶, Michael Uder⁶, Frank W. Roemer^{6,8} and Rafael Heiss⁶

Abstract

Objectives The purpose of this study was to assess morphological and quantitative changes of the anterior cruciate ligament (ACL) and cartilage after ACL repair.

Methods 7T MRI of the knee was acquired in 31 patients 1.5 years after ACL repair and in 13 controls. Proton density-weighted images with fat saturation (PD-fs) were acquired to assess ACL width, signal intensity, elongation, and fraying. T2/T2* mapping was performed for assessment of ACL and cartilage. Segmentation of the ACL, femoral, and tibial cartilage was carried out at 12 ROIs. The outcome evaluation consisted of the Lysholm Knee Score and International Knee Documentation Committee (IKDC) subjective score and clinical examination.

Results ACL showed a normal signal intensity in 96.8% and an increased width in 76.5% after repair. Fraying occurred in 22.6% without having an impact on the clinical outcome (Lysholm score: 90.39 ± 9.75 , $p = 0.76$ compared to controls). T2 analysis of the ACL revealed no difference between patients and controls ($p = 0.74$). Compared to controls, assessment of the femoral and tibial cartilage showed a significant increase of T2* times in all ROIs, except at the posterolateral femur. Patients presented a good outcome in clinical examination with a Lysholm score of 87.19 ± 14.89 and IKDC of 80.23 ± 16.84 .

Conclusion T2 mapping results suggest that the tissue composition of the ACL after repair is similar to that of a native ACL after surgery, whereas the ACL exhibits an increased width. Fraying of the ACL can occur without having any impact on functional outcomes. T2* analysis revealed early degradation at the cartilage.

Clinical relevance statement MRI represents a noninvasive diagnostic tool for the morphological and compositional assessment of the anterior cruciate ligament after repair, whereas knowledge about post-surgical alterations is crucial for adequate imaging interpretation.

Key Points

- There has been renewed interest in repairing the anterior cruciate ligament with a proximally torn ligament.
- T2 times of the anterior cruciate ligament do not differ between anterior cruciate ligament repair patients and controls.
- T2 mapping may serve as a surrogate for the evaluation of the anterior cruciate ligament after repair.

Keywords Magnetic resonance imaging, Knee, Ligaments, Cartilage, Orthopedics

*Correspondence:
Milena L. Pachowsky
milena.pachowsky@gmail.com
Full list of author information is available at the end of the article

Introduction

One of the most common knee injuries among adolescent and mid-aged athletes is the tear of the anterior cruciate ligament (ACL) [1]. Reconstruction of the ACL with hamstring or patellar tendon autografts has been the standard of care in surgical treatments of ACL tears for many years [2, 3]. The dogma that the ACL cannot heal has been called into question during the last years, and it was shown that certain tears may have a healing capacity and exhibit better clinical outcomes compared to non-healed ACLs [4–6]. Hence, ACL repair techniques have made a resurgence in recent years. However, the topic raises diverging opinions among orthopedic surgeons and leads to discussions about the benefit of restoring native anatomic features versus the risks of healing failure and re-rupture. Preserving the native tissue and proprioception [7, 8], the potentially decreased postoperative pain and increased range of motion have been described as important advantages [9]. Recent and historical study results suggest that primary ACL repair (meaning the preservation of the tissue) is reserved for proximal tears due to better vascularity [10] and good healing potential [11].

The time required to complete the remodeling process and the imaging appearance in MRI are unknown for ACL repair. Imaging methods help surgeons and patients to gather information about the status of the injured and treated joint. Magnetic resonance imaging (MRI) is the most widely used imaging technique for monitoring ACL grafts after surgical reconstruction [12–14]. High-field MRI at 3 Tesla (T) and, in particular, ultrahigh-field MRI at 7 T suggests better visualization of small anatomical structures and give better diagnostic performance [15]. The signal-to-noise ratio (SNR) typically increases at least linearly with magnetic field strength [15, 16]. This gain might be used to increase spatial resolution and for a better visualization of the microstructure of ACL repair during follow-up examinations [17]. Besides morphological imaging, compositional MRI techniques, including T2/T2* mapping, are potential candidates to assess ACL remodeling and cartilage [18–22]. It allows a noninvasive quantification of tissues' water content and assessment of its anisotropy, thereby providing a proxy of structural changes in the collagen matrix [22]. Previous research established quantitative MRI mapping techniques as noninvasive, reproducible, and reliable biomarkers to evaluate connective tissues [23].

The objective of this study was to perform an analysis of the morphological imaging appearance of the ACL after primary repair at a single center and to assess the structural properties of the ACL repair tissue and also the cartilage of the knee 1.5 years after surgery using high resolution and compositional MRI at 7 T. Additionally,

we aimed to assess the clinical outcome of the patients after primary ACL repair.

Material and methods

For this study, ethics approval was granted by the Clinical Ethics Committee of the local university. Written informed consent was obtained from all participating patients and healthy controls.

Patients and healthy controls

All consecutive patients who underwent arthroscopic repair of the ACL between 01/2018–06/2018 were enrolled in the study and selected for a prospective investigation. The participants of the control group were age-matched and had no history of knee injury and no incidental findings in the MRI. Inclusion criteria for the patient group were: unilateral acute proximal ACL rupture, no previous knee ligament surgery, and absence of ligament injury of the contralateral knee. Preoperative magnetic resonance imaging confirming a proximal avulsion tear of the ACL was required. Exclusion criteria were the presence of grade 3 or 4 cartilage degeneration both on MRI and in arthroscopy and intraoperative insufficient distal remnant length (leading to ACL repair with a tendon graft). The arthroscopic primary ACL was performed within 2–3 weeks after injury and followed a standardized surgical approach.

ACL repair surgical technique

All surgeries followed a structured protocol. A standardized arthroscopic surgical approach was performed with two standard portals (anterolateral and anteromedial). The ACL had to have a sufficient distal remnant length to reapproximate it to the femoral footprint. In brief, the remnant was sutured with the scorpion needle using a non-resorbable suture (No. 2 FiberWire sutures (Arthrex)). For the transosseous button fixation, a femoral tunnel was drilled from the insertion site to the lateral femoral cortex. Button and sutures were then carried through the hole, and the button was flipped on the lateral femoral condyle. Sutures were pulled through the button. All patients received additional internal bracing (FiberTape, Arthrex) with ACL repair. This technique reinforces the ligament as a secondary stabilizer by protecting it during the healing phase [24]. The ligament was then reapproximated to its footprint by tightening the sutures. Through a third skin incision over the medial tibia head, a second drill hole was made (between the anteromedial tibia cortex and the anterior part of the ACL tibia insertion). The tape was channeled distally along the ligament, through the drill hole, and exits at the anteromedial cortex of the tibia, where it

Table 1 Acquisition parameters of 7T knee MRI

Sequences	PD tse fs sag	PD tse fs cor	PD tse fs tra	T2 mapping para-sag	T2* mapping sag
Time of repetition (ms)	4800.0	4400.0	4400.0	2500.0	20.0
Time of echo (ms)	38.0	38.0	38.0	14.7, 29.4, 44.1, 58.8, 73.5, 88.2	2.68, 5.07, 7.46, 9.85, 12.24, 14.63
Field of view (mm)	160	160	160	160	160
Voxel size (mm)	0.2 x 0.2 x 2.5	0.2 x 0.2 x 2.5	0.2 x 0.2 x 2.5	0.4 x 0.4 x 2.0	0.5 x 0.5 x 0.5
Acquisition time (min)	6:54	3:20	3:20	4:19	6:10

was tied over a button. The FiberTape forms an adjustable loop through the femoral button and the tape was tensioned in full extension of the knee.

Clinical follow-up investigation

The follow-up investigation was scheduled 1.5 years after the surgery. Data for the evaluation were collected in a clinical examination and by means of a survey on subjective well-being and fitness. Patient-reported outcome scores were documented, consisting of the Lysholm Knee Score [25] and IKDC Subjective Score [26]. The clinical follow-up examination of the patients included effusion, range of motion (ROM), ligament stability, and the IKDC score.

Imaging follow-up investigation

7 T MRI was performed 1.5 years after the surgery in all patients using a standardized MRI protocol. Age-matched healthy controls were examined with the same protocol.

Image acquisition

MRI was performed on a 7 T MRI (MAGNETOM Terra, Siemens Healthineers) in combination with a dedicated 1-channel transmit/ 28-channel receive knee array coil (Quality Electrodynamics). Five days prior to the MRI, daily routine activities were allowed, but not sports. Patients were in a supine position with the knee tightly fixed and fully extended in a neutral rotation position in the center of the coil. Proton-density turbo spin echo sequences with fat saturation (PD-fs) in three planes (transversal, coronal, sagittal) were acquired for the morphological assessment. T2 mapping for the quantitative evaluation of the ACL was performed using a parasagittal plane, providing in-plane images of the entire course of the ACL. Sagittal T2* mapping for the assessment of the femoral and tibial cartilage was acquired (Table 1).

Image analysis

Morphological MRI assessment

All 7 T images were assessed with regard to width, continuity, elongation, and signal intensity of the ACL repair by one radiologist and one orthopedic surgeon, both with

special interest in musculoskeletal MRI. The reading was performed together in consensus. After 6 months, the reading was repeated separately by both to obtain inter- and intra-observer reliability.

The width of the ACL was assessed in the sagittal, coronal, and transversal planes and graded according to the following subjective subcategories: normal, increased, and decreased. The widest diameter of the ACL was also measured in the sagittal images.

The continuity of the ACL was evaluated in the sagittal plane with the following gradation: continuous, fraying, and non-continuous. Fraying describes the loosening of ACL tissue with the bulging of ACL fibers into the knee joint. We compared Lysholm scores from patients with fraying with those patients whose ACL tissue had a continuous appearance to determine whether fraying had an effect on the clinical outcome.

The signal intensity of the ACL was assessed according to the following aspects: Homogenous hyperintense and normal heterogeneous appearance [27]. Signal intensity was assessed in both sagittal and coronal planes. In addition, the ACL was judged for the presence of elongation, meaning a subjective curved prolongation of the ligaments' course.

Quantitative MRI assessment

For the compositional analysis of the ACL and the articular cartilage T2 maps, respectively T2* maps, were used. The MRI data were transferred to a Syngo (Leonardo) workstation (Siemens Healthineers). T2/T2* maps were obtained using a pixel-wise, mono-exponential, non-negative least-squares-fit analysis. The parallel analysis of morphological and quantitative series allowed for direct comparison and co-registration of anatomic and compositional data sets.

The ACL tissue was divided into 2 ROIs (cranial and caudal) for calculating the average T2 values derived from the T2 maps of the base of the ACL and the former tip of the remnant, see Fig. 1.

The T2* maps of the cartilage were analyzed using a region-of-interest analysis (ROI) according to previous recommendations [28]. ROI analysis was performed for the tibial and femoral cartilage surfaces of the knee joint.

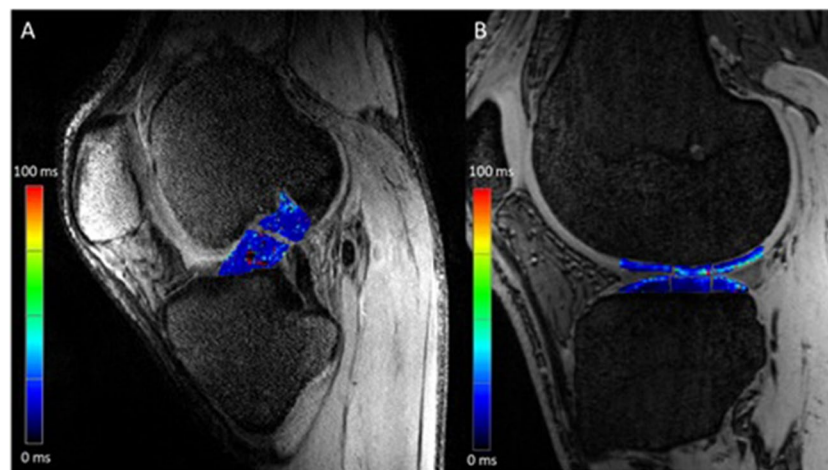


Fig. 1 **A** T2 MRI image of the first echo of parasagittal T2 mapping with merged regions of interest of the corresponding T2 map for the anterior cruciate ligament of a 26-year-old female patient after ACL repair. **B** Image of the first echo of sagittal T2* mapping with merged regions of interest of the corresponding T2* map for the tibial and femoral cartilage

The ROIs were applied manually, and the mean T2* values for each ROI were calculated automatically. Three regions of interest (anterior, central, and posterior) were placed, each at the medial and lateral aspect of the tibia and femur, ending up with 12 regions in total for cartilage assessment (Fig. 1). Two neighboring slices at each anatomic location were segmented to reduce partial volume effects.

After a delay of 6 months, quantitative measurements were repeated to obtain reliability.

Statistical analysis

Statistical analyses were performed using the SPSS 24.0 software (IBM Corporation). Continuous variables are displayed with means \pm standard deviations (SDs). Nominal variables are described with frequencies (%). In the first step of statistical analysis, the group of patients with concomitant injuries was compared to those with isolated ACL rupture. Due to no relevant differences, we pooled the data of these groups.

Results of patients and the control group were compared, using independent t tests for continuous variables and chi-squared tests or Fisher exact tests (for samples with a value < 5 in the contingency table) for nominal data. All tests were two-sided, and a difference of $p < 0.05$ was considered statistically significant.

The inter- and intrareader reproducibility were evaluated using (i) Cohen Kappa for nominal categorical variables (signal intensity and elongation) and (ii) weighted Kappa for ordered categorical variables (width and continuity). Kappa values (K) of 0.41–0.60, 0.61–0.80, and 0.81–1.0 are considered to indicate moderate, substantial, and almost perfect agreement, respectively. The reliability of T2 analysis of the ACL repair and T2* of the cartilage

was evaluated by using the intraclass correlation coefficient (ICC). The ICC values were graded as follows: excellent reliability ($0.75 > \text{ICC} \leq 1$), fair to good reliability ($0.4 \geq \text{ICC} \leq 0.75$), and poor reliability ($0 \geq \text{ICC} < 0.4$).

Results

Study population

In total, 31 patients with ACL repair were enrolled in the study, and 13 healthy controls were without any history of knee injury. Demographic data are displayed in Table 2.

Seven patients presented with focal cartilage defects on MRI, with four patients having Outerbridge grade 1 and 3 patients with grade 2 lesions. None of these cartilage defects was placed at the anatomic locations of quantitative T2* cartilage assessment. No further pathologies, such as meniscal tears or accompanying injuries of ligaments other than the ACL, were detected. In the MRI of healthy controls, no pathologies at the knee joint were present.

Clinical assessment

The interval between injury of the knee and surgery was 14.35 ± 7.73 days. Acquisition of the MRI and clinical assessment was performed with a mean follow-up time of 18.29 ± 6.49 months after the surgery. The patient-reported outcomes of the entire ACL repair cohort were a mean Lysholm score of 87.19 ± 14.89 and a mean IKDC score of 80.23 ± 16.84 .

ROM assessment showed on average, maximal extension/flexion of 4/0/136 degrees of the patients' knees on the operated side and 5/0/142 on the non-operated side.

The majority of the patients (26, 83.87%) with ACL repair showed no effusion, three patients (9.68%) showed

Table 2 Demographic data of patients and controls

Demographic data	Bracing	Control	
<i>n</i>	31	13	
	Mean ± SD	Mean ± SD	<i>p</i> value difference
Age (years)	28.79 ± 8.26	28.31 ± 2.84	n.s.
Weight (kg)	79.31 ± 10.94	76.46 ± 12.89	n.s.
Height (cm)	1.76 ± 0.08	1.78 ± 9.13	n.s.
BMI (kg/m ²)	25.33 ± 2.91	23.85 ± 2.56	n.s.
Gender (male vs. female %)	64.5 vs. 35.5	61.5 vs. 38.5	n.s.

mild effusion, one patient had moderate effusion, and one patient had severe effusion.

The manual Lachman test was assessed as normal for 12 of the patients (38.71%), as nearly normal for 17 of the patients (54.84%), and as abnormal for two patients (6.5%).

One patient reported a failure after ACL repair in the sense of a re-rupture, which resulted in a failure rate of 3% in our patient population.

Image analysis

Morphological MRI assessment of the ACL repair

The width of the ACL repair was assessed as normal in the majority of the coronal slices (82.4 %), as normal in 11.8% of the cases in the sagittal plane, and in 17.6 % of the transversal views. Increased width of the ACL after repair was described in the sagittal (76.5%) and transversal (70.6%) plane (Fig. 2). In the control group, all of the ACLs were assessed as normal in all planes, see Table 3, section A. The width of the reattached ACLs was 1.04 ± 0.23 cm, and the ACLs of controls had an average width of 0.87 ± 0.15 cm ($p = 0.026$).

Continuity and signal intensity of the ACL repair

Among the patients, 23 individuals had MR morphologically continuous ACL after 1.5 years, representing 74.2% of the included patients. Fraying was detected in seven patients (22.6%) (Fig. 3, section B). One patient had a non-continuous ACL. In the control group, all 13 subjects (100%) had a continuous ACL, see Table 3, section B.

In the comparison regarding the Lysholm score between the patients with fraying (Lysholm score mean of 91.25 ± 7.96 points) and those with continuous ACL (Lysholm score mean of 90.39 ± 9.75 points), no statistically significant difference occurred (p value = 0.76).

The single patient with re-rupture after ACL repair described clinical deterioration, which was also reflected in the Lysholm score. The average Lysholm score of the patients with continuous ACL was 90.27 points; the patient with re-rupture had a Lysholm score of 26 points.

In the assessment of the signal intensity, there was a normal signal intensity in both the sagittal and coronal planes in 30 of the patients and a homogeneously hyperintense signal in one patient. An elongation of the ACL was described in nine patients (29%), whereas no elongation was present in the healthy controls.

Quantitative MR assessments—T2/T2* mapping

Anterior cruciate ligament The ACL tissue showed no statistically significant difference when compared regarding the T2 time between ACL repair and ACL of healthy controls, see Table 4. In addition, there was no difference in the comparison between the proximal and distal portions of ACL T2 time after repair ($p = 0.91$).

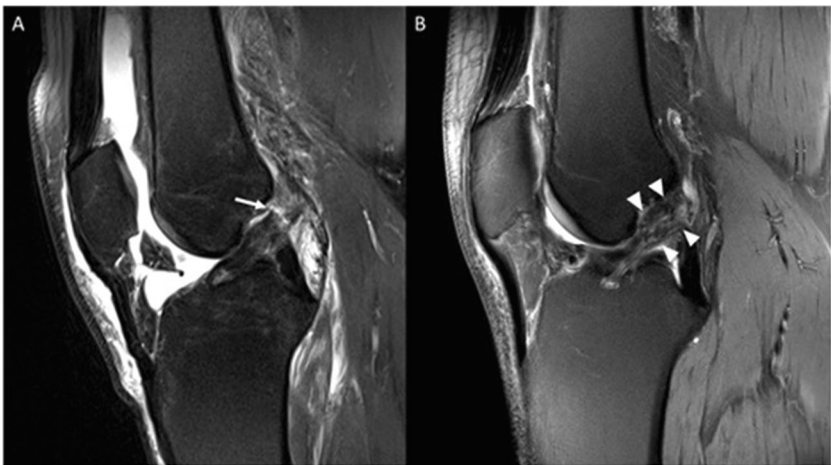


Fig. 2 **A** 1.5T proton density-weighted fat-saturated MRI image of a 23-year-old male patient with a tear of the proximal ACL (arrow) after knee distortion. **B** 7T proton density-weighted fat-saturated MRI image of the same patient 1.5 years after primary ACL repair. The ACL appears continuous with an increased width in the proximal portion (arrowheads)

Table 3 Morphological assessment of the ACL in patients and controls, A width, B continuity, C signal intensity

A: Width of ACL	Patients	Controls
Sagittal		
Normal	4 (11.8%)	13 (100%)
Increased	26 (76.5%)	0 (0%)
Decreased	1 (2.9%)	0 (0%)
Coronal		
Normal	28 (82.4%)	13 (100%)
Increased	2 (5.9%)	0 (0%)
Decreased	1 (2.9%)	0 (0%)
Transversal		
Normal	6 (17.6%)	13 (100%)
Increased	24 (70.6%)	0 (0%)
Decreased	1 (2.9%)	0 (0%)
B: ACL continuity		
Continuous	23 (74.2%)	13 (100%)
Fraying	7 (22.6%)	0 (0%)
Non-continuous	1 (3.2%)	0 (0%)
C: ACL signal intensity		
Sagittal		
Homogenous hyperintense	1 (3.2%)	0 (0%)
Normal signal intensity	30 (96.8%)	13 (100%)
Coronal		
Homogenous hyperintense	1 (3.2%)	0 (0%)
Normal signal intensity	30 (96.8%)	13 (100%)

Cartilage T2* values of the ROIs in the femoral and tibial cartilage showed higher values in the ACL repair group, with significant differences in all ROIs except at the posterolateral femur, see Table 5.

Reliability of qualitative and quantitative results

Inter-reader agreements revealed almost perfect agreement for width ($K = 0.90$), continuity ($K = 0.85$), elongation ($K = 0.94$), and the signal intensity ($K = 0.94$) of the ACL repair. Intrareader agreements of both the radiologist and the orthopedic surgeon also showed almost perfect agreements for width ($K = 0.90$, $K = 0.84$), continuity ($K = 0.86$, $K = 0.91$), elongation ($K = 1$, $K = 0.94$), and signal intensity ($K = 0.87$, $K = 0.82$). Excellent reliability was observed for both T2 values of the ACL repair and T2* values of the cartilage with an ICC of 0.94, respectively with an ICC of 0.89.

Discussion

Our study demonstrates a good functional outcome 1.5 years after primary arthroscopic ACL repair, whereas the ACL appears often with an increased width in MRI. In 23% of the patients, fraying of the ACL occurred without having any impact in regard to the functional outcome.

Quantitative assessment of ACL repair using T2 mapping suggests a similar biochemical tissue composition compared to matched healthy controls. In contrast, quantitative cartilage analyses using T2* mapping indicate early cartilage degradation in patients with ACL repair at the femoral and tibial articular surface.

An improved understanding of the pathophysiology of ligamentous healing has led to increasing interest in treating acute proximal ACL avulsions with primary surgical repair techniques [29], whereas knowledge about the morphological imaging appearance of the ACL and its structural properties after primary repair is very limited. The historical approach of primary ACL repair led to disappointing outcomes [29]. The attempt to overcome the limitations of the past has triggered the development of new surgical techniques [29]. In general, proximal tear patterns have better healing potential than distal or mid-substance tears, with better outcomes in younger patients [30]. In addition, some forms of internal bracing, with either nonabsorbable sutures, scaffolds, or a graft, have been described to increase the success rate of the procedure [30]. The reinforcement of the ACL with internal bracing may protect the ligament during the healing phase, supporting early mobilization, and is thought to encourage natural healing of the ligament [24, 31]. All enrolled patients in our study were treated with arthroscopic suture and internal bracing in acute proximal ACL ruptures by the same surgeon and showed a good functional outcome with a Lysholm score of 87.19 and an IKDC score of 80.23. DiFelice et al described in a case series of 11 patients with proximal ACL rupture and arthroscopic ACL repair with internal bracing a Lysholm score of 93.2 and IKDC score of 86.4 after a mean follow-up time of 3.5 years, which is in line with our study [32]. They reported a treatment failure in one patient, resulting in a failure rate of 9% [32]. One of our patients (3%) also suffered an ACL failure in the sense of a re-rupture caused by a repeated distortion.

MRI is an indispensable tool in the appropriate preoperative and postoperative management of knee ligament injury [27, 33]. A meta-analysis about the diagnostic efficacy of 3T MRI for knee injuries using arthroscopy as a reference standard reported a mean sensitivity of 92% and a mean specificity of 99% for the identification of ACL injuries [34]. In addition, a superior diagnostic efficacy for assessing ACL integrity was described when compared with studies of 1.5T scanners [34]. In general, higher magnetic field strengths provide a higher signal-to-noise ratio, which can be used to increase spatial resolution [15]. In studies comparing knee MRI at 3T and 7T with comparable acquisition times improved overall diagnostic confidence with significantly higher diagnostic accuracy for small joint structures and subtle lesions [35, 36]. However, regardless of the field strength and resolution, knowledge about the imaging appearance after surgical ACL

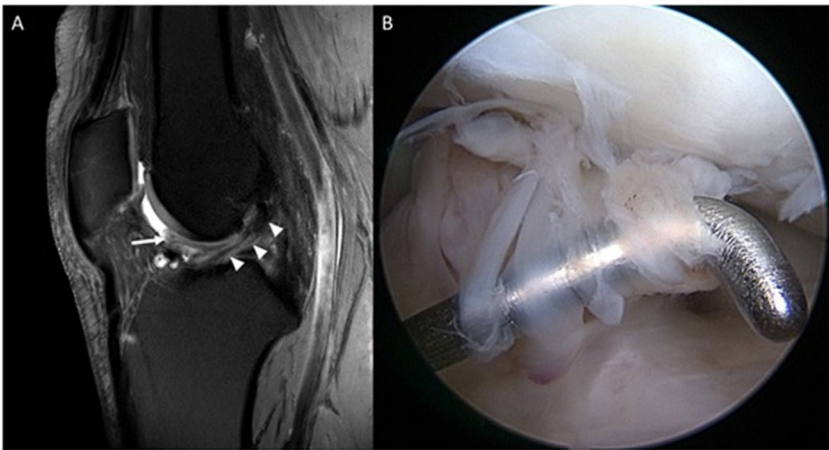


Fig. 3 **A** 7T proton density-weighted fat-saturated MRI image of a 24-year-old male patient 1.5 years after primary ACL repair with fraying of the ACL and prolapse of ACL fibers into the intercondylar notch (arrow). The remaining parts of the ACL appear continuous (arrowheads). **B** Corresponding arthroscopic appearance of fraying in the same patient. The repaired ACL itself was continuous and stable

Table 4 T2 values of the ACL in patients and controls

T2 values (ms) ACL	Bracing mean ± SD	Control mean ± SD	p value difference
Proximal/cranial	29.09 ± 25.73	30.83 ± 10.74	0.743
Distal/caudal	29.79 ± 32.75	31.47 ± 10.79	0.801

Table 5 T2* values of the femoral and tibial cartilage in patients and controls

T2* values (ms)	Bracing	Control	
Cartilage			
	Mean ± SD	Mean ± SD	p value difference
ROI			
Medial			
Femoral anterior	20.68 ± 6.22	10.95 ± 3.01	< 0.001
Femoral central	25.53 ± 11.52	12.68 ± 3.69	< 0.001
Femoral posterior	28.46 ± 7.16	20.66 ± 6.04	0.003
Tibial anterior	17.66 ± 8.45	11.68 ± 2.78	0.020
Tibial central	18.45 ± 6.16	12.97 ± 2.15	0.004
Tibial posterior	25.53 ± 5.72	13.47 ± 2.79	< 0.001
Lateral			
Femoral anterior	21.91 ± 8.07	12.01 ± 2.94	< 0.001
Femoral central	21.41 ± 4.46	17.79 ± 3.72	0.020
Femoral posterior	27.46 ± 6.71	24.87 ± 4.49	0.228
Tibial anterior	22.68 ± 6.05	13.66 ± 2.52	< 0.001
Tibial central	28.06 ± 9.66	15.41 ± 3.12	< 0.001
Tibial posterior	30.01 ± 8.91	16.27 ± 3.62	< 0.001

repair is crucial for a correct imaging interpretation. In our study using a 7T MRI a significant increased width of the ACL after repair in the sagittal plane occurred compared

to healthy controls (1.04 ± 0.23 cm vs. 0.87 ± 0.15 cm, $p = 0.026$). The ACL itself appeared with normal heterogeneous signal intensity in 96.8% of all our patients at follow-up. Seven patients (22.6%) presented with fraying of the ACL after repair, meaning a loosening of ACL tissue with bulging of ACL fibers into the joint. Knowledge about a potential fraying of the ACL after surgical repair seems to be from outstanding importance for imaging interpretation. There was no statistical difference between patients with fraying compared to patients with continuous ACL repair regarding the Lysholm Score, indicating that the fraying does not necessarily have a clinical relevance. This means that fraying alone, with good clinical examination results, is not necessarily a cause for concern for the patient or surgeon. Herewith, our results join the sparse existing literature about the imaging appearance of the ACL after repair. Ferretti et al reported a normal morphology of the ACL in 10 patients (100%) 6 months after surgical repair, whereas the surgical technique was comparable to our study [37]. The signal intensity of the ACL after repair was rated as isointense in nine of ten patients and intermediate in one of ten patients 6 months after surgery. Possibly morphological alterations (increased width, fraying), as described in our cohort, are not visible 6 months after surgery and develop in the course of time due to continuous or abrupt changes. For other surgical procedures such as ACL reconstruction with hamstring autograft, also a continuous maturation process in the first 2 years after surgery is reported [38].

Besides benefits for morphological imaging, the most striking advantage of ultra-high-field MRI at 7T might be the increased feasibility of performing compositional imaging [17, 19, 22, 39]. Compositional MRI techniques such as T2 and T2* mapping enable noninvasive tissue quantification, providing information about structural changes and

tissues' molecular status [19, 20, 22, 39]. T2 and T2* relaxation times are influenced by the orientation of collagen, collagen content, and tissue hydration and have been used both for ACL and knee cartilage assessment at 7T MRI [20]. Excellent inter-rater and intra-rater reliability regarding T2 values of the ACL in patients with osteoarthritis (OA) and in healthy controls were described before for 3T and 7T MRI, which is in line with our results [20]. The quantitative ACL assessment using T2 mapping in our study revealed no significant difference between patients and matched healthy controls, implying that the tissue composition remains intact. This supports the idea that ACL repair can restore nearly normal knee joint biomechanics.

However, quantitative analysis of femoral and tibial articular cartilage using T2* mapping revealed significantly increased values in our patients with ACL repair compared to healthy controls. Previous examinations of T2* in patients with OA and after ACL injury have shown that T2* values in articular cartilage are typically elevated with increased cartilage degeneration, as well as after ACL reconstruction [40, 41].

There are some limitations to consider. First is the small sample size, with 31 patients and 13 controls. Second is the lack of arthroscopic and histopathological validation of the MRI findings, which is not justifiable for ethical reasons. Third, we only used 7T MRI and did not perform a comparison with other field strengths or with other imaging techniques. Fourth, the lack of histopathological correlation between ACL tissue and articular cartilage, which required an ex vivo approach and was not the intent of the present study. However, comparative assessments of histological and quantitative MRI features have previously been performed, in particular for T2* analysis of the articular cartilage at the knee [40].

Conclusion

Our study results indicate an identical biochemical tissue composition of the ACL after repair 1.5 years after surgery, whereas the ACL is accompanied by an increased width in 7T MRI imaging. Fraying of the ACL can occur without having any impact in regard to the functional outcome. Knowledge about morphological changes of the ACL after repair may be crucial for a correct imaging interpretation. Although advantages of ACL repair over reconstruction techniques are anticipated in regard to restoring native anatomic tissue and preserving proprioception T2* analysis indicates early cartilage degradation in our patients. Further prospective multicenter randomized controlled trials are warranted to elucidate repair versus reconstruction for proximal anterior cruciate ligament tears.

Abbreviations

ACL	Anterior Cruciate Ligament
ICC	Intraclass correlation coefficient
IKDC	International Knee Documentation Committee
PD-fs	Proton density-weighted images with fat saturation
ROM	Range of motion
SD	Standard deviation
SNR	Signal-to-noise ratio

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Declarations

Guarantor

The scientific guarantor of this publication is Milena L. Pachowsky.

Conflict of interest

The authors of this manuscript declare relationships with the following companies: Roemer (last 36 months - outside of the submitted work): Consultant to Grünenthal, Shareholder & CMO Boston Imaging Core Lab (BICL), LLC. The other authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

Statistics and biometry

One of the authors has significant statistical expertise. However, no complex statistical methods were necessary for this paper.

Informed consent

Written informed consent was obtained from all subjects (patients) in this study.

Ethical approval

Institutional Review Board approval was obtained (Ethik-Kommission der Friedrich-Alexander-Universität Erlangen-Nürnberg).

Study subjects or cohorts overlap

No study subjects or cohorts have been previously reported.

Methodology

- prospective
- experimental
- performed at one institution

Author details

¹Department of Internal Medicine 3 – Rheumatology and Immunology, University Hospital Erlangen, Friedrich-Alexander-Universität Erlangen-Nürnberg, Ulmenweg 18, 91054 Erlangen, Germany. ²Department of Orthopaedic and Trauma Surgery, Waldkrankenhaus St. Marien, Erlangen, Germany. ³Department of Trauma and Orthopaedic Surgery, University Hospital Erlangen, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany. ⁴Department of Trauma and Orthopaedic Surgery, Klinikum Traunstein, Traunstein, Germany. ⁵Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany. ⁶Institute of Radiology, University Hospital Erlangen, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany. ⁷Division of Medical Physics in Radiology, German Cancer Research Center (DKFZ), Heidelberg, Germany. ⁸Quantitative Imaging Center (QIC), School of Medicine, Boston University, Chobanian & Avedisian, Boston, MA, USA.

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