Title

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Authors

Shimizu, Tomohiro
Samaan, Michael A
Tanaka, Matthew S
et al.

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Abnormal biomechanics at six months are associated with cartilage degeneration at three years following anterior cruciate ligament reconstruction

Tomohiro Shimizu, MD, PhD[1,3], **Michael A. Samaan, PhD**[2], **Matthew S. Tanaka, BS**[2], **Valentina Pedoia, PhD**[2], **Richard B. Souza, PT, PhD**[2,4], **Xiaojuan Li, PhD**[2], and **C. Benjamin Ma, MD**[1]

[1]Department of Orthopaedic Surgery, University of California, San Francisco

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

[3]Department of Orthopaedic Surgery, Faculty of Medicine and Graduate School of Medicine, Hokkaido University

[4]Department of Physical Therapy and Rehabilitation Science, University of California, San Francisco

Abstract

Purpose: The purpose of this study was to investigate the changes in landing biomechanics over a three-year period and its correlation with cartilage degenerative changes in the medial tibiofemoral joint of the knee after anterior cruciate ligament reconstruction (ACLR) using magnetic resonance (MR) $T1_\rho$ mapping.

Methods: Thirty-one ACL injured patients underwent magnetic resonance imaging (MRI) of the injured knee prior to ACLR and three years after ACLR as well as biomechanical analysis of a drop-landing task at six months and three years after ACLR. Sixteen healthy individuals were recruited and underwent knee MRI and biomechanical assessment during a drop-landing task. $T_{1\rho}$ cartilage relaxation times were calculated for the medial femur and tibia.

Results: ACLR patients exhibited increased peak vertical ground reaction forces (VGRF), VGRF impulse, peak knee flexion moment (KFM) and KFM impulse from six months to three years ($P<0.001$, respectively). Although the ACLR knees showed significantly lower peak VGRF and KFM at six months ($P<0.001$, respectively) when compared to the controls, there were no significant differences at three years. At three years, ACLR patients showed higher $T_{1\rho}$ values over the medial femur ($P<0.001$) and tibia ($P=0.012$) when compared to their preoperative and healthy

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Corresponding Author: C.Benjamin Ma, MD, Department of Orthopaedic Surgery, University of California, San Francisco, Orthopaedic Institute 1500 Owens Street, San Francisco CA 94158, Phone: (415) 353-7566, Fax: (415) 885-3838, maben@orthosurg.ucsf.edu.

This study was performed at the University of California San Francisco.

control values. Within the ACLR group, side to side differences in peak VGRF and sagittal knee biomechanics at six months were associated with increased $T_{1\rho}$values from baseline to three years.

Conclusion: The results of this longitudinal study show that landing biomechanics are altered after ACLR but biomechanical abnormalities tend to recover at three years after ACLR. Differences in lower extremity mechanics during a landing task at six months may be associated with cartilage degeneration at three years following ACL injury and reconstruction.

Keywords

posttraumatic osteoarthritis; ACL reconstruction; drop landing; $T_{1\rho}$; biomechanics

INTRODUCTION

Anterior cruciate ligament (ACL) injured knee is at significant risk of developing post-traumatic osteoarthritis (PTOA) even after ACL reconstruction (ACLR).[1–3] Systematic reviews have shown that over 50% of patients will have radiographic signs of osteoarthritis 10–20 years after ACL reconstruction (ACLR).[4] Mechanisms underlying the development of early PTOA are not well understood. Potential interventions to prevent the onset of PTOA are most likely to be effective in the early post-operative phase before structural changes have occurred.[5] Therefore, it is critical to identify potentially modifiable risk factors related to early PTOA following ACLR.

Quantitative magnetic resonance (MR) $T_{1\rho}$ mapping provides a non-invasive method to evaluate cartilage compositional changes related to OA. Specifically, an increase in cartilage $T_{1\rho}$ relaxation time is related to a loss of glycosaminoglycan and potential cartilage degeneration.[6, 7] Changes in $T_{1\rho}$ can occur before morphological abnormalities are visualized on radiographs or MR images, and thus quantitative MR-based measurements such as $T_{1\rho}$ are reported to evaluate early stage knee OA.[8, 9] Elevated knee cartilage $T_{1\rho}$ relaxation times have been reported as early as 1 year following ACLR, indicating the sensitivity of this quantitative measure in assessing early signs of knee joint cartilage degeneration.[10–12]

Various studies have demonstrated associations between ACLR gait biomechanics and knee joint degeneration[13–16] yet most ACLR patients are of a young and athletic population that performs 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 re-injury after ACLR[17–20] yet these landing tasks have not been used to assess for potential connections between altered lower extremity joint biomechanics and medial tibiofemoral joint (MTFJ) degeneration after ACLR. Previous cross-sectional studies have shown that ACLR patients demonstrate limb asymmetries during a landing task,[20, 21] yet another study found that male handball athletes that underwent ACLR did not exhibit limb asymmetries during a landing task.[22] In addition, these biomechanical studies are cross-sectional in nature and little information is available regarding the longitudinal changes in landing mechanics in ACLR patients. Hence, it is of great interest to understand whether or not longitudinal changes occur in landing biomechanics after ACLR and if these changes are related to cartilage degeneration.

The purpose of this study was to investigate the changes in landing biomechanics over a three-year period and its correlation with cartilage degenerative changes in the medial tibiofemoral joint of the knee after anterior cruciate ligament reconstruction (ACLR) using magnetic resonance (MR) T_{1p} mapping. We hypothesized that longitudinal changes in landing biomechanics from six months to three years after ACLR would be related to cartilage degeneration after ACLR.

MATERIALS AND METHODS

Subjects

This prospective study was approved and all study participants provided written informed consent prior to participation (IRB number; 11–06734). Patients with unilateral ACL injuries were recruited after ACL injury but before ACLR from September 2011 to May 2014. This study focused on 31 subjects (from among the 53 recruited prior to ACLR as part of an ongoing observational study) who had MRI data at prior to ACLR and landing biomechanics at six months after ACLR.(Fig.1) Exclusion criteria were 1) concomitant ligamentous injuries that needed surgical treatment, 2) history of inflammatory or primary osteoarthritis, 3) previous knee surgery, non-operatively treated ACL, meniscus, or cartilage injury and 4) abnormal contralateral knee. Subjects were excluded from follow-up if they declined to receive ACLR or if meniscal repair was required (N=4), since they would undergo a different rehabilitation protocol and weight-bearing requirements. The re-rupture cases during observational period were also excluded (N=4). Six patients (13.3%) were lost follow up from six months, first drop landing test, to three years after ACLR and two patients could not do sufficient drop landing test at three years. On the other hand, seven ACLR patients with partial meniscectomy (N=7) were not excluded since they would undergo same rehabilitation protocol.

Surgery and Rehabilitation

All thirty-one patients underwent ACLR by one of three board-certified, fellowship-trained orthopedic surgeons at a single institution using either hamstring autograft or soft tissue allograft such as posterior tibialis or hamstring (CBMa, CA and BF). Anatomic single-bundle ACLR was performed. The femoral tunnels were drilled using anteromedial portal drilling. All patients had same fixation method with suspensory femoral fixation and interference tibial fixation.

All patients participated in a standard post-operative ACL rehabilitation program at our sports medicine clinic. Immediate post-operative recovery emphasized control of pain and swelling, and regaining motor control. The operative knee was kept in a hinged knee brace at all times, which was locked in extension while walking until quadriceps control and normal gait were achieved. The primary focus for the first six weeks was on return of normal range of motion and quadriceps control. Return to running was allowed at approximately four months, when core stability was appropriately achieved, and return to sport at six to eight months, as long as the patient had achieved appropriate functional milestones.

Sixteen healthy control subjects with no history of knee injury or surgery were recruited and underwent similar MR-imaging and biomechanical assessments as the ACLR patients at baseline and three years after first visit. The reconstructed and contralateral limb of the ACLR patients and the dominant limb of the control participants defined as the leg that could kick a ball the furthest[23] was used for testing. Power analysis was performed to detect 10% difference in T1rho cartilage measurements at 3 years between the ACLR and contralateral limb with a power of 80% at a significance level of 0.05. 26 patients were needed and we over recruited for this study.

Landing Analysis

Three-dimensional (3D) position data were recorded using a 10-camera motion capture system (Vicon, Oxford, UK) 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 forty-one retroreflective markers was used to collect three-dimensional position data.16 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 using markers placed at the iliac crests, anterior superior iliac spines and at the L5/S1 joint. Femur and shank tracking was performed using rigid clusters consisting of four markers each and were placed at the lateral thighs and shanks. Foot tracking was performed using a marker placed at the fifth metatarsal head and a rigid cluster of three markers placed on the heel shoe counter. After all markers were placed on the participant, a one-second static calibration trial was obtained. All calibration markers were then removed from the participant.

The drop jump task, as previously described,[17] involved the participant standing on a 30cm platform, stepping off with one foot and landing with one foot on each of the force plates. The participants were instructed to land with both feet contacting the ground simultaneously, and then immediately jump as high as possible (Fig. 2). A successful trial was defined as one where the participant 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 successful drop jump trials were collected and used for analysis.

The standing calibration trial was used to create a seven-segment model in Visual3D (C-Motion, Germantown, MD) consisting of the pelvis, bilateral thighs, lower legs and feet. Both marker trajectory and GRF data were filtered using a low-pass, fourth order Butterworth filter with a cutoff frequency of 12 Hz.[24] Local joint coordinate systems were created and an unweighted least squares method was used to describe segment position and orientation.[25] Lower extremity joint kinematics were resolved using a Cardan rotation sequence of X-Y’-Z”, where knee extension, abduction and external rotation angles were considered negative. All joint angles were normalized to the standing calibration trial. Ground reaction force data were normalized to the participant’s body weight (BW). Initial contact was defined as a vertical GRF (VGRF) of 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). External sagittal plane knee joint moment was normalized to each participant's body mass (Nm/kg). Joint moment impulse was calculated as the time-based integral of a particular joint moment (Nm·ms/kg). The variables of interest for this study included peak knee flexion angle, peak external sagittal and knee joint moment impulses. The peak ipsilateral VGRF and peak contralateral VGRF during the stance phase (first 50 % of stance phase) were determined. The ipsilateral VGRF impulse during the stance phase of the drop-jump task was calculated as the time-based integral of the VGRF (BW·ms). Side to side differences (SSD) were calculated as the difference between the ipsilateral and contralateral biomechanical parameter. These variables were computed for each trial and the average of the three successful trials were used for statistical analyses.

MR Image Acquisition and Analysis

MR images of the knee were acquired using a 3T MR Scanner (General Electric, Milwaukee, WI) and a quadrature transmit/8-channel phased-array receive knee coil (Invivo, Orlando, FL). All subjects were positioned supine with their knee in neutral rotation and full extension. Two MR sequences were obtained: 1) Sagittal intermediate-weighted, fluid sensitive, fat-saturated 3D fast spin-echo (CUBE) images [repetition time (TR), 1500 ms; echo time (TE), 25 ms; echo train length, 32; matrix, 384 × 384; field of view (FOV), 16 cm; and slice thickness, 1 mm; acquisition time, 8 min 13 sec]; and 2) Sagittal combined 3D $T_{1\rho}$ image sequence [TR/TE, 9 ms/3 ms; FOV, 14 cm; matrix, 256 × 128; slice thickness, 4 mm; views per segment, 64; spin-lock frequency, 500 Hz; $T_{1\rho}$ time of spin-lock, 0, 10, 40, 80 ms; acquisition time, 9 min 37 s].[26]

To facilitate image registration and cartilage segmentation, the CUBE images were down-sampled in the sagittal direction to match the images of the first echo of the $T_{1\rho}$ sequence. Articular cartilage of the medial tibia (MT) and medial femoral (MF) condyles were segmented semi-automatically on the CUBE images using an in-house program developed with MATLAB (The MathWorks, Natick, MA) using edge detection and Bézier splines.[27]

An intensity-based multi-resolution pyramidal approach was used to rigidly register the CUBE images to the first echo of the $T_{1\rho}$ image and these registered images were used for cartilage segmentation (semi-automatic method) of the MT and MF.[28] The MT and MF were then divided into seven sub-regions within the boundaries of the menisci (Fig. 3). Regions of interest were created around each of the sub-regions and were used to analyze $T_{1\rho}$ cartilage values within these sub-regions. The central MF sub-region was sub-divided into three regions (anterior: cMFa, central: cMFc and posterior: cMFp) in order to assess the cartilage composition within the weight bearing region of the MF. In order to ensure that similar regions were assessed at follow-up time points, all $T_{1\rho}$ images of the follow-up scans were registered to the first echo of the $T_{1\rho}$ image of the injured (ACLR: baseline scan) or dominant knee (Control).[28] $T_{1\rho}$ mapping was performed on a pixel by pixel basis, using a two-parameter, mono-exponential fitting algorithm, where the $T_{1\rho}$ relaxation time was calculated as the mean of all of the pixels within a particular sub-region. Average global of the MF and MT, and weight bearing region with high risk of cartilage damage and degeneration in ACLR joint[12] (cMFc and cMT) $T_{1\rho}$ values were calculated at the baseline and three-year follow-up time points.[26]

Statistical analysis

Chi-squared or independent t-tests were used to compare differences in subject demographics. A multivariate analysis of variance (MANOVA) with Tukey's post-hoc comparisons test was used to compare $T_{1\rho}$ values and landing biomechanics between ACLR patients and control participants. Paired t-tests with Bonferroni corrections were used to examine the effect of time and side to side differences of $T_{1\rho}$ values and landing biomechanics within ACLR patients. Linear regression models adjusted for age, gender, BMI and time from injury to surgery were built to evaluate the associations between changes in biomechanical parameters and $T_{1\rho}$ relaxation times within the ACLR patients. All statistical analyses were performed using SPSS Statistics version 23.0 (IBM Corporation, Armonk, NY) with a significance level set at 0.05.

RESULTS

Subject Characteristics

A total of thirty-one ACLR patients and sixteen controls completed the required data collections for this study. No significant differences were observed in demographics between ACLR patients and control groups (Table 1).

Landing Biomechanics

ACLR patients exhibited lower peak VGRF at six months in the reconstructed limb when compared to the control group (P=0.002) however there were no differences in peak VGRF between the reconstructed limb at three years post-surgery with the control knee joints (P=0.245). Compared to the contralateral knee, the reconstructed knee joint also exhibited lower peak VGRF at six months but these differences were resolved at three years post-ACLR. In addition, ACLR patients exhibited significantly increased peak ipsilateral VGRF and VGRF impulse from six months to three years post-ACLR (Table 2). ACLR patients exhibited significant SSD in peak VGRF (P<0.001) and VGRF impulse (P<0.001) at six months, yet there were no significant SSD at three years. ACLR patients exhibited significant increases in SSD of peak VGRF (P<0.001) and VGRF impulse (P<0.001) at three years compared to at six months post ACLR.

The ACLR patients exhibited a significantly lower peak knee flexion angle (KFA) at six months (P=0.029) compared to the controls (Table 2). ACLR patients exhibited significant increases in the peak knee flexion moment (KFM) (P<0.001) and KFM impulse (P<0.001) from six months to three years, yet the peak KFM and KFM impulse were significantly lower within ACLR patients compared to the controls at both six months and three years follow-up time points. ACLR patients exhibited significant SSD in peak KFA (P<0.001), peak KFM (P<0.001) and KFM impulse (P<0.001) at six months, yet there were no significant SSD at three years. ACLR patients exhibited significant larger SSD of peak KFM (P<0.001) and KFM impulse (P<0.001) at three years compared to at six months.

Cartilage $T_{1\rho}$ Relaxation Times

At baseline, no significant differences were observed in the global MF, cMFc, the global MT and cMT $T_{1\rho}$ relaxation times between the ACLR knee and the control knee (Table 3). At three years, the ACLR demonstrated significantly higher $T_{1\rho}$ relaxation times within the global MF (P<0.001), cMFc (P=0.001) and the global MT (P=0.022) compared to the controls. The ACLR knee showed significant increases in $T_{1\rho}$ relaxation times within the global MF (P<0.001), cMFc (P<0.001) and global MT (P=0.012) from baseline to three years. The contralateral knee showed a significant increase in the global MF $T_{1\rho}$ relaxation times (P<0.001) from baseline to three years. The ACLR knee showed a significantly larger increase in cMFc $T_{1\rho}$ relaxation times from baseline to three years compared to the contralateral knee (4.7±0.8 vs 1.6±0.7) (P=0.004). On the other hand, there was no significant changes form baseline to three years in control group.

Correlations between Changes in Landing Characteristics and Cartilage Relaxation Times

A lower SSD of the peak VGRF at six months was associated with larger increases in global MT $T_{1\rho}$ relaxation times (β=−0.423, P=0.045) (Fig. 4A). A lower SSD of the peak KFM at six months was associated with larger increases in cMFc (β=−0.461, P=0.028) (Fig. 4B), global MT (β=−0.459, P=0.029) and cMT (β=−0.438, P=0.037) $T_{1\rho}$ relaxation times. A lower SSD of the KFM impulse at six months was associated with larger increases in global MF (β=−0.528, P=0.017), cMFc (β=−0.417, P=0.043) and cMT (β=−0.406, P=0.044) $T_{1\rho}$ relaxation times. A lower SSD of peak KFA at six months was associated with larger increases in global MF (β=−0.480, P=0.020) (Fig. 4C) and cMFc (β=−0.465, P=0.033) $T_{1\rho}$ relaxation times.

An increase in peak ipsilateral VGRF from six months to three years was associated with larger increases in global MF (β=0.581, P=0.013) (Fig. 5A) relaxation times. An increase in peak KFM of the ACLR knee from six months to three years was also associated with larger increases in cMT $T_{1\rho}$ relaxation times (β=0.401, P=0.046) (Fig. 5B). An increase in KFM impulse of the ACLR knee from six months to three years was also associated with larger increases in global MT (β=0.484, P=0.020) and cMT (β=0.412, P=0.043) $T_{1\rho}$ relaxation times. On the other hand, an increase in peak KFA of the ACLR knee from six months to three years was associated with larger decreases in global MF (β=−0.535, P=0.019) and cMFc (β=−0.403, P=0.046) (Fig. 5C) $T_{1\rho}$ relaxation times.

DISCUSSION

This preliminary study aimed to investigate the longitudinal changes in landing biomechanics after ACLR and the correlation between changes in landing biomechanics with cartilage degeneration. In the current study, it was demonstrated that longitudinal changes in lower extremity biomechanics, particularly in the V GRF, KFM and KFA, during a landing task may be relevant in understanding the mechanism of posttraumatic MTFJ OA in the ACLR population. Recent studies on gait analysis after ACLR reported higher peak VGRF and peak external KFM and KAM, which may lead to higher mechanical loading on the MTFJ and contribute to the development of MTFJ OA,[29, 30] yet gait is not a high-demand task for the ACLR population. Although understanding the effects of gait on MTFJ degeneration in ACLR is important, many of the ACLR patients are young and athletic that perform high-demand tasks such as jumping and landing. One recent systemic review about the appropriate selection of motion tasks after ACLR reported that landing task are best performed during the early stages of recovery and are recommended after ACLR.[31]

The results of this study at six months are consistent with previous work that assessed one year longitudinal changes in peak ipsilateral VGRF of ACLR patients during a drop jump task.[32] More specifically, ACLR patients demonstrated a decrease in peak ipsilateral VGRF, compared to the contralateral knee joint at six months and twelve months after ACLR.[32] On the other hand, this three years follow-up study showed that the ACLR patients exhibited similar peak VGRF compared to the healthy controls at three years, which may indicate a restoration of the applied peak VGRF during the drop landing task in ACLR patients. These results suggest that ACLR patients demonstrate altered VGRF patterns at an early stage after ACLR yet these VGRF patterns become similar to healthy controls at three years after ACLR, representing the mechanical improvement that is necessary for patients to resume regular activities. Although the peak ipsilateral VGRF is restored to similar levels as the healthy controls at three years after ACLR, the ACLR patients demonstrated altered knee joint biomechanics during the drop landing at six months and three years. Specifically, ACLR subjects perform the drop landing with reduced peak KFM, KFM impulse and peak KFA compared to healthy controls at both at six months and three years. These results suggest that the ACLR patients exhibit biomechanical adaptations during the drop landing task by reducing the knee joint loads and angle yet ACLR patients tend to increase the overall lower extremity loading (VGRF) during the early stages of recovery.

Despite these biomechanical adaptations, our results demonstrate the worsening of the MTFJ cartilage health from baseline to three years. Although $T_{1\rho}$ relaxation time of the contralateral knee showed an increase from baseline to three years, similar to the ACLR knee, this might be explained by increased VGRF experienced by the contralateral limb during the early stages of recovery. Within the ACLR patients in the current study, increases in the peak VGRF, peak KFM and KFM impulse were associated with larger increases in $T_{1\rho}$ values within the medial compartment, indicating cartilage degeneration at three years after ACLR. On the other hand, a lower increase of peak KFA was associated with larger increases in $T_{1\rho}$ values within the medial compartment, suggesting that the ACLR patients that demonstrate a more stiff-landing may be at a higher risk for posttraumatic knee osteoarthritis. This current study also found that lower SSD of peak VGRF, peak KFM, KFM impulse and peak KFA at six months were associated with larger increases in $T_{1\rho}$ values within the medial compartment, suggesting that ACLR patients that have lower limb asymmetry during the early recovery period might have a higher risk for posttraumatic knee osteoarthritis. Although lower limb asymmetry in ACLR patients has been associated with poor functional performance on return to sports readiness testing[24] and risk of second ACL injury,[33] the results of this longitudinal study suggest that lower limb asymmetry in ACLR patients may also be related to worse knee joint cartilage health. Therefore, the results of the current study may suggest that the restoration of biomechanical asymmetry at an early stage after ACLR may potentially aid in reducing posterior MTFJ cartilage degeneration.

As a clinical relevance, our findings provide that rehabilitation to prevent of increases of peak VGRF and KFM, and limb asymmetry could be useful for posttraumatic osteoarthritis after ACLR. Although Paterno et al. focused on limb asymmetry after ACLR for the risk of secondary injury, they recommended for an attempt to decrease residual limb asymmetries that clinicians should consider incorporating similar principles of ACL injury prevention into the late stages of ACLR rehabilitation[20, 33]. For reducing VGRF or joint moment, Tsai et al. reported increasing range of motion of hip and knee flexion reduced tibiofemoral shear and compressive forces[34]. Moreover, DiStefano et.al. reported that injury prevention program performed as a warm-up could reduce vertical ground-reaction forces[35]. Therefore, range of motion exercise from early stage of rehabilitation after ACLR is useful for reducing VGRF and joint moment, and injury prevention program in the late stages of rehabilitation could be useful for preventing posttraumatic osteoarthritis.

Limitation

Several limitations need to be considered when interpreting the results of this study. First, these subjects were not inclusive of only athletes who have experience in completing jumping activities and were not homogeneous in terms of the surgical technique. This study was not powered to investigate among only athlete with high activity and the differences among graft choices. Additionally, due to the nature of longitudinal studies, loss to follow up presented a limitation giving us a modest sample size. Second, a relatively short follow-up time was implemented in this study to monitor early stage knee OA. Nonetheless, the longitudinal nature of the current study provides a unique approach to determining and understanding the associations of drop landing mechanics and knee cartilage degeneration. Third, all patients underwent a single bundle anatomic ACL reconstructions and therefore, our results are limited by single surgical technique with same fixation methods. Finally, this current study did not investigate landing biomechanics prior to ACL injury and therefore, it is unable to determine whether or not these ACLR patients exhibited altered loading patterns before injury that may be responsible for MTFJ cartilage degeneration.

Conclusion

The results of this longitudinal study show that landing biomechanics are altered after ACLR but biomechanical abnormalities tend to recover at three years after ACLR. Differences in lower extremity mechanics during a landing task at six months may be associated with cartilage degeneration at three years following ACL injury and reconstruction.

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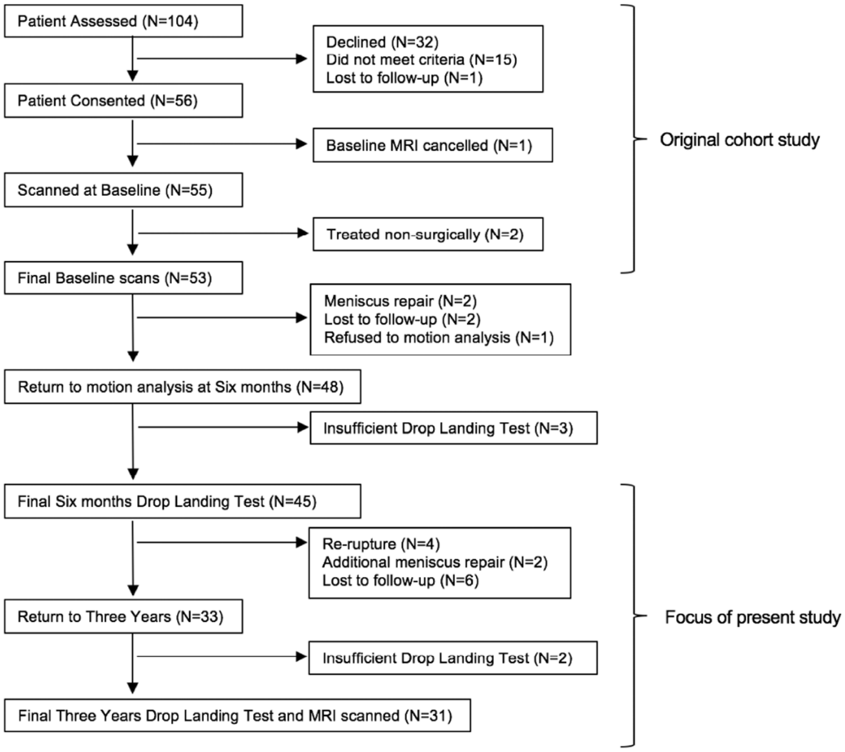

Figure 1:

Flow diagram of study subjects.

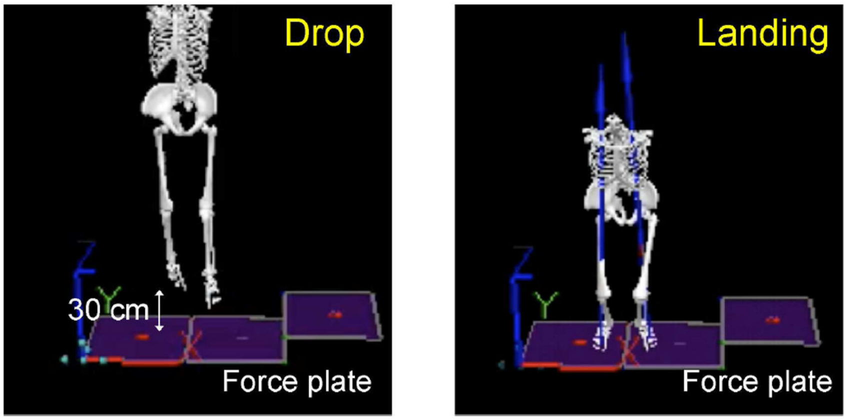

Figure 2:

Drop landing.

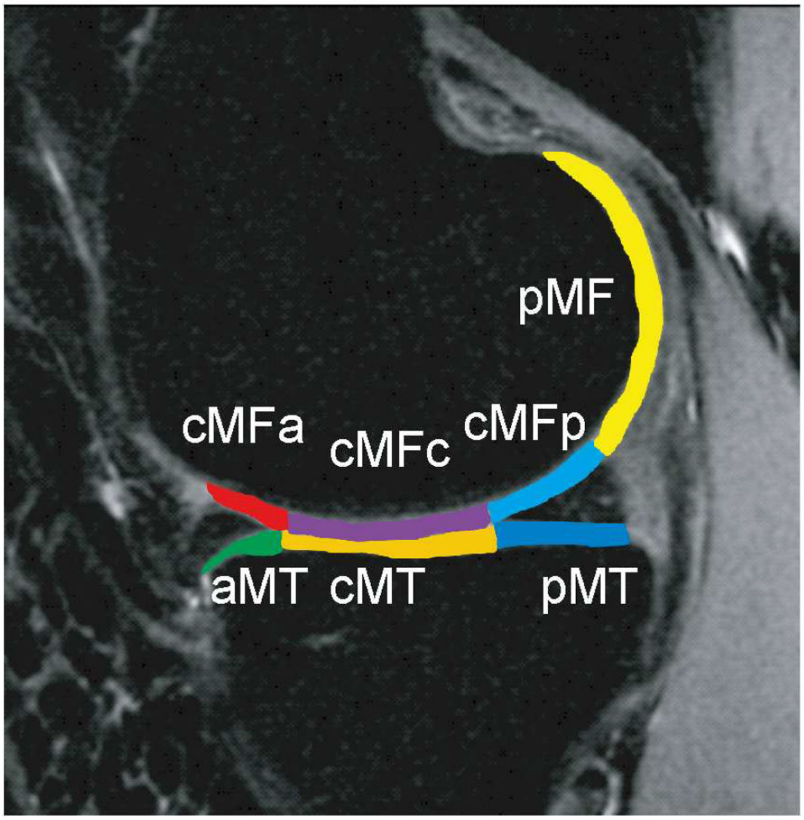

Figure 3:

The medial tibiofemoral joint was divided into various sub-compartments within the medial femoral condyle (MF) and medial tibia (MT) for $T_{1\rho}$ cartilage mapping. The letters a, c and p indicate anterior, central and posterior, respectively.

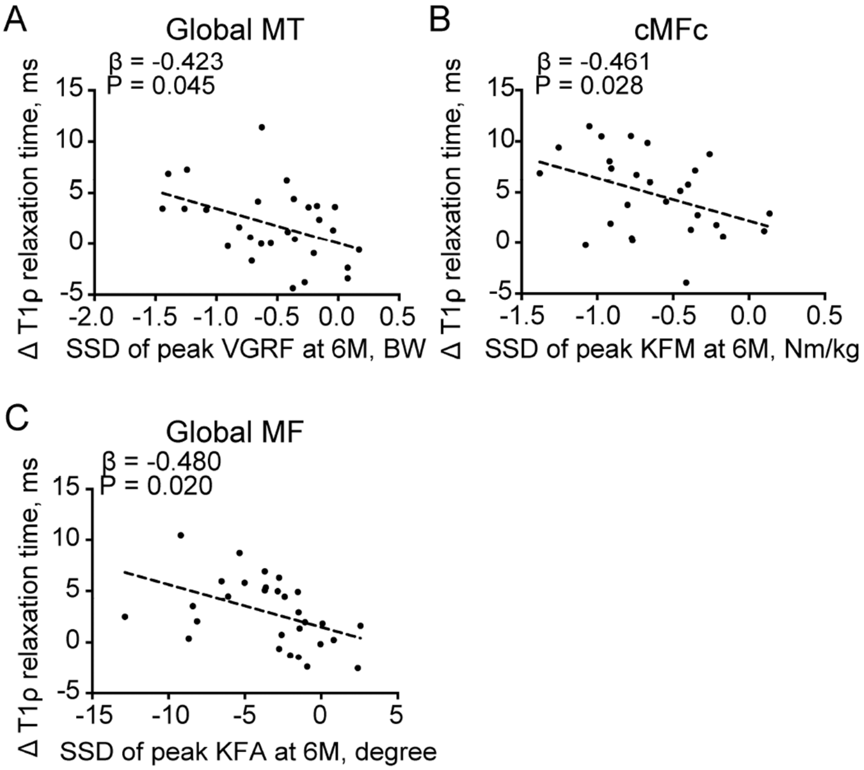

Figure 4:

Correlations between side to side differences (SSD) of biomechanics at six months and changes of $T_{1\rho}$ relaxation time from baseline to three years after ACLR. (A) Scatter plot of SSD of peak VGRF and change of $T_{1\rho}$ relaxation time of global MT. (B) Scatter plot of SSD of peak KFM and change of T1ρ relaxation time of cMFc. (C) Scatter plot of SSD of peak KFA and change of $T_{1\rho}$ relaxation time of global MF.

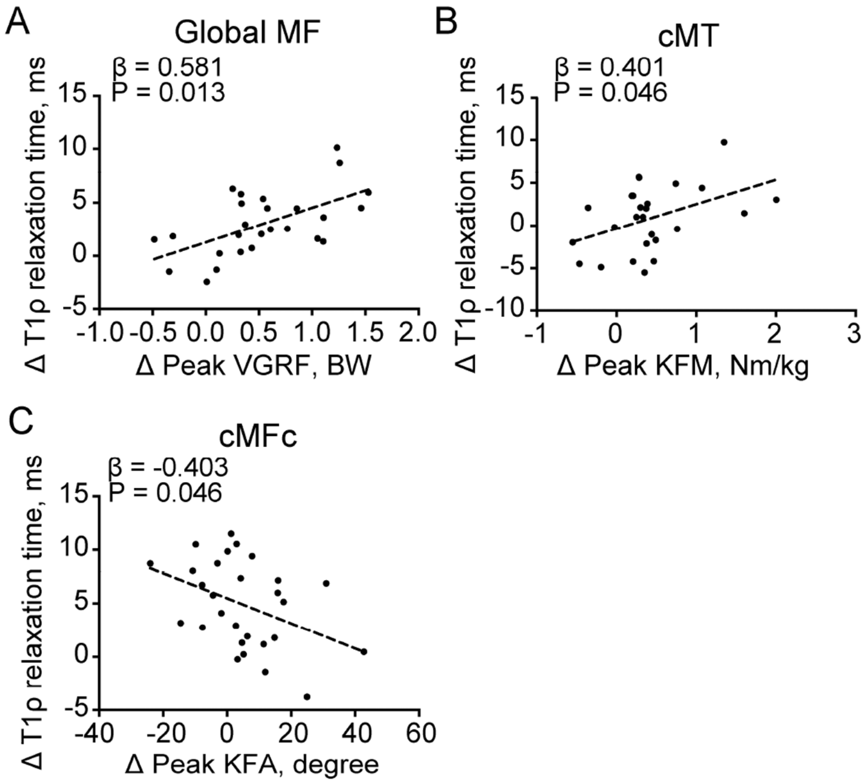

Figure 5:

Correlations between changes of biomechanics from six months to three years and changes of $T_{1\rho}$ relaxation time from baseline to three years after ACLR. (A) Scatter plot of change of peak VGRF and change of $T_{1\rho}$ relaxation time of global MF. (B) Scatter plot of change of peak KFM and change of $T_{1\rho}$ relaxation time of cMT. (C) Scatter plot of change of peak KFA and change of $T_{1\rho}$ relaxation time of cMFc.

Table 1.

Subject demographics represented as the mean (standard error of mean).

	ACLR, N = 31 Mean (SD)	Control, N = 16 Mean (SD)	*P* value
Sex	17 male, 14 female	10 male, 6 female	0.61
Age, years	31.3 (1.4)	31.7 (1.3)	0.88
Height, m	1.73 (0.02)	1.73 (0.02)	0.94
Mass, kg	70.6 (2.3)	70.0 (1.9)	0.88
BMI, kg/m^2	23.5 (0.4)	23.9 (0.5)	0.67
Time from injury to baseline, days	64.9 (8.3)		
Time from injury to surgery, days	72.2 (9.6)		
Graft type			
Hamstring autograft, N	22		
Soft tissue allograft, N	9		

Table 2.

Biomechanics during the stance phase of the drop landing task for the anterior cruciate ligament reconstruction (ACLR) patients at six months, three years and the controls are presented as the mean (standard error of the mean).

	ACLR		**Contralateral**		**SSDinACL**	**subjects**	**Controls**
	6 months	**3 years**	**6 months**	**3 years**	**6 months**	**3 years**	
PeakVGRF,BW	1.26 (0.06) *	1.75 (0.09) †	1.78 (0.09)	1.65 (0.06)	−0.50 (0.08) ‡	0.09 (0.08) †	1.59 (0.09)
VGRFimp,BWms	452 (20)	529 (14) *†	560 (21)	527 (14)	−108 (16) ‡	0 (13) †	460 (18)
Peak KFA, degree	84.1 (2.6) *	88.9 (2.1)	87.3 (2.6)	90.6 (2.2)	−3.2 (3.6) ‡	−1.8 (4.0)	94.2 (3.3)
Peak KFM, Nm/kg	1.40 (0.07) *	1.78 (0.07) *†	2.04 (0.05)	1.93 (0.09)	−0.65 (0.09) ‡	−0.14 (0.07) †	2.00 (0.08)
KFM imp, Nm·ms/kg	381 (25) *	524 (25) *†	626 (30)	568 (28)	−245 (28) ‡	−43 (124) †	665 (43)

An * indicates a statistically significant difference with the controls.

A † indicates a statistically significant difference between 6 months and 3 years.

A ‡ indicates a statistically significant difference between ACLR and Contralateral.

VGRF: vertical ground reaction force, BW: Body Weight, imp: impulse, KFM: knee flexion moment, KFA: knee flexion angle, SSD: side to side difference.

Table 3.

$T_{1\rho}$ relaxation times (ms) for the anterior cruciate ligament reconstruction (ACLR) patients at baseline, three years and the controls represented as the mean (standard error of the mean).

	ACLR		**P value**		**Contralateral**		**Control**	
	BL	**3Y**	**BLvs3Y**	**3Yvs Control**	**BL**	**3Y**	**BL**	**3Y**
Global MF	39.4 (0.5)	42.5 (0.5) *†	<0.001	<0.001	38.7 (0.6)	41.3 (0.7) *†	38.3 (0.6)	40.3 (0.7)
cMFc	37.1 (0.6)	41.7 (0.6) *†	<0.001	0.001	37.5 (0.9)	39.1 (0.9) *	36.8 (0.4)	38.5 (0.6)
Global MT	35.2 (0.5)	36.8 (0.6) *†	0.012	0.022	35.7 (0.6)	36.1 (0.6)	34.3 (0.7)	35.8 (0.8)
cMT	34.3 (0.6)	35.4 (0.7)	0.128	0.323	35.1 (0.7)	35.0 (0.8)	34.3 (0.8)	34.7 (0.8)

An * indicates a statistically significant difference with control at baseline.

A † indicates a statistically significant difference between baseline and three years.

ACLR, anterior cruciate ligament reconstruction; MF, medial femur; MT, medial tibia; c, central; BL, baseline; 3Y, three years