Patients With Abnormal Limb Kinetics at 6 Months After Anterior Cruciate Ligament Reconstruction Have an Increased Risk of Persistent Medial Meniscal Abnormality at 3 Years

Tomohiro Shimizu,*†‡ MD, Alexander R. Markes,* MS, Michael A. Samaan,†§ PhD, Matthew S. Tanaka,† MS, Richard B. Souza,†|| PhD, Xiaojuan Li,†¶ PhD, and C. Benjamin Ma,*# MD

Investigation performed at the University of California, San Francisco, California, USA

Background: Several reports have shown that altered biomechanics after anterior cruciate ligament reconstruction (ACLR) are associated with the development of posttraumatic osteoarthritis. However, it is not fully understood whether altered biomechanics are associated with meniscal changes after ACLR.

Purpose: To investigate changes in gait and landing biomechanics over a 3-year period and their correlation with meniscal matrix alterations present before and after ACLR through use of magnetic resonance T1ρ/T2 mapping, which can allow detection of early meniscal degeneration.

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

Methods: A total of 36 patients with ACLR and 14 healthy controls were included in this study. All patients underwent magnetic resonance imaging and biomechanical analysis during gait of the injured knee and contralateral knee preoperatively and at 6 months, 1 year, 2 years, and 3 years after ACLR, as well as biomechanical analysis during drop-landing from 6 months to 3 years postoperatively. To evaluate biochemical changes of the mensical matrix, T1ρ/T2 relaxation times of the meniscus were calculated.

Results: Mean T1ρ/T2 values of ACLR knees were significantly higher than values in the contralateral and control knees in the posterior lateral and medial horns up to 1 year after surgery; however, the differences were not seen at 3 years after surgery. The ACLR knee exhibited significantly lower peak knee flexion moment and angle during gait at 6 months compared with baseline and continued to decrease until 3 years. The ACLR knee exhibited significantly lower peak vertical ground-reaction force and peak knee flexion moment and angle during landing at 6 months. However, the differences were no longer present at 3 years. Biomechanics at 6 months had significant correlations with changes of mean T1ρ/T2 values in the medial posterior horn from 6 months to 3 years after ACLR.

Conclusion: Although mean T1ρ/T2 values of meniscus seen before ACLR improved after 3 years, approximately 30% of patients with ACLR did not show decreases from 6 months to 3 years. Patients with abnormal lower limb kinetics of the ACLR knee at 6 months showed less recovery in the medial posterior horn from 6 months to 3 years, suggesting that biomechanical parameters during the early stage of recovery might be potential biomarkers for predicting persistent medial meniscal abnormality after ACLR.

Keywords: ACL reconstruction; biomechanics; meniscus; MRI

Anterior cruciate ligament reconstruction (ACLR) is one of the most common orthopaedic procedures performed in the United States.[28] ACLR is performed in an attempt to restore knee stability and allow the patient to return to athletic activity. It is also thought that ACLR will provide protection from subsequent meniscal injuries, which may ultimately help decrease the progression of degenerative joint disease. Nonetheless, despite surgery to restore knee stability after ACL injury, long-term progression of post-traumatic changes still occurs.[1,2,10,13,26,27] Although altered lower extremity joint biomechanics are commonly reported after ACL injury[17,36] and may contribute to cartilage lesions and subsequent development of knee osteoarthritis,[21,22,35,41] little is known about the associations between altered biomechanics and meniscal changes after ACLR.

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The meniscal fibrocartilage structure is composed primarily of type I collagen (98%), proteoglycans (<1%), and water (1%).[40] As shown in previous studies, meniscal damage is linked to biochemical changes in the meniscus as defined by damage to the collagen-proteoglycan matrix, which is strongly associated with osteoarthritic cartilage loss.[4,19,44] Quantitative magnetic resonance imaging (MRI) techniques are able to assess these differences in the changing biochemical composition of the meniscus.[44] Previous studies used magnetic resonance (MR) T1ρ and T2 mapping to evaluate the differences between the menisci of healthy controls and patients who had undergone ACLR as well as patients with mild or severe osteoarthritis and found that meniscal MR quantification can be used to differentiate these groups.[32,42,44] Quantitative MRI thus provides the opportunity for early detection of compositional differences within a damaged meniscus.

Various studies have demonstrated associations between ACLR gait biomechanics and knee joint degeneration.[6,21,22,31,33,41] However, most patients with ACLR are young and active, perform more dynamic tasks, and tend to experience higher knee joint loading on a daily basis. Landing tasks are widely used to screen for risk of ACL injury and risk of reinjury after ACLR.[18,23,30] However, these landing tasks have been used less frequently to assess for potential connections between altered lower extremity joint biomechanics and knee joint degeneration after ACLR. A recent systematic review reported that landing tasks are best compared with walking, jogging, cutting and so on, and are therefore recommended during the early stages of recovery after ACLR.[12] Although recent studies showed that the biomechanical changes during landing at early stages of recovery were associated with cartilage degeneration[35] and joint laxity[34] after ACLR, association with meniscal change after ACLR has not been investigated. Hence, it is of great interest to understand whether the biomechanical changes after ACLR are related to meniscal degeneration.

This study had 2 aims: (1) to investigate the longitudinal changes in meniscal T1ρ/T2 values and biomechanics during gait and landing tasks after ACLR and (2) to investigate the associations between changes in meniscal composition using T1ρ/T2 mapping and biomechanics in patients with ACLR. We hypothesized that altered biomechanics at an early stage after ACLR would be associated with meniscal degeneration after ACLR.

METHODS

Participants

This study was approved by the institutional committee for human research at our institution, and informed consent was obtained from all participants. The study was compliant with the Health Insurance Portability and Accountability Act (HIPAA). Patients with unilateral ACL injuries were recruited after ACL injury but before ACLR from September 2011 to May 2014. This study focused on 36 participants (from among the 53 recruited before ACLR as part of an ongoing observational study) who had MRI and biomechanics data from prior to their operation through 3 years after ACLR (Figure 1).

Exclusion criteria were (1) concomitant ligamentous injuries requiring surgical treatment, (2) history of inflammatory or primary osteoarthritis, (3) previous knee surgery, and (4) an abnormal contralateral knee. We excluded 4 patients with meniscal repair because they would undergo a different rehabilitation protocol and have different weightbearing requirements. Furthermore, 4 patients with rerupture during follow-up were excluded. A further 8 patients were lost to follow-up from baseline to 3 years after ACLR. However, 6 patients with partial meniscectomy were not excluded because they would undergo the same rehabilitation protocol.

Surgery and Rehabilitation

All 36 patients underwent ACLR by 1 of 3 board-certified, fellowship-trained orthopaedic surgeons (C.B.M.) at a single institution using either hamstring tendon autograft or soft tissue allograft such as posterior tibialis or hamstring. Graft choices and their factors with regard to outcomes and morbidity were discussed with patients. The choice was determined with consent from the patient. Anatomic single-bundle ACLR was performed. The femoral tunnels were drilled by use of anteromedial portal drilling. All patients had the same fixation method with suspensory femoral fixation and interference tibial fixation.

All patients participated in a standard postoperative ACL rehabilitation program at our sports medicine clinic. Immediate postoperative recovery emphasized control of pain and swelling and regaining motor control. The operative knee was kept in a hinged knee brace at all times for 3

[#]Address correspondence to C. Benjamin Ma, MD, 1500 Owens Street, Suite 186, Department of Orthopaedic Surgery, University of California, San Francisco, CA 94158, USA (email: maben@ucsf.edu).

*Department of Orthopaedic Surgery, University of California, San Francisco, California, USA.

[†]Musculoskeletal Quantitative Imaging Research Group, Department of Radiology and Biomedical Imaging, University of California, San Francisco, California, USA.

[‡]Department of Orthopaedic Surgery, Faculty of Medicine and Graduate School of Medicine, Hokkaido University, Hokkaido, Japan.

[§]Department of Kinesiology and Health Promotion, University of Kentucky, Lexington, Kentucky, USA.

[‖]Department of Physical Therapy and Rehabilitation Science, University of California, San Francisco, California, USA.

[¶]Department of Biomedical Engineering, Program of Advanced Musculoskeletal Imaging (PAMI), Cleveland Clinic, Cleveland, Ohio, USA.

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Ethical approval for this study was obtained from the University of California, San Francisco Institutional Review Board (ref No. 197169).

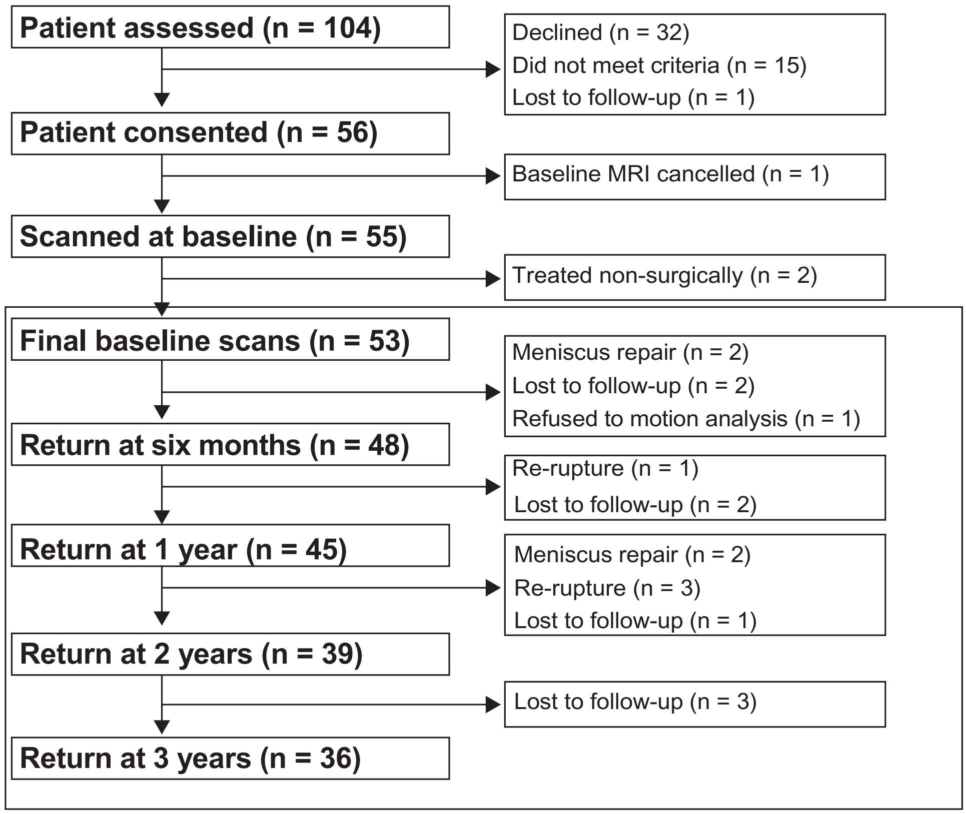

Figure 1. Flowchart of study participants. MRI, magnetic resonance imaging.

weeks, which was locked in extension while the patient was walking until quadriceps control and normal gait were achieved. All patients were compliant and were monitored by a physical therapist during that time. The primary focus for the first 6 weeks was return of normal range of motion and quadriceps control. Return to running was allowed at approximately 4 months, when core stability was appropriately achieved, and return to sport was allowed at 6 to 8 months, as long as the patient had achieved appropriate functional milestones.

We recruited 14 healthy control participants with no history of knee injury or surgery who underwent similar MRI and biomechanical assessments. The reconstructed and contralateral limbs of the patients with ACLR and the dominant limb of the control participants, defined as the leg that could kick a ball the farthest,[5] were used for testing.

MR Image Acquisition

MR images of the knee were acquired through use of a 3.0-T MR scanner (General Electric) and an 8-channel phased-array knee coil (Invivo). All participants were positioned in supine with their knee in neutral rotation and full extension. We obtained 2 MR sequences: (1) sagittal intermediate-weighted, fluid-sensitive, fat-saturated 3-dimensional (3D) fast spin-echo images (repetition time [TR], 1500 ms; echo time [TE], 25 ms; echo train length, 32; matrix, 384 $\times$ 384; field of view [FOV], 16 cm; slice thickness, 1 mm; acquisition time, 8 minutes 13 seconds) and (2) sagittal combined 3D T1ρ/T2 image sequences (TR/TE, 9/3 ms; FOV, 14 cm; matrix, 256 $\times$ 128; slice thickness, 4 mm; views per segment, 64; spin-lock frequency, 500 Hz; T1ρ time of spin-lock, 0, 10, 40, 80 ms; T2 preparation TE, 0, 13.7, 27.3, 54.7 ms; acquisition time, 9 minutes 37 seconds).[25]

Quantitative MRI Analysis

Segmentations for meniscal relaxation time measurements were performed through use of an in-house program designed with MATLAB (MathWorks) based on edge detection and Bezier splines, which demonstrated excellent scan-rescan reproducibility of meniscal T1ρ measurements (coefficient of variation $<5\%$).[8,9] Menisci were segmented into 4 subcompartments: anterior and posterior horn of the lateral meniscus and anterior and posterior horn of the medial meniscus. A separate in-house-designed MATLAB semiautomated software was used to auto-segment MR images of the same knees at later time points after reconstruction registered onto the T1ρ echo sequence of the baseline image. Images of patients who underwent concomitant partial or total meniscectomy with ACLR ($n = 7$) were manually segmented at 6 months, and those segmentations were registered onto T1ρ echo sequences of later time points due to the potentially large iatrogenic change in the meniscal shape at 6 months.

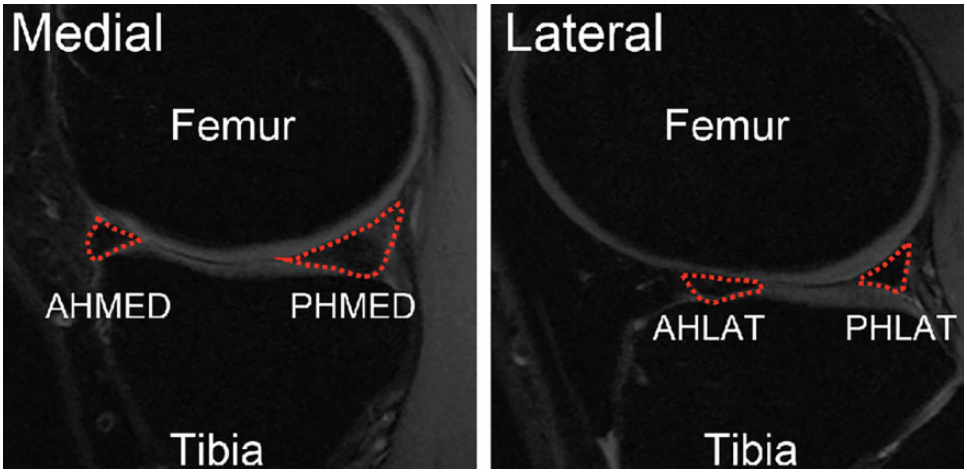

Figure 2. Segmentation images of the 4 meniscal compartments. AHLAT, anterior horn of the lateral meniscus; AHMED, anterior horn of the medial meniscus; PHLAT, posterior horn of the lateral meniscus; PHMED, posterior horn of the medial meniscus.

Auto-segments were quality checked and transferred onto T1ρ and T2 maps corresponding to their respective time points and were used to generate mean T1ρ and T2 values for the anterior horn of the lateral meniscus (AHLAT), posterior horn of the lateral meniscus (PHLAT), anterior horn of the medial meniscus (AHMED), and posterior horn of the medial meniscus (PHMED) using methods previously demonstrated (Figure 2).[3,42]

Biomechanical Analysis

We recorded 3D position data using a 10-camera motion capture system (Vicon) at a sampling rate of 250 Hz. Ground-reaction force (GRF) data were collected using 2 embedded force platforms (Advanced Mechanical Technology) at a sampling rate of 1000 Hz. A marker set consisting of 41 retroreflective markers was used to collect 3D position data.[33] Calibration markers were placed bilaterally at the greater trochanters, lateral and medial femoral epicondyles, lateral and medial malleoli, and first metatarsal head. Pelvic tracking was performed through use of markers placed at the iliac crests, anterior superior iliac spines, and the L5/S1 joint. Femur and shank tracking was performed using rigid clusters consisting of 4 markers each placed at the lateral thighs and shanks. Foot tracking was performed through use of a marker placed at the fifth metatarsal head and a rigid cluster of 3 markers placed on the heel shoe counter. After all markers were placed on the participant, a 1-second static calibration trial was obtained. All calibration markers were then removed from the participant.

Gait Analysis

Participants were instructed to walk at a controlled speed of 1.35 m/s. A trial was considered successful when the foot of the tested limb fell within the borders of the force platform from initial contact to toe-off and the speed was within 5% (0.07 m/s) of the target speed. For each participant, 3 successful trials were obtained.

Kinematic and kinetic data were computed through use of Visual3D (C-Motion). GRF data were normalized to participants' body mass (in kilograms). Marker trajectory and GRF data were low-pass filtered with cutoff frequencies of 6 and 50 Hz, respectively. Lower extremity joint kinematics were calculated through use of a Cardan rotation sequence in the order of flexion-extension, abduction-adduction, and internal-external rotation.[43] Net joint moments were normalized to each participant's body mass and reported as external moments (Nm/kg). The peak knee flexion moment (KFM), knee flexion angle (KFA), and vertical ground-reaction force (VGRF) during the initial loading response of stance (from initial contact to first peak KFA) were computed.[38] The mean values of 3 successful trials were exported. Gait data from the reconstructed knees and contralateral knees of the ACLR group as well as the dominant knees of the control group were used for statistical analysis.

Landing Analysis

The drop jump task, as previously described,[18] involved the participant standing on a 30-cm platform, stepping off with 1 foot, and landing with 1 foot on each of the force plates. The participants were instructed to land with both feet contacting the ground simultaneously and to then immediately jump as high as possible. A successful trial was defined as one in which the participants stepped off the platform (as opposed to jumping off or lowering themselves down), landed simultaneously with both feet with 1 foot on each force plate, and immediately performed a maximal vertical jump. We collected 3 successful drop jump trials that were used for analysis.

Both marker trajectory and GRF data were filtered through use of a low-pass, fourth-order Butterworth filter with a cutoff frequency of 12 Hz.[16] Local joint coordinate systems were created, and an unweighted least squares method was used to describe segment position and orientation.[39] Initial contact was defined as a VGRF greater than 20 N. The stance phase of the task was defined as initial contact to toe-off and was time normalized to 101 points. All data were analyzed during the landing phase of the task (stance phase). The variables of interest for this study included peak KFM and KFA. The peak ipsilateral VGRF and peak contralateral VGRF during the stance phase (first 50% of stance phase) were determined.

Statistical Analysis

Paired *t* tests were used to examine the effect of side-to-side differences in biomechanics and T1ρ/T2 values. A multivariate analysis of variance with Tukey post hoc comparisons was used to compare T1ρ/T2 values and biomechanics between patients with ACLR and control participants. Repeated-measures 1-way analyses of variance were used to examine the effect of time on participants' biomechanics and T1ρ/T2 values. When a significant main effect of time was found, post hoc Bonferroni tests were conducted for pairwise comparison. Association with biomechanics at 6 months and changes in biomechanics from 6 months to 3 years were calculated through use of Pearson correlation. Linear regression models adjusted for age, sex, and body mass index were built to determine the associations between changes in biomechanical parameters and T1ρ/T2 values in the patients with ACLR. Power analysis was performed to detect 10% difference in T1ρ meniscal measurements in our previous work[44] between the ACLR and contralateral limb with a power of 80% at a significance level of .05. We needed 30 patients, and we over-recruited for this study. All statistical analyses were performed through use of SPSS Statistics Version 23.0 (IBM Corp) with a significance level set at .05.

RESULTS

Patient Demographics

A total of 36 patients with ACLR and 14 control participants completed the required data collections for this study. No significant differences were observed in demographics between patients with ACLR and the control group (Table 1).

TABLE 1
Patient Demographics[a]

	ACLR (n = 36)	Control (n = 14)	*P*
Sex, n, M/F	20/16	9/5	.574
Age, y	31.5 ± 7.6	31.4 ± 4.9	.606
Height, m	1.72 ± 0.10	1.72 ± 0.08	.829
Mass, kg	71.3 ± 12.1	68.9 ± 8.9	.880
Body mass index, kg/m^2	23.9 ± 2.5	23.6 ± 1.9	.604
Time from injury to surgery, d	76.7 ± 52.8		
Graft type, n			
Hamstring tendon autograft	24		
Soft tissue allograft	12		

[a]Values are expressed as mean ± SD unless otherwise noted. ACLR, anterior cruciate ligament reconstruction; F, female; M, male.

T1ρ/T2 Meniscal Relaxation Times

In the ACLR knees, T1ρ and T2 values of PHMED and PHLAT were significantly higher than those of the contralateral knees at baseline, 6 months, and 1 year. The T1ρ values of PHLAT and T2 values of PHMED and PHLAT were also significantly higher than those of the control knees (Table 2). No differences were seen between the ACLR and contralateral or control knees at 2 years and 3 years, except for the T2 value for the PHMED of the ACLR and contralateral knees at 2 years. A significant decrease was noted in T1ρ of PHLAT and T2 values at 3 years of PHMED and PHLAT when compared with their values at 6 months.

Gait Analysis

Patients with ACLR exhibited significantly lower peak VGRF and KFM of ACLR knees at 6 months compared with the contralateral knee (Table 3). Additionally, the ACLR knee exhibited significantly lower peak KFM from 6 months to 3 years and lower peak KFA from 1 year to 3 years compared with the control participants.

Landing Analysis

No differences were found in biomechanics at 6 months after surgery between patients receiving autograft and allograft. The patients with ACLR performed the drop landing task with significantly lower peak VGRF using the reconstructed limb compared with the contralateral limb at both 6 months and 1 year after surgery. However, peak VGRF became similar at 1, 2, and 3 years and showed no difference between the contralateral and control knees (Table 4). The patients with ACLR had significantly lower peak KFM compared with the contralateral knee at 6 months and 1 year. However, peak KFM in the reconstructed limb was similar to that of the contralateral limb at 2 years after surgery. The patients with ACLR had significantly lower peak KFA when compared with the contralateral knee at 6 months and 1 year. However, peak KFA in the reconstructed limb was similar to that of the contralateral limb at 2 years after surgery.

Correlations Between Biomechanics at 6 Months and Changes of Meniscal T1ρ and T2 Values

No significant association was seen between biomechanics during gait at 6 months and changes in meniscal T1ρ/T2 values from 6 months to 3 years. In patients with ACLR, peak VGRF during landing at 6 months was associated

TABLE 2
Longitudinal T1ρ and T2 Values From Baseline to 3 Years in the Posterior Horn of the Medial and Lateral Menisci[a]

	Baseline	6 Months	1 Year	2 Years	3 Years	Control
T1ρ value						
PHMED						
ACLR (dominant)	18.7 ± 3.7[b]	19.3 ± 4.3[b]	18.7 ± 3.7[b]	18.5 ± 4.0	17.9 ± 3.4	18.3 ± 1.7
Contralateral	17.3 ± 2.5	17.0 ± 1.9	16.9 ± 1.7	17.0 ± 2.1	17.3 ± 2.4	18.0 ± 2.0
PHLAT						
ACLR (dominant)	18.9 ± 2.8[b,c]	18.7 ± 3.2[b,c]	18.6 ± 3.6[b,c]	17.2 ± 2.6	17.4 ± 2.3[d]	16.8 ± 1.1
Contralateral	16.9 ± 2.5	16.8 ± 2.6	16.8 ± 2.6	16.4 ± 2.3	16.4 ± 2.5	17.3 ± 2.0
T2 value						
PHMED						
ACLR (dominant)	12.8 ± 2.3[b,c]	13.1 ± 2.5[b,c]	13.2 ± 2.7[b,c]	12.6 ± 2.7[b]	12.0 ± 2.1[d]	11.3 ± 1.1
Contralateral	11.5 ± 1.4	11.7 ± 1.4	11.7 ± 1.4	11.6 ± 1.1	11.7 ± 1.4	11.4 ± 1.4
PHLAT						
ACLR (dominant)	13.1 ± 1.8[b,c]	13.0 ± 1.8[b,c]	13.3 ± 2.6[b,c]	12.3 ± 2.1	12.1 ± 1.7[d]	11.3 ± 1.5
Contralateral	12.0 ± 1.7	12.0 ± 1.7	12.0 ± 1.6	12.0 ± 1.6	11.7 ± 1.3	11.7 ± 1.4

[a]Values are expressed in milliseconds as mean ± SD. ACLR, anterior cruciate ligament reconstruction; PHLAT, posterior horn of the lateral meniscus; PHMED, posterior horn of the medial meniscus.
[b]Statistically significant difference with contralateral.
[c]Statistically significant difference with control dominant.
[d]Statistically significant difference compared with 6 months after ACLR.

TABLE 3
Longitudinal Biomechanical Analysis During Gait From Baseline to 3 Years[a]

	Baseline	6 Months	1 Year	2 Years	3 Years	Control
Peak VGRF, BW						
ACLR (dominant)	1.13 ± 0.12	1.15 ± 0.08[b]	1.16 ± 0.07	1.16 ± 0.08	1.15 ± 0.07	1.19 ± 0.07
Contralateral	1.15 ± 0.14	1.17 ± 0.08	1.16 ± 0.07	1.14 ± 0.10	1.15 ± 0.07	1.18 ± 0.06
Peak KFM, Nm/kg						
ACLR (dominant)	0.53 ± 0.25	0.41 ± 0.20[b,c]	0.47 ± 0.23[c]	0.46 ± 0.23[c]	0.41 ± 0.23[c]	0.64 ± 0.20
Contralateral	0.62 ± 0.29	0.54 ± 0.27	0.52 ± 0.25	0.42 ± 0.25	0.45 ± 0.25	0.69 ± 0.25
Peak KFA, deg						
ACLR (dominant)	20.8 ± 5.8	15.6 ± 5.7	15.2 ± 5.5[c]	13.4 ± 6.4[c]	14.3 ± 6.4[c]	19.0 ± 4.6
Contralateral	20.2 ± 6.3	16.8 ± 6.8	16.0 ± 5.8	12.4 ± 6.5	14.1 ± 6.6	19.9 ± 5.3

[a]Values are expressed as mean ± SD. ACLR, anterior cruciate ligament reconstruction; BW, body weight; KFA, knee flexion angle; KFM, knee flexion moment; VGRF, vertical ground-reaction force.
[b]Statistically significant difference with contralateral.
[c]Statistically significant difference with control dominant.

with changes in T1ρ values ($\beta = -0.414$; $P = .038$) and T2 values ($\beta = -0.376$; $P = .045$) in the PHMED from 6 months to 3 years (Figure 3A). Peak KFM during landing at 6 months was associated with a change in T2 value ($\beta = -0.424$; $P = .023$) in the PHMED from 6 months to 3 years (Figure 3B). A negative correlation suggested improvement in meniscal tissue quality with better kinetic measurements. No significant association was found between biomechanics during landing at 6 months and changes in meniscal T1ρ/T2 values in the AHLAT, PHLAT, and AHMED from 6 months to 3 years.

DISCUSSION

This longitudinal study examined changes in biomechanics during gait and landing and MR-based meniscal degeneration from baseline to 3 years after ACLR. Menisci play an important role in knee joint stability and stress distribution, both of which help to maintain the integrity of the articular cartilage. Understanding the mechanism and prevalence of posttraumatic meniscal degeneration is important to help treat posttraumatic osteoarthritis and monitor its development after ACL injuries. Although previous studies have focused on the association between altered biomechanics after ACLR and posttraumatic osteoarthritis or secondary injury,[6,18,30,31,33,35] little information is available about the association between altered biomechanics and meniscal injury after ACLR. This study showed that altered biomechanical parameters at 6 months, especially during landing after ACLR, were associated with changes in T1ρ/T2 relaxation values in the PHMED from 6 months to 3 years, suggesting that biomechanical parameters during the early stage of recovery

TABLE 4
Longitudinal Biomechanical Analysis During Landing From 6 Months to 3 Years[a]

	6 Months	1 Year	2 Years	3 Years	Control
Peak VGRF, BW					
ACLR (dominant)	1.28 ± 0.28[b,c]	1.45 ± 0.37[b,d]	1.62 ± 0.45[d]	1.75 ± 0.45[d]	1.66 ± 0.36
Contralateral	1.76 ± 0.48	1.75 ± 0.50	1.83 ± 0.50	1.65 ± 0.31	1.57 ± 0.47
Peak KFM, Nm/kg					
ACLR	1.37 ± 0.41[b,c]	1.57 ± 0.48[b,c]	1.74 ± 0.44[c,d]	1.81 ± 0.42[c,d]	2.00 ± 0.30
Contralateral	2.00 ± 0.30	1.91 ± 0.46	1.80 ± 0.30	1.93 ± 0.47	2.04 ± 0.33
Peak KFA, deg					
ACLR	84.3 ± 14.2[b,c]	85.5 ± 16.8[b]	85.8 ± 13.5	89.3 ± 11.8[d]	94.2 ± 13.2
Contralateral	87.5 ± 14.3	88.3 ± 16.4	86.0 ± 13.7	91.1 ± 12.3	95.6 ± 13.5

[a]Values are expressed as mean ± SD. ACLR, anterior cruciate ligament reconstruction; BW, body weight; KFA, knee flexion angle; KFM, knee flexion moment; VGRF, vertical ground-reaction force.
[b]Statistically significant difference with contralateral.
[c]Statistically significant difference with control dominant.
[d]Statistically significant difference compared with 6 months after ACLR.

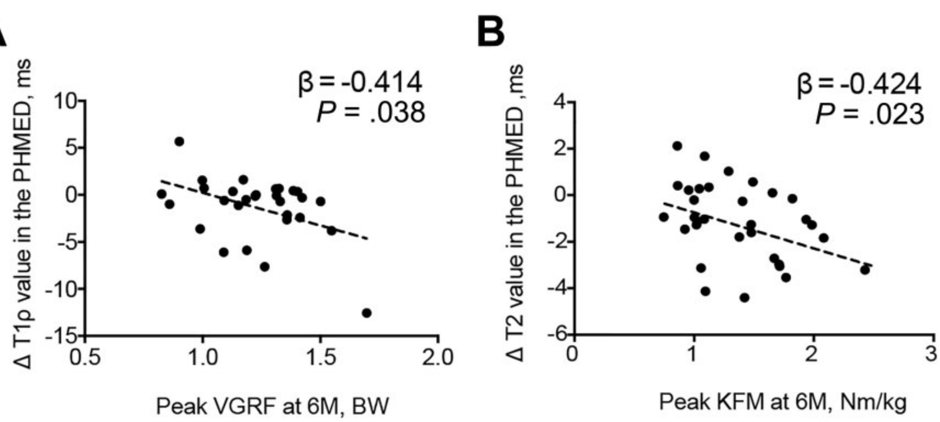

Figure 3. (A) Correlation between peak vertical ground-reaction force (VGRF) at 6 months and change in T1ρ value in the posterior horn of the medial meniscus (PHMED) from 6 months to 3 years in the anterior cruciate ligament reconstruction (ACLR) cohort. (B) Correlation between peak knee flexion moment (KFM) at 6 months and change in T2 value in the PHMED from 6 months to 3 years in the ACLR cohort. BW, body weight.

might be potential biomarkers for predicting persistent medial meniscal abnormality after ACLR.

This study showed that T1ρ/T2 values of menisci in ACLR knees remained elevated over the values for contralateral and control knees in the weightbearing posterior portions of the meniscus up to 1 year in the PHLAT and 2 years in the PHMED. Additionally, at 3 years there were no significant differences between imaging markers of the ACLR knees and contralateral or control knees, demonstrating gradual improvement of biochemical meniscal matrix status after ACLR. This improvement in the PHMED is similar to previous work which showed that ultrashort TE T2 values in the posterior medial meniscus in an ACLR cohort without meniscal tears decreased 17% over 2 years after ACLR.[11] The mechanics of this improvement from baseline might be explained by the recent report that ACLR affects the contact pattern between the medial meniscal posterior segment and the medial femoral condyle and can reduce the deformation of the medial meniscal posterior segment in the knee-flexed position by reducing abnormal anterior tibial translation.[20] In contrast, in the current study, approximately 30% of patients with ACLR did not show decreases in T1ρ/T2 values in the PHMED from 6 months to 3 years. These findings are consistent with a recent large cohort study that showed that the overall risk of subsequent meniscal surgery was low after ACLR; however, the relative risk of subsequent meniscal surgery was higher in the ACLR knee compared with the contralateral knee.[14]

The biomechanical findings during gait in the current study are consistent with a recent meta-analysis that reported progressive changes in walking kinematics and kinetics after ACL injury and ACLR.[37] The biomechanical findings during landing in the current study are also consistent with previous work that assessed 1-year longitudinal changes in peak ipsilateral VGRF of patients with ACLR during a drop jump task.[29] At 3 years, the patients with ACLR exhibited similar peak VGRF and KFM compared with healthy controls, which may indicate restoration of the applied peak VGRF and KFM during the landing task in patients with ACLR. Although no significant associations were seen between biomechanics at 6 months during gait, peak VGRF and KFM at 6 months during landing had significant association with changes in T1ρ/T2 value in the PHMED from 6 months to 3 years, suggesting that landing mechanics during the early stage of recovery might be a potential biomarker for predicting medial meniscal abnormality after ACLR; this finding supports the recent systematic review that suggested that landing tasks are best performed during the early stages of recovery and are recommended after ACLR.[12] A recent report also showed that differences in kinematic measurements at 6 months are correlated with cartilage degeneration at 3 years.[35]

No significant associations were found between biomechanics during both tasks and changes in T1ρ/T2 value in the PHLAT. Bone marrow edema-like lesions in patients with ACL injury are commonly seen in the posterior lateral tibia.[15] Additionally, a previous report showed that in patients with ACLR, cartilage T1ρ/T2 values in the posterior tibial subcomponent were elevated from values before surgery.[24] Therefore, this elevated T1ρ/T2 value in the PHLAT up to 1 year may be related to the increased incidence of lateral meniscal injuries seen at the time of acute ACL rupture but less with subsequent degeneration.

Regarding clinical relevance, kinetics during a landing task can be important biomechanical parameters during the early postoperative period in predicting subsequent meniscal injuries after ACLR as well as posttraumatic osteoarthritis and knee joint laxity after ACLR. This is an important finding, as patients tend to increase their activity 6 months after ACLR. We should consider a different return-to-play protocol for patients who have significantly abnormal landing mechanics at 6 months.

One limitation of this study is the small sample size of patients with ACLR. Despite the small sample size, the longitudinal nature of the current study allows us to look at kinematic and meniscal changes within participants. In this study, all patients underwent a single-bundle anatomic ACLR, and therefore our interpretations are limited to this type of surgical technique. Future studies should investigate the effects of various ACLR techniques such as the double-bundle ACLR or extra-articular ligament augmentations. Another limitation of this study is that we included participants with partial meniscectomy. This decision was made because patients with and those without partial meniscectomy undergo the same rehabilitation protocol and there were no significant differences in MRI findings and biomechanics between these patients, we included them in the analysis. However, a recent study reported that gait mechanics after ACLR differed according to medial meniscal treatment.[7] Therefore, in the future, a study with a larger sample size should be conducted to confirm the findings from the current study and to investigate the differences between patients with and without partial meniscectomy.

CONCLUSION

Although mean T1ρ/T2 values of the meniscus seen before ACLR improved after 3 years, approximately 30% of patients with ACLR did not show decreases (ie, improvement) from 6 months to 3 years. Patients with lower peak VGRF and KFM at 6 months during landing showed less recovery (as indicated by T2 values) in the medial posterior horn from 6 months to 3 years, suggesting that abnormal landing kinetics during the early stage of recovery might be potential biomarkers for predicting medial meniscal abnormality after ACLR.

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