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Frontal plane knee mechanics and medial cartilage MR relaxation times in individuals with ACL reconstruction : A pilot study

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Abstract

Background—The objective of this pilot study was to evaluate cartilage $T_{1\rho}$ and T_2 relaxation times and knee mechanics during walking and drop-landing for individuals with anterior cruciate ligament reconstruction (ACL-R).

Methods—Nine patients (6 men and 3 women, Age 35.8 ± 5.4 years, BMI 23.5 ± 2.5 kg/m²) participated 1.5 \pm 0.8 years after single-bundle two-tunnel ACL reconstruction. Peak knee adduction moment (KAM), flexion moment (KFM), extension moment (KEM), and peak varus were calculated from kinematic and kinetic data obtained during walking and drop-landing tasks. $T_{1\rho}$ and T_2 times were calculated for medial femur (MF), and medial tibia (MT) cartilage and compared between subjects with low KAM and high KAM. Biomechanical variables were compared between limbs.

Results—The high KAM group had higher $T_{1\rho}$ for MT ($p = 0.01$), central MT ($p = 0.05$), posterior MF ($p = 0.04$), posterior MT ($p = 0.01$); and higher T_2 for MT ($p = 0.02$), MF ($p = 0.05$) posterior MF ($p = 0.002$) and posterior MT ($p = 0.01$). During walking, ACL-R knees had greater flexion at initial contact ($p = 0.04$), and lower KEM ($p = 0.02$). During drop-landing, the ACL-R knees had lower KAM ($p = 0.03$) and KFM ($p = 0.002$).

Conclusion—Patients with ACL-R who have higher KAM during walking had elevated MR relaxation times in the medial knee compartments. These data suggest that those individuals who have undergone ACL-R and have higher frontal plane loading, may be at a greater risk of knee osteoarthritis.

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CONFLICT OF INTEREST

None of the authors report any conflicts of interest.

Keywords

T1 ρ ; T2; gait; drop-landing; knee adduction moment

INTRODUCTION

Over 50% of individuals with an anterior cruciate ligament (ACL) injury and reconstruction develop post-traumatic osteoarthritis (PTOA).¹⁻³ Multiple studies have shown that individuals with ACL-reconstruction (ACL-R) continue to demonstrate abnormal walking mechanics of the reconstructed knee when compared to the contralateral knee and compared to control subjects.⁴⁻⁶ It has been hypothesized that abnormal gait mechanics may contribute to altered cartilage loading and subsequent PTOA following an ACL-R.⁷ Specifically, higher external knee adduction moment (KAM) and dynamic knee varus during walking have been implicated in the pathogenesis of knee OA.⁸⁻¹¹ These metrics, along with static varus deformity,¹² are associated with an increase in frontal plane knee loading predisposing the medial knee cartilage to greater loading and subsequent degeneration.^{8, 13, 14} Furthermore, abnormal movement patterns for the reconstructed knee have also been demonstrated for other activities including running,⁴ stair climbing,^{5, 7} and drop landing.¹⁵⁻¹⁷ However, there are also studies that report no difference in KAM⁷ or lower KAM in the ACL-R knees.⁵ Hence, it is possible that considerable variability in movement patterns exists post ACL-R between individuals. Those who have movement patterns characterized with high KAM may have greater risk of cartilage degeneration compared to those who do not have such movement patterns. Although, some recent work has shown an association between abnormal knee sagittal kinematics during walking, and cartilage morphology in individuals with ACL-R,¹⁸ no studies have been performed to evaluate the relationship between frontal plane knee mechanics and early cartilage degeneration in individuals with ACL-R. Therefore, it is important to evaluate if cartilage composition post ACL-R is different between individuals who have high KAM vs. those who have low KAM.

Early changes in knee OA consist of loss of proteoglycans (PG) and increase in water content of the articular cartilage, along with loosening, disorganization and loss of collagen matrix.¹⁹ Loss of PG and collagen disruption hampers the load bearing ability of cartilage leading to further cartilage degeneration.¹⁹ These biochemical changes can be detected using non-invasive quantitative MR imaging techniques of T_{1 ρ} and T₂ relaxation times which are sensitive to loss of PG and collagen disruption respectively, and are promising biomarkers of early disease²⁰⁻²⁴. An increase in T_{1 ρ} and T₂ relaxation times indicates loss of PG and disruption of collagen matrix, which is invisible to conventional radiography and morphologic MR imaging^{20, 23-26}. It has been shown that in people with ACL injuries, or knee OA, there is an increase in these MR relaxation times showing cartilage degeneration^{20, 23-26}.

Abnormal knee mechanics following an ACL-R, especially greater KAM, may be related to accelerated medial knee cartilage degeneration. However, association of these MR relaxation time parameters with frontal plane knee mechanics in individuals with ACL-R has not been performed. If abnormal frontal plane mechanics are associated with early

cartilage degeneration in individuals with ACL-R, it may allow for development of early intervention programs targeted at training healthier movement patterns. Hence, the objective of this pilot study was to evaluate the articular cartilage $T_{1\rho}$ and T_2 relaxation times, and knee mechanics during walking and drop-landing for individuals with ACL-R. Specifically, we evaluated the differences in medial articular cartilage global and sub-regional $T_{1\rho}$ and T_2 relaxation times between individuals with high vs. low KAM during walking post ACL-R.

METHODS

Subjects

Nine patients (6 men and 3 women, Age 35.8 ± 5.4 years, BMI 23.5 ± 2.5 kg/m²) were referred by their orthopaedic surgeon 1.5 ± 0.8 years after single-bundle two-tunnel ACL reconstruction. Six patients had isolated ACL repair with either posterior tibialis allograft (from cadaver) or hamstring autograft (from self), one patient had concurrent partial lateral meniscectomy with hamstring autograft, one patient had concurrent partial medial meniscectomy with posterior tibialis allograft and one patient had concurrent medial meniscus repair with posterior tibialis allograft. The study was performed in accordance with the rules of our institution's Committee on Human Research. Informed consent was obtained from each patient after the nature of the study had been explained.

Motion Analysis

Three-dimensional kinematic data were collected at 250 Hz using a passive 10-camera system (VICON, Oxford Metrics, UK), and kinetic data were collected at 1000 Hz from two embedded force platforms (AMTI, Watertown, MA). Fourteen millimeter spherical retro-reflective markers were placed on bony landmarks of bilateral lower extremities for identification of joint centers and rigid clusters placed on the lateral surface of the subject's thighs, legs and heel shoe counters were used to track segment motions²⁷. Each subject performed a walking task and a drop jump task. For the walking task, patients were instructed to walk at a pace of 1.3 ± 0.07 m/s. A trial was considered acceptable when there was clean foot-strike on any of the force platforms and the speed was within $\pm 5\%$ of the defined speed. Three good trials were collected from both lower extremities. The drop jump task, as described by Pollard et al²⁸, involved the patient standing on a 30.5cm platform and stepping off with one foot landing on each of the force plates. The subjects were instructed to land with both feet contacting the ground simultaneously, and then immediately jump "as high as possible". A successful trial was defined as one where the patient stepped off the platform (as opposed to jumping off or lowering themselves down), landed with both feet simultaneously with one foot on each force plate and immediately performed a maximal vertical jump. Three drop jump trials were collected.

Kinematic and kinetics were calculated using Visual3D (C-motion, Georgetown, MD). All net joint moments are expressed as external moments and normalized to body mass (Nm/kg). Variables were calculated for the stance phase when the foot was in contact with ground and included – peak KAM (early stance), peak external knee flexion moment (KFM) (early stance during walking, not present during drop-landing), peak external knee extension moment (KEM) (late stance during walking), and peak adduction angle (peak varus). 1st

peak KAM (early stance) was selected to stratify the subjects into high-KAM and low-KAM groups because it has been shown to be related to progression of knee OA and medial cartilage and meniscus damage in earlier studies.^{9, 29, 30}

MR Imaging

Imaging for the ACL-R knee was performed using a 3T GE Signa HDx MR Scanner (General Electric, Milwaukee, WI, USA) and an 8-channel phased-array knee coil (Invivo, Orlando, FL, USA) with the patient in a supine position. The imaging protocol included clinical T2-weighted FSE images (TR/TE=4300/51ms, FOV = 14cm, matrix=512x256, 2 mm slice thickness), sagittal 3D fat-saturated high-resolution spoiled gradient-echo (SPGR) images (TR/TE=15/6.7ms, FOV = 14cm, matrix =512x512, 1mm slice thickness) and 3D T_{1ρ}/T₂ quantification sequence developed previously in our lab³¹ (TR/TE=9.1/3.3ms, TSL: 0/10/40/80 msec, spin-lock frequency: 500Hz, FOV= 14cm, matrix=256x128, 4 mm slice thickness; for T₂: preparation TE = 0/13.7/27.3/54.7 msec; total acquisition time = 9 min 30 sec).

Medial femoral condyle (MF), and medial tibia (MT) cartilage compartments were segmented on multiple slices semi-automatically in high resolution SPGR images using the in-house software developed with Matlab (Mathworks, Natick, MA, USA) based on edge detection and Bezier splines³². These compartments were further divided into sub-regions as shown in Figure 1. T_{1ρ} and T₂ maps were reconstructed by fitting the T_{1ρ}- and T₂-weighted images pixel-by-pixel to the equations below using in-house developed software:

$$S(TSL) \propto \exp(-TSL/T_{1\rho}) \text{ for } T_{1\rho}$$

$$S(TE) \propto \exp(-TE/T_2) \text{ for } T_2$$

T_{1ρ} and T₂ maps were rigidly registered to SPGR images and cartilage contours generated from SPGR images after segmentation were overlaid to the registered T_{1ρ} and T₂ maps. Mean T_{1ρ} and T₂ values were calculated in defined regions. To reduce artifacts caused by partial volume effects with synovial fluid, pixels with relaxation time greater than 130 ms in T_{1ρ} or 100 ms for T₂ maps were removed from the data used for quantification.

Statistical Analysis

Patients were divided into two groups using median peak KAM during walking: Group A) low KAM, and Group B) high KAM. Mean and standard deviation for all variables were calculated. Group comparisons were made using independent samples t-tests for MF and MT T_{1ρ} and T₂ relaxation time parameters. Paired t-tests were used to compare the sagittal plane metrics, peak KAM, peak varus angle during the walking and drop-landing tasks between the ACL-R and contralateral knees. All statistical analyses were done using SPSS (SPSS Inc. Chicago, IL) with one-tailed significance level set at p = 0.05.

RESULTS

Motion Analysis

Frontal plane analyses showed no significant differences between the ACL-R and contralateral knees for peak KAM (Mean \pm SD - ACL-R: 0.53 ± 0.20 Nm/kg vs. contralateral: 0.58 ± 0.19 Nm/kg, $p = 0.12$) and peak varus angle (Mean \pm SD - ACL-R: 2.64 ± 3.09 vs. contralateral: $2.86\pm 2.86^\circ$, $p = 0.39$) during walking. Sagittal plane analyses showed that during walking, the ACL-R patients made initial contact with greater knee flexion (Mean \pm SD - ACL-R: $4.3\pm 4.3^\circ$ vs. contralateral: $3.0\pm 3.9^\circ$, $p = 0.04$), had a lower peak external extension moment (Mean \pm SD - ACL-R: -0.44 ± 0.12 Nm/kg vs. contralateral: -0.50 ± 0.11 Nm/kg, $p = 0.02$), and a close to significance lower peak external flexion moment (Mean \pm SD - ACL-R: 0.44 ± 0.11 Nm/kg vs. contralateral: 0.53 ± 0.20 Nm/kg, $p = 0.06$).

During drop-landing, the ACL-R knees had lower peak KAM Mean \pm SD - (ACL-R: 0.23 ± 0.18 vs. contralateral: 0.32 ± 0.18 Nm/kg, $p = 0.03$) but the peak varus angle was no different (Mean \pm SD - ACL-R: 5.0 ± 7.5 vs. contralateral: $3.6\pm 4.4^\circ$, $p = 0.13$). In the sagittal plane, the ACL-R knees had lower peak external knee flexion moment (Mean \pm SD - ACL-R: 1.68 ± 0.36 vs. contralateral: 2.12 ± 0.40 Nm/kg, $p = 0.002$).

Medians for the peak KAM during walking was calculated to be 0.367 Nm/kg. Patients were stratified into those with KAM below the median (Group A: Low KAM, $n = 5$) and those with KAM greater than the median (Group B: High KAM, $n = 4$). (Table 1).

MR Relaxation Times

Table 2, and Figures 2–3 show that data for MR relaxation times for the two groups. On comparing the MR relaxation times for the reconstructed knee between the two groups, it was seen that Group B had higher $T_{1\rho}$ relaxation times for MT ($p = 0.01$, Figure 2) and for MF ($p = 0.06$, Figure 2) with a difference close to significance. Sub-compartment analyses (Table 2) showed that the Group B had higher $T_{1\rho}$ relaxation times for central MT ($p = 0.05$), posterior MF ($p = 0.04$), posterior MT ($p = 0.01$). For T_2 relaxation times, Group B had higher values for MT ($p = 0.02$, Figure 3) and MF ($p = 0.05$). Sub-compartmental analyses (Table 2) showed higher T_2 times for posterior MF ($p = 0.002$) and posterior MT ($p = 0.01$).

DISCUSSION

This goal of this pilot study was to explore the relationship between key frontal plane loading metrics which are known to be a risk factor for knee OA, and medial knee articular cartilage MR relaxation times, in individuals with ACL-R. The key finding from this study was that people with ACL-R who demonstrate high KAM show elevated articular cartilage MR relaxation times in the medial knee compartments compared to those with low KAM. KAM is considered a surrogate measure of medial knee loading during functional activities^{8, 13, 14}. It has been shown to be a risk factor for progression of knee OA⁹. Individuals with knee OA who have greater frontal plane loading have a higher rate of cartilage loss²⁹, increased incidence of medial knee cartilage lesions³³, and medial

meniscus extrusion³⁰. Earlier work has also shown that KAM during drop-landing is related to medio-lateral $T_{1\rho}$ relaxation times ratio in young healthy adults²⁷. Hence, higher frontal plane loading and medial cartilage overload may lead to changes in medial knee cartilage composition as assessed using MR relaxation time parameters. Based on these data individuals with ACL-R who move with patterns that may lead to higher frontal plane loading may be at greater risk of PTOA. These individuals may benefit from a screening and targeted interventions to change these movement patterns and potentially prevent PTOA.

Current interventions for preventing the onset or progression of idiopathic knee OA or PTOA have been shown to be ineffective³⁴. People with ACL-R are at a particularly high risk of PTOA^{2, 3}. It has been hypothesized that abnormal gait mechanics may contribute to altered cartilage loading and subsequent PTOA following an ACL-R⁷. Multiple studies have shown that individuals with ACL-reconstruction (ACL-R) continue to demonstrate abnormal walking mechanics of the reconstructed knee when compared to the contralateral knee and compared to control subjects⁴⁻⁶. Higher KAM in the ACL-R knees compared to control knees has been reported^{6, 35}. However, other studies have reported no difference in KAM⁷ or even lower KAM in the ACL-R knees⁵. We also did not find a statistically significant difference in KAM between the ACL-R and contralateral knees. These results suggest that there may be significant variability in the movement patterns in individuals post ACL-R³⁵. This is supported by the observation of higher KAM in women with ACL-R compared to men with ACL-R³⁶. Hence future studies should consider studying sub-groups of individuals with ACL-R who demonstrate higher frontal plane loading longitudinally. This approach may allow for identification of risk factors specific to the sub-group that walks with greater frontal plane loading.

Earlier studies have also reported increased knee flexion at initial contact and lower sagittal plane moments in knees with ACL-R compared to contralateral or control knees^{5, 18, 37}. We also found higher knee flexion at initial contact and lower sagittal plane moments during walking. These sagittal plane patterns have been thought to be related to altered cartilage loading and subsequent degeneration. Greater knee flexion at initial contact was recently shown to be related with cartilage morphology¹⁸. The authors found significant correlation between knee flexion angle at initial contact and region of thickest femoral cartilage. However, they did not find a significant difference in the region of thickest femoral cartilage between the ACL-R and contralateral knees even though the ACL-R knees landed with greater flexion. They concluded that in the ACL-R knees, thinner cartilage areas may experience higher loading, potentially leading to degeneration.

MR relaxation times allow for non-invasive and early detection of cartilage degeneration. An increase in $T_{1\rho}$ and T_2 relaxation times indicates an increase in water, loss of proteoglycans and disruption of collagen matrix^{20, 21, 23, 38-40}. Numerous studies have shown that people with knee OA have higher $T_{1\rho}$ and T_2 relaxation times compared to healthy control subjects^{20, 21, 24}. Earlier studies also report higher $T_{1\rho}$ and T_2 relaxation times in ACL-R knees compared to the contralateral and control knees^{41, 42}. Cartilage composition as assessed using MR relaxation times could be related to the loading experience by the cartilage during daily activities. A recent study reported significant associations between sagittal, frontal, and transverse plane kinetics during hopping and

drop-landing tasks, and $T_{1\rho}$ and T_2 relaxation times²⁷. The results from this pilot study suggest that in individuals with ACL-R, higher frontal plane loading may be related to early cartilage degeneration, and MR relaxation times may be related to differences in movement patterns. Biomechanical studies have shown that following ACL-R the contact mechanics and contact area do not return to normal.^{37, 43} The medial contact area was smaller following ACL-R at 0° and 15° of flexion compared to normal knees along with greater cartilage deformation.³⁷ Also, the cartilage contact was located relatively more posteriorly and laterally on tibial plateaus in people with ACL-R during a weight-bearing knee flexion activity. Although, direct correlation between our data and these previous findings is not possible, our findings of higher MR relaxation times in central and posterior compartments could be related to these altered mechanics. However, future studies with larger samples and longer follow-up are needed to confirm these findings.

One major limitation of our study is the small number of patients. Also, our cohort was not homogenous in terms of the types of grafts, and concomitant injuries. Hence, the results need to be confirmed with larger samples. Also, we did not have information on the activity levels of these patients. It is plausible that amount of daily activity may be related to cartilage composition. This should be evaluated in future studies as well. KAM during walking could be affected by lower extremity alignment,¹² angle of toe-out,^{44, 45} step width,⁴⁶ and the type of shoes worn.⁴⁷ The angle of toe-out and step-width were not different between the high KAM and low KAM groups in our cohort for both tasks (data not shown). However, we did not account for these and other variables in our analyses considering the preliminary nature of the work and future studies with larger samples and a control group are needed to investigate these associations. Finally, this study followed patients over an average period of 1.5 years following ACL-R. Considering the chronic nature of OA, longer follow-up is needed to evaluate these changes further.

To conclude, we found that people with ACL-R who have movement patterns characterized by higher KAM during walking had elevated MR relaxation times in the medial knee compartments. These data suggest that it may be possible that those individuals who have undergone ACL-R and have higher frontal plane loading, may be at a greater risk of PTOA. Hence, screening for these potentially harmful movement patterns may offer opportunities to develop targeted interventions for this subgroup of patients with ACL-R. Future studies with larger cohorts and longitudinal follow-up will be needed to confirm these preliminary findings.

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Highlights

- 9 patients 1.5 years following ACL reconstruction participated.
- Evaluated medial knee cartilage MR relaxation times.
- Evaluated the mechanics of walking and drop-landing.
- High T1 ρ and T2 in patients with high knee adduction moment during walking.

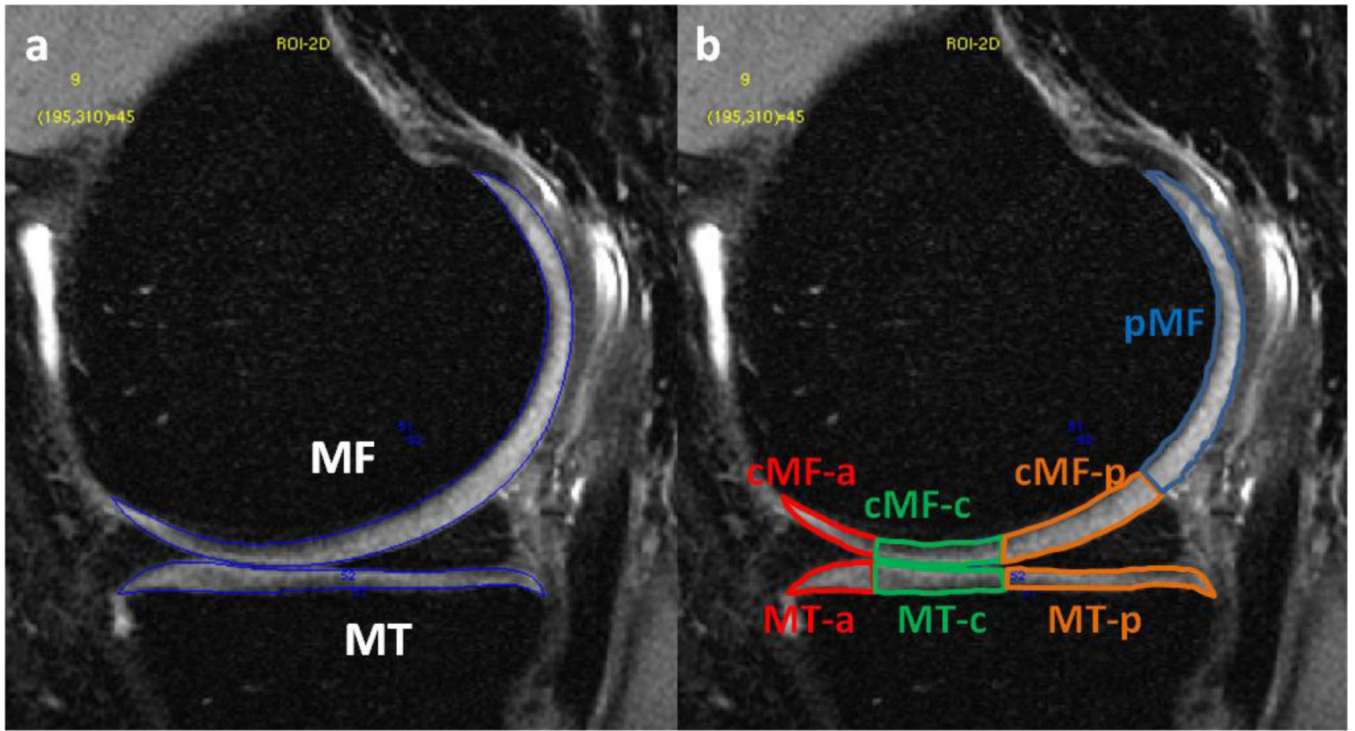


Figure 1.

T1ρ in High vs. Low KAM

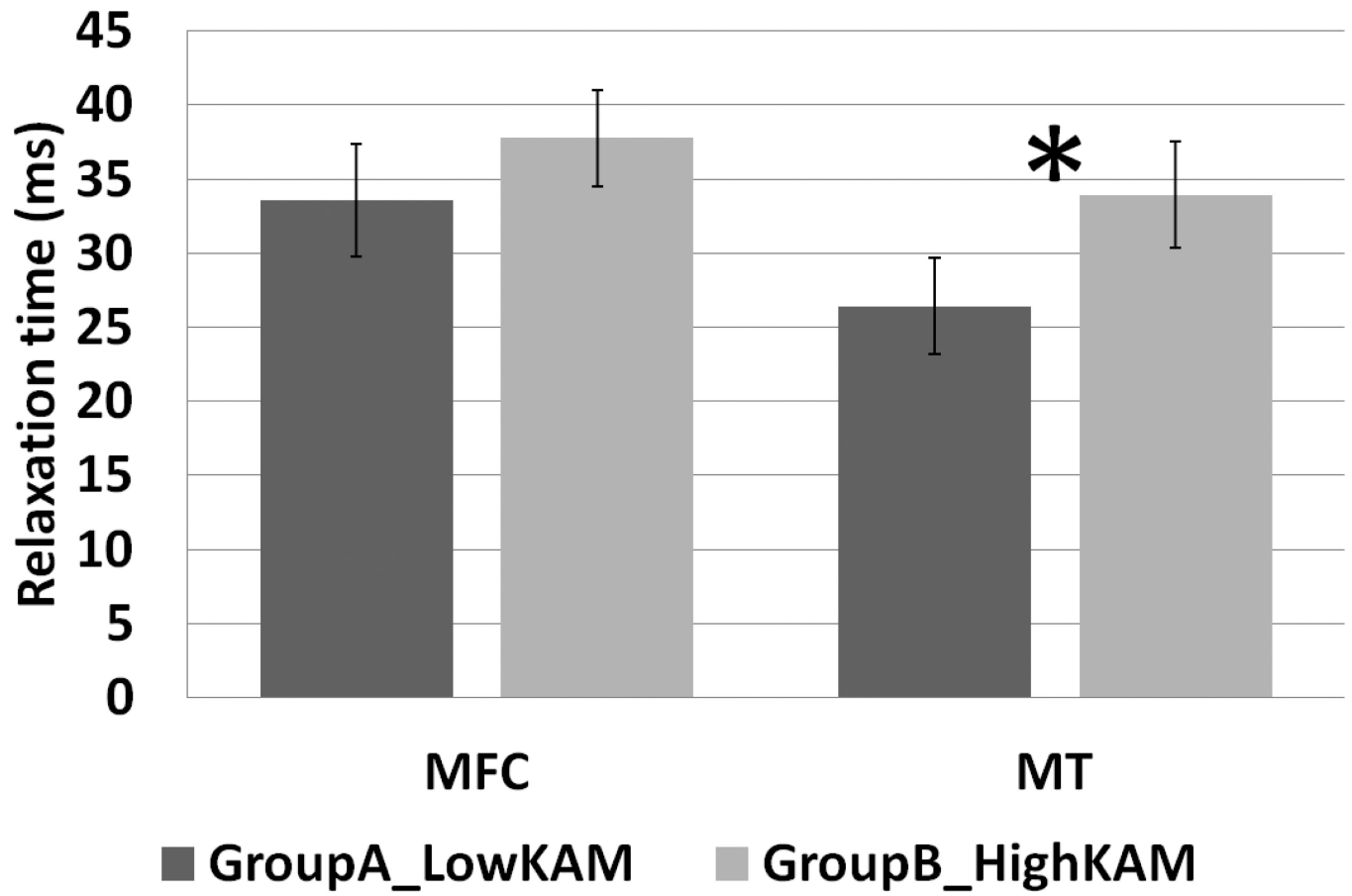


Figure 2.

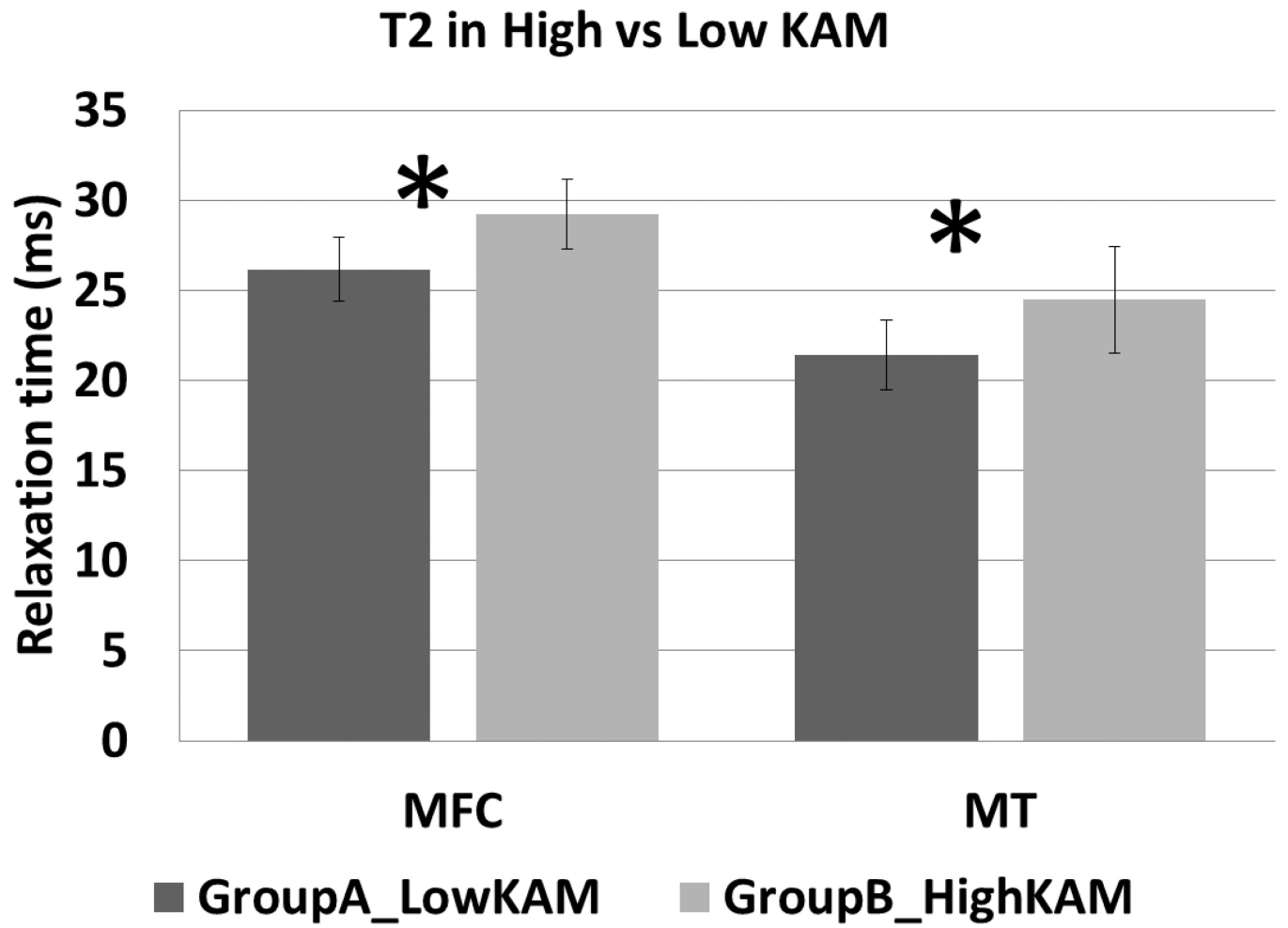


Figure 3.

Table 1

ACL-reconstructed patients grouped by knee biomechanics

	A: Low KAM (n = 5)	B: High KAM (n =4)	p-value
Age	29.0±17.0	36.9±2.2	0.20
BMI	22.7±1.7	24.4±3.3	0.17
Peak KAM during walking (Nm/kg)	0.30±0.05	0.54±0.12	<0.01

Table 2

Mean \pm Standard Deviation for Sub-compartment $T_{1\rho}$ and T_2 relaxation times for the two groups.

		A: Low KAM (n = 5)	B: High KAM (n = 4)	p-value
$T_{1\rho}$ relaxation times (msec)				
Femur	cMF-a	41.8 \pm 7.8	38.3 \pm 9.6	0.28
	cMF-c	34.6 \pm 3.9	36.8 \pm 5.1	0.23
	cMF-p	29.8 \pm 6.1	35.3 \pm 8.5	0.15
	pMF	33.4 \pm 4.7	38.9 \pm 2.3	0.04
Tibia	MT-a	30.6 \pm 7.1	28.9 \pm 6.2	0.36
	MT-c	29.4 \pm 2.3	32.4 \pm 2.4	0.05
	MT-p	21.4 \pm 4.7	32.8 \pm 6.8	0.01
T_2 relaxation times (msec)				
Femur	cMF-a	31.1 \pm 5.3	29.1 \pm 6.3	0.31
	cMF-c	28.1 \pm 2.6	26.9 \pm 4.5	0.32
	cMF-p	23.2 \pm 3.3	27.7 \pm 6.3	0.11
	pMF	25.4 \pm 0.9	30.4 \pm 2.6	0.002
Tibia	MT-a	27.0 \pm 4.7	22.6 \pm 2.4	0.07
	MT-c	23.3 \pm 4.2	25.5 \pm 2.6	0.20
	MT-p	19.0 \pm 1.8	26.4 \pm 4.9	0.01