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Abnormal Tibiofemoral Kinematics Following ACL Reconstruction are Associated with Early Cartilage Matrix Degeneration Measured by MRI T1rho

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Abstract

Purpose—Altered kinematics following ACL-reconstruction may be a cause of post-traumatic osteoarthritis. T_{1ρ} MRI is a technique that detects early cartilage matrix degeneration. Our study aimed to evaluate kinematics following ACL-reconstruction, cartilage health (using T_{1ρ} MRI), and assess whether altered kinematics following ACL-reconstruction are associated with early cartilage degeneration.

Methods—Eleven patients (average age: 33±9 years) underwent 3T MRI 18±5 months following ACL-reconstruction. Images were obtained at extension and 30° flexion under simulated loading (125 N). Tibial rotation (TR) and anterior tibial translation (ATT) between flexion and extension, and T_{1ρ} relaxation times of the knee cartilage were analyzed. Cartilage was divided into five compartments: medial and lateral femoral condyles (MFC/LFC), medial and lateral tibias (MT/LT), and patella. A sub-analysis of the femoral weight-bearing (wb) regions was also performed. Patients were categorized as having “abnormal” or “restored” ATT and TR, and T_{1ρ} percentage increase was compared between these two groups of patients.

Results—As a group, there were no significant differences between ACL-reconstructed and contralateral knee kinematics, however, there were individual variations. T_{1ρ} relaxation times of the MFC and MFC-wb region were elevated (p = 0.05) in the ACL-reconstructed knees compared to the uninjured contralateral knees. There were increases (p = 0.05) in the MFC-wb, MT, patella and overall average cartilage T_{1ρ} values of the “abnormal” ATT group compared to “restored” ATT group. The percentage increase in the T_{1ρ} relaxation time in the MFC-wb cartilage approached significance (p=0.08) in the “abnormal” versus “restored” TR patients.

Conclusions—Abnormal kinematics following ACL-reconstruction appears to lead to cartilage degeneration, particularly in the medial compartment.

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Keywords

biomechanics; cartilage; imaging; knee; knee ligaments; osteoarthritis

Introduction

Injury of the anterior cruciate ligament (ACL) is common, with an annual incidence of 81 per 100,000, and reconstructions numbering at 107,000 per year in the United States alone. (1,2) ACL rupture has been associated with functional impairment secondary to joint instability, meniscal injury, and ultimately osteoarthritis (OA). (3-5) The rate of OA following ACL injuries is controversial. Long term database studies evaluating soccer players following ACL injury showed the development of radiographic degenerative joint disease in injured knees to be 51 percent, while the rate of OA in the contralateral knee was only 8 percent. (6) A recent review also estimated that 50 percent of patients developed OA 10 to 20 years following ACL injury. (7) However, in contrast, a meta-analysis showed the rate of radiographic OA to be lower, especially in those patients with an isolated ACL tears (with no meniscal injury) who displayed a 0-13 percent prevalence of OA. (4) Despite these findings, ACL reconstruction has not been shown to decrease the rate of OA despite the immediate improvements in stability. (4)

Knee kinematics have been studied with a variety of modalities, including gait analysis, (8-13) dual-plane fluoroscopy, (14,15) stereoradiographic analysis, (16) and magnetic resonance (MR) kinematics. (17,18) In vivo analysis of tibiofemoral kinematics following ACL injury has shown differences between the ACL-injured and contralateral uninjured legs. (8,10-13,16-18) In general, anterior-posterior (A-P) laxity of the knee has been considered largely restored following reconstruction. (10,16,19) However, it has been suggested that the most popular surgical technique – the single bundle transtibial reconstruction, with either bone patellar tendon bone or hamstrings grafts – fails to restore normal kinematics, specifically with respect to rotational stability. (10-13,16,18) The observed changes in knee joint motion are thought to modify loading patterns. And these changes in kinematics have been suggested as one of the significant factors contributing to post-traumatic OA development in ACL injured patients. (5,8,9,19-21). Investigators have recommended that femoral drilling through anteromedial portal drilling may better restore rotational laxity, and thus, may have better outcomes. However, its effect on preventing OA development have yet to be determined.

It has proven difficult to show a direct relationship between changes in knee kinematics and the development of radiographic evidence of degenerative joint disease. This difficulty is largely a result of the relatively long time between injury and resultant morphological cartilage changes seen in OA. However, advancements in imaging technology such as quantitative magnetic resonance imaging (MRI) – $T_{1\rho}$ and T_2 quantification as well as delayed gadolinium enhanced MRI for cartilage (dGEMRIC) techniques – allow for the early detection of biochemical changes in the cartilage matrix associated with OA. (22-28) Novel imaging techniques such as $T_{1\rho}$ MRI coupled with MR kinematics may allow for analysis of tibiofemoral kinematics as well as early detection of cartilage matrix degeneration.

The purpose of our study was to explore the relationship between abnormal tibiofemoral kinematics following ACL reconstruction and early degeneration of the cartilage matrix, as measured by $T_{1\rho}$ relaxation times. Our hypotheses are threefold: 1) ACL reconstruction using a single bundle anteromedial drilling technique will not restore normal knee kinematics, particularly with respect to tibial rotation; 2) ACL-reconstructed knees will

exhibit elevated $T_{1\rho}$ relaxation times in the medial compartment cartilage of the knee when compared to the contralateral knee; 3) Patients with abnormal knee kinematics, relative to the contralateral knee, will exhibit higher cartilage $T_{1\rho}$ relaxation times compared to those patients with restored tibiofemoral kinematics.

Methods

Subjects

Eleven patients (7 women; mean age, 33 ± 9 years), with no previous history of knee injury, with unilateral ACL reconstruction performed by the same surgeon were recruited for this cross sectional study. MR images were acquired 18 ± 4.5 months following reconstruction. Nine patients received hamstring tendon autografts, two patients received allografts. None of the patients required meniscectomy or meniscal debridement, however one patient received an all-inside medial meniscus repair. Additionally, none of the patients required any cartilage debridement, and no patients were noted to have greater than Outerbridge grade 1 chondrosis. At the time of enrollment, all contralateral uninjured knees had no history of knee osteoarthritis, clinical osteoarthritis symptoms, previous knee injuries, or knee surgeries. The committee on Human Research at our institution approved all procedures used in this study, and each patient gave informed consent prior to participation.

Surgical reconstruction

All patients underwent anteromedial portal drilling of femoral tunnel. The femoral tunnel was drilled independent of the tibial tunnel through the anteromedial portal. The knee was hyperflexed more than 120 degrees of flexion while drilling the femoral tunnel. The tibial tunnel was drilled through the center of the tibial stump of the torn ACL through an anteromedial incision. All except one fixation were achieved using Endobutton-CL (Smith and Nephew) and Biointrafix (Mitek). One patient received an Achilles tendon allograft which was fixed using metal interference screw on the femoral side and Biointrafix on the tibial side. All patients underwent the same post-operative rehabilitation protocol with partial weight-bearing with crutches with 3 weeks and long-leg brace. Patients are not allowed to perform running or cutting maneuvers until 4 months post-operatively. They were allowed to return to sports once they regained adequate proprioception and control, which varied between 6-9 months post-operatively.

MR Imaging Procedures

MR images were acquired to assess *in vivo* three-dimensional tibiofemoral kinematics and cartilage health (using $T_{1\rho}$ imaging), employing techniques previously developed in our laboratory. (17,18,24,25) Patient had both knees scanned at one visit, at which point both cartilage and kinematics scans were acquired during one exam. Subjects were positioned on a previously described custom loading device. (17,18) (Figure 1) Prior to kinematic scans, SPGR and $T_{1\rho}$ sequences were acquired in an unloaded fully extended position. While acquiring the kinematic scans – fast spin echo (FSE) sequences in both full extension and 30 degrees of flexion – an axial compressive force of 125 N was applied to the plantar surface of the patient's foot. (24,25) Knee flexion was limited by the size of the knee coil and the height of the MR scanner's bore. The total scan time, including set up, was approximately one hour per knee.

MR Imaging Protocol

MRI of the knee was performed using a 3T GE Excite Signa MR Scanner (General Electric, Milwaukee, WI, USA) and an 8-channel phased-array knee coil (Invivo, Orlando, FL,

USA). Parallel imaging was performed for all imaging sequences with an array spatial sensitivity technique (ASSET) using an acceleration factor of 2.

Cartilage Imaging Protocol

Sagittal high spatial resolution volumetric fat-suppressed spoiled-gradient-echo (SPGR; relaxation time (TR)/echo time (TE) = 18/3.5 ms, flip angle = 12, field of view (FOV) = 14 cm, matrix = 512×512 , in-plane spatial resolution = $0.273 \times 0.273 \text{ mm}^2$, slice thickness = 1mm, band width (BW) = 31.25 kHz, number of excitations = 1) and 3D $T_{1\rho}$ sequences were acquired. The $T_{1\rho}$ images were obtained using a spin-lock technique followed by SPGR acquisition using transient signals evolving towards steady-state with the following parameters: TR/TE = 7.4/2.7 ms, time of recovery = 1500 ms, FOV = 14 cm, matrix = 256×192 , slice thickness = 4 mm, BW = 31.25 kHz, views per segment = 64, time of spin-lock (TSL) = 0/10/40/80 ms, FSL = 500 Hz. Previous studies from our lab showed excellent reproducibility of cartilage $T_{1\rho}$ quantification using this method. The average coefficient-of-variation (CV) of mean $T_{1\rho}$ values for cartilage was 1.6% with repeated measures (28).

Kinematic Imaging Protocol

Sagittal T_2 weighted FSE images were acquired (TR/TE = 4000 ms / 50.96 ms, FOV = 16cm, 512×256 matrix, slice thickness of 1.5 mm) to assess kinematics.

Data Analysis

Kinematic Analysis—The tibiae of both the flexed and extended positions were semi-automatically segmented in FSE images by use of B-splines created with in-house software run in MATLAB (The MathWorks, Natick, MA, USA). The tibial shape in the flexed position was registered to the tibial shape in the extended position by use of an iterative closest-point shape-matching algorithm. (29) As a result, the tibia was held fixed, and kinematic parameters were calculated by analyzing the motion of the femur relative to the tibia. (Figure 2) Coordinate systems were created for the tibia and femur, as previous described. (17,18) In-house kinematic software calculated excursions of anterior tibial translation (ATT) and tibial rotation (TR) between extension and flexion. The intraobserver and interobserver reproducibilities of the analysis techniques used in this study amount to 2 to 3 pixels (0.6 mm to 0.9 mm) for translations and approximately 1.5 degrees for rotation. (17)

Quantitative Cartilage Assessment—Cartilage subcompartments were segmented semi-automatically on high-resolution SPGR images using in-house MATLAB-based software. (24,25) Previous studies from our lab showed high inter-observer and intraobserver reproducibility of this method. The knee was divided into five compartments: medial and lateral femoral condyles (MFC/LFC), medial and lateral tibia (MT/LT), and patella (PAT). Furthermore, in femoral condyles, the weight bearing (wb) region of the femoral condyles – the area overlying and between the meniscal horns as well as the regions overlying the meniscal body – were also evaluated. (Figure 3)

$T_{1\rho}$ maps were reconstructed by fitting the $T_{1\rho}$ images pixel by pixel using a Levenberg-Marquardt mono-exponential fitting algorithm developed in-house using the following equation:

$$S(TSL) \propto \exp(TSL/T_{1\rho}).$$

The SPGR images were rigidly registered to the reconstructed $T_{1\rho}$ maps using R-View registration toolkit (<http://rview.colin-studholme.net>). 3D cartilage segmentation contours

were overlaid on the $T_{1\rho}$ maps, and manually corrected to remove artifacts caused by partial volume effects with synovial fluid. Mean $T_{1\rho}$ relaxation times were calculated in the defined regions.

Statistical Analysis

ACL-reconstructed knees were compared to their uninjured contralateral counterpart. Within subject differences in kinematic parameters and $T_{1\rho}$ relaxation times in each defined subcompartments between injured and uninjured knees were explored using a paired samples t tests ($\alpha = 0.05$). Changes in kinematic parameters were calculated by subtracting the uninjured knee's kinematic parameter from the injured knees kinematic parameter:

$$\begin{aligned}\Delta \text{ ATT} &= \text{Injured ATT} - \text{Uninjured ATT} \\ \Delta \text{ TR} &= \text{Injured TR} - \text{Uninjured TR}\end{aligned}$$

The percent change in $T_{1\rho}$ relaxation time was calculated between the injured and uninjured knee using the following equation:

$$\frac{(\text{Injured } T_{1\rho} - \text{Uninjured } T_{1\rho})}{(\text{Uninjured } T_{1\rho})} * 100\%$$

“Restored” Versus “Abnormal Kinematics”

Patients were grouped as having “restored” kinematics or having “abnormal” kinematics. Patients were considered to have “restored” ATT if $\Delta \text{ ATT} < \text{SD}_{\text{ATT}}$, where SD_{ATT} is defined as the group standard deviation of ATT of the contralateral normal knees. Patients were considered to have “restored” TR if $\Delta \text{ TR} < \text{SD}_{\text{TR}}$, where SD_{TR} is defined as the group standard deviation of TR of the contralateral knees (Table 1).

After patients were grouped as having “abnormal” or “restored” ATT or TR, the difference in $T_{1\rho}$ relaxation times of defined cartilage subcompartments between these two groups were explored using one-tailed independent samples t tests ($\alpha = 0.05$).

Results

Kinematic Analysis

As a group, with respect to A-P position in the extended and flexed positions, as well as the A-P translation between those positions, there were no differences between the reconstructed and contralateral knees. When moving from extension to flexion, reconstructed knees translated on average 0.2 ± 2.89 mm posterior, while the contralateral normal knees translated on average 0.8 ± 3.85 mm anterior. (Table 2)

Moving from extension to flexion, the tibiae in both knees underwent relative internal rotation. There were no significant differences in absolute position of rotation in the tibiae in either the flexed or extended position. Moreover, despite having on average a greater arc of tibial rotation between extension and flexion in the reconstructed knees, there was not a statistically significant difference when compared to the contralateral knees. (Table 2)

$T_{1\rho}$ Quantification of Cartilage

The medial and patellar compartments of two patients were excluded secondary to $T_{1\rho}$ image artifact. For the remainder of the images, when comparing the reconstructed and contralateral healthy knees, there was a statistically significant ($p < 0.05$) elevation in the

$T_{1\rho}$ relaxation times of the injured MFC. (Table 3) Furthermore, there was also a statistically significant increase in the $T_{1\rho}$ relaxation times of the MFC-wb region in the reconstructed knees. (Table 3) There were no statistically significant differences in the $T_{1\rho}$ relaxation times of the MT, LFC, LT, or PAT between reconstructed and uninjured contralateral knees.

Relationship between cartilage $T_{1\rho}$ values and Kinematics

The average and standard deviation of ATT and ITR in the healthy contralateral healthy leg were 3.85 mm and 4.7 degrees respectively. We defined any subjects that had difference of more than one SD in their, ATT or ITR, between their knees as “abnormal” while those with less than one SD to be “restored.” Seven patients were defined as having “restored” ATT and 4 were defined as having “abnormal” ATT. Three patients were defined as having “restored” TR and 8 were defined as having “abnormal” TR. (Figure 4) There were statistically significant ($p < 0.05$) increases in the $T_{1\rho}$ relaxation times of the MFC-wb region, MT, PAT, and overall cartilage average in those patients with relatively “abnormal” ATT compared to those with “restored” ATT. (Figure 5) The percentage change in the cartilage $T_{1\rho}$ relaxation time of those patients with “abnormal” and “restored” TR showed no statistical significance. However, the percentage increase in the $T_{1\rho}$ relaxation time of the MFC-wb region approached significance in patients with relatively “abnormal” TR relative to those with “restored” TR (12.1% vs. 0.2%; $p = 0.08$).

Discussion

Contrary to our hypothesis, our results did not show any significant differences in knee kinematics between ACL-reconstructed and healthy contralateral knees. However, consistent with our hypothesis, ACL-reconstructed knees showed elevated cartilage $T_{1\rho}$ relaxation times in the medial compartment. Integrating our kinematic and cartilage data, our study suggests a possible link between tibiofemoral kinematics following ACL reconstruction and early cartilage matrix degeneration, particularly in the medial compartment.

Kinematic Analysis

Our kinematic results suggest that a single-bundle anteromedial portal drilling technique of ACL reconstruction largely restores knee kinematics. There were no statistically significant differences in ATT, consistent with previous studies. (10,16,19) However, contrary to previous studies, we did not show any significant differences in tibial rotation between injured and contralateral legs. (10,12,13,18) Improvement in knee kinematics in this cohort is likely related to differences in surgical technique and differences in experimental methodologies. It has been suggested that an ‘anatomic’ single bundle ACL reconstruction, as used in this study, can better restore knee kinematics compared to transtibial single bundle ACL reconstruction that was used in several previous studies. (10,18) Furthermore, it has been shown that kinematics can vary between low and high demand activities in ACL-reconstructed knees, and this might partially explain the differences in results of our study and those using motion analysis. (10,16,19) Nevertheless, our finding of a 1.9° external rotation offset at extension is in agreement with several motion analysis studies that examined ACL-reconstructed patients during the stance phase of running (10) and walking (12), and showed rotational offsets of 3.8° and 2.3° of relative external rotation throughout the stance phase.

$T_{1\rho}$ Quantification of Cartilage

Utilizing $T_{1\rho}$ MRI, a technique that has been shown to be sensitive to proteoglycan loss, our results indicate cartilage matrix degeneration within 18 months following ACL

reconstruction. Our findings are significant as we are showing early evidence of cartilage degeneration prior to any gross morphologic changes. The finding of significantly elevated $T_{1\rho}$ values in the medial side are consistent with a number of cohort studies which also reported a high prevalence of medial OA in ACL-injured and reconstructed knees. (30-32) Moreover, in a recent MRI-based study, Frobell et al demonstrated an increase in cartilage thickness in the central MFC cartilage one year following ACL injury, which they speculated indicated early cartilage degeneration. (33) We theorize that the combination of elevated forces transferred through the medial compartment (34) in conjunction with alterations in the knee kinematics following reconstruction leads to the early medial compartment cartilage degeneration detected by quantitative $T_{1\rho}$ MRI.

Relationship between cartilage $T_{1\rho}$ values and Kinematics

It has been hypothesized that changes to the loading patterns of the knee may influence the health and breakdown of knee cartilage. (5,8,9,20-21) However, given the long latent period between ACL injury and the development of radiographic degenerative joint disease, it is difficult to show a connection between kinematics and cartilage damage using conventional radiographic techniques. In this unique study, we stratified the patients based on their kinematics following ACL reconstruction in an attempt to identify loading patterns that might be deleterious to articular cartilage, and used $T_{1\rho}$ MRI to evaluate cartilage composition.

As a group, the reconstructed knees had similar knee kinematics when compared to the contralateral limb, however, there were individual variations that fell outside our definition of “restored” kinematics. Our findings suggest that reconstructed knees with “abnormal” patterns of ATT relative to their contralateral knee have increased cartilage breakdown in the medial compartment (MFC-wb and MT) as well as the patella. Moreover, “abnormal” patterns of tibial rotation also appear to potentially predispose patients to early cartilage breakdown in the MFC-wb region. Andriacchi et al showed that subtle changes in tibial rotation (9) as well as anterior-posterior translations (21) have significant effects on knee cartilage thickness, particularly in the medial compartment.

Limitations

There are several limitations of this study. First, our study cohort is small and our study design is cross sectional. Additionally, there was some heterogeneity amongst the surgeries of our patients, with 2 patients not receiving hamstring autografts and one patient requiring medial meniscus repair. However, the technique of ACL reconstruction is the same performed by the same surgeon to minimize surgical variability. Moreover, without more patients with meniscal injury, we cannot extrapolate the impact of meniscal injury on cartilage damage following ACL reconstruction.

Additionally, the use of the contralateral knee as a nested control creates some issues. While it is reasonable to compare cartilage quality between knees, there is a chance that the patient’s contralateral knee may not be entirely “healthy” despite our efforts to screen patients for previous knee damage. Excessive physical activity, previous occult knee injury, and gait adaptation following surgery are all potential confounders that must be considered. On the other hand, using contralateral knee as controls accounts for the physiological variation in cartilage composition and knee kinematics between subjects that age and activity level matching alone cannot account for. Lastly, although we are using methods that have been previously used and validated, we are not having our patients engage in a functional task to evaluate joint kinematics. Nevertheless, our methods allow for in vivo direct measures of motions of bone and soft tissues in the joint rather than indirect measures of joint motion. Additionally, the 125N load being subjected to the patients’ knees is less

than the physiologic load applied during daily functional tasks. However we chose this loading configuration as a compromise between sufficient loading, and subject tolerance of a load over the imaging time to avoid motion artifact. Using this loading configuration, our previous studies have demonstrated changes with ACL injuries, reconstructions and difference in outcome following different ACL reconstructions (17,18). In the future, we aim to collect data on a larger prospective cohort and combine more functional and clinical data, which will allow us to further test our hypothesis that kinematic changes following ACL reconstruction affect cartilage health and to better stratify kinematic and cartilage changes following ACL injury and reconstruction.

Conclusion

As early as 18 months following ACL reconstruction, the medial femoral condyle, and in particular the weight-bearing region, appears to have signs of cartilage matrix degeneration. Matrix degeneration, particularly in the medial compartment, may in part be explained by altered tibiofemoral kinematics in both the anterior-posterior plane as well as tibial rotation. Moreover, our results may imply that the medial compartment cartilage is more sensitive to changes in loading patterns. Given the relatively early timeframe in which our patients were imaged, it would seem reasonable to assume the $T_{1\rho}$ changes would be accentuated with longer follow-up, and further connections between kinematics and $T_{1\rho}$ relaxation times might become evident. $T_{1\rho}$ and kinematic MRI are promising tools for quantitative evaluation for both biochemical and biomechanical abnormalities in ACL-injured and reconstructed knees.

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Figure 1. Schematic of MR loading device. Subject lies supine on the MRI table, and the loading device applies an axial compressive load to plantar surface of the foot. Subjects are imaged in the flexed and extended positions, as pictured in the figure.

Figure 2.

Flowchart describing the image processing process. Once subjects are imaged in the 2 positions (a), the sagittal fast spin echo (FSE) then used to segment the tibia and the femur in both positions (b). The segmentations are then reformatted into a three-dimensional shape (c) and finally the tibiae in flexed and extended positions are rigidly registered to one another (d) in order to determine the relative anterior tibial translation (ATT) and tibial rotation (TR) between the two positions.

Figure 3.

An example cartilage segmentation of the medial femoral condyle (MFC), medial femoral condyle weight bearing region (MFC-wb) and medial tibia (MT). Femoral condyles and tibias are segmented separately on SPGR images and overlaid on $T_{1\rho}$ maps. The femoral condyle segmentations are further subdivided into the weight bearing region (as diagramed above). This region is defined as the cartilage overlying the meniscal horns and meniscal body as well as the cartilage between the meniscal horns.

Figure 4.

Subjects were divided into those with “abnormal” and “restored” kinematics, as pictured here in this dual axis graph. Subjects were defined as having abnormal kinematics if the difference between the ACL-reconstructed and contralateral healthy legs (delta anterior tibial translation or delta tibial rotation) was not within one standard deviation (defined as the standard deviation of the uninjured knees). The solid horizontal line represents one standard deviation (based upon the healthy contralateral knees) for both anterior tibial translation and tibial rotation. Those subjects between the two standard deviation lines are defined as having “restored” kinematics while those outside the standard deviation lines have “abnormal” kinematics. Anterior tibial translation and tibial rotation were considered separately.

Figure 5. Graphical comparison of the percentage increase (%) in the $T_{1\rho}$ relaxation times (between the ACL-reconstructed and contralateral healthy knees) across all compartments of the knee, including the weight bearing (wb) subcompartments of the femoral condyles, stratified by abnormal and restored anterior tibial translation (ATT). * $p < 0.05$

Table 1

Subjects were grouped into those with “Abnormal” or “Restored” anterior tibial translation (ATT) and tibial rotation (TR), based upon the magnitude of difference in the kinematics between their ACL-reconstructed and contralateral knees. If the difference in kinematics (Δ ATT or Δ TR) was greater than one standard deviation (SD) relative to the contralateral side, kinematics were considered “abnormal,” otherwise kinematics were considered “restored.”

“Restored” ATT		“Abnormal” ATT	“Restored” TR		“Abnormal” TR
Δ ATT	SD _{ATT}	Δ ATT > SD _{ATT}	Δ TR	SD _{TR}	Δ TR > SD _{TR}

Δ ATT = Injured ATT – Uninjured ATT; Δ TR = Injured TR – Uninjured TR

SD_{ATT}: the group standard deviation of ATT of the contralateral knees; SD_{TR}: the group standard deviation of TR of the contralateral knees

Table 2

Kinematic comparison of ACL-Reconstructed (Injured) and contralateral knees. Tibial rotation (TR) values and Flexion/Extension angles are reported in degrees while anterior tibial translation (ATT) values are reported in (mm). Negative values represent internal tibial rotation and posterior tibial translations.

	Reconstructed Knee	Contralateral Knee	p-value
<i>TR—Extension</i>	-1.91 ± 7.22	-3.76 ± 4.23	0.44
<i>TR—Flexion</i>	-6.83 ± 6.184	-5.55 ± 5.56	0.62
<i>TR</i>	-4.92 ± 5.50	-2.82 ± 4.69	0.17
<i>ATT</i>	0.20 ± 2.89	-0.76 ± 3.85	0.48
<i>Flexion Angle</i>	29.2 ± 6.6	28.4 ± 7.2	0.65
<i>Extension Angle</i>	-1.7 ± 5.9	-3.1 ± 3.4	0.53

Table 3

Comparison of $T_{1\rho}$ relaxation times in all compartments (Lateral femoral condyle, LFC; Lateral Femoral Condyle weight bearing region, LFC-wb; Lateral Tibia, LT, Medial Femoral Condyle, MFC; Medial Femoral Condyle weight bearing region, MFC-wb; Medial Tibia, MT; Patella, PAT; Overall Cartilage Average, Overall) between ACL-Reconstructed (Injured) and contralateral (Healthy) knees. Relaxation times are reported in milliseconds.

	LFC	LFC-wb	LT	MFC	MFC-wb	MT	PAT	Overall
<i>Injured Knees</i>	42.3 ± 4.1	41.0 ± 5.3	37.6 ± 4.6	42.6 ± 3.7	42.2 ± 5.9	39.9 ± 6.6	40.2 ± 5.6	40.2 ± 4.0
<i>Healthy Knees</i>	40.5 ± 2.8	38.6 ± 4.3	36.7 ± 3.1	39.8 ± 3.3	38.5 ± 4.0	39.9 ± 4.4	40.5 ± 3.8	39.2 ± 2.6
<i>p-value</i>	0.08	0.13	0.20	0.04*	0.01*	0.48	0.42	0.10

*
p < 0.05