Increases in Joint Laxity After Anterior Cruciate Ligament Reconstruction Are Associated With Sagittal Biomechanical Asymmetry

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Purpose: To investigate the longitudinal changes in landing mechanics and knee kinematics for patients both before and 3 years after anterior cruciate ligament reconstruction (ACLR) and to investigate the association between changes in landing mechanics and magnetic resonance knee kinematics. **Methods:** Thirty-one ACLR patients were included in the study. All patients underwent magnetic resonance imaging and biomechanical analysis of a drop-landing task using the injured knee and contralateral knee preoperatively and at 6 months and 3 years after ACLR. For evaluations of knee joint anteroposterior laxity, tibial position was calculated using quantitative loaded magnetic resonance methods. **Results:** The ACLR knee exhibited a significantly lower peak vertical ground reaction force and peak external knee flexion moment and angle at 6 months compared with the contralateral knee; however, the differences were resolved at 3 years. Tibial position was significantly more anterior on the injured side, and the side-to-side difference (SSD) in tibial position exhibited a significant increase from 6 months to 3 years. Among ACLR knees, a greater SSD in peak knee flexion moment at 6 months was associated with an increase in the SSD in anterior tibial translation from 6 months to 3 years. **Conclusions:** Although landing mechanics and clinical outcomes recovered in patients with ACLR in this study, anteroposterior translation failed to be restored at 3 years after surgery. In addition, patients who have low knee flexion moments in early stages could have greater anteroposterior laxity. **Clinical Relevance:** Because of the adverse consequences of abnormal knee kinetics on anterior laxity after ACLR, efforts to improve knee movement patterns should be initiated.

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Knee joint laxity is associated with an increased risk of meniscal injury and cartilage degeneration.[1-4] Although anterior cruciate ligament reconstruction (ACLR) has been successful at restoring functional stability to prevent these problems in most patients,[5] persistent abnormal anteroposterior and rotatory joint laxity has been shown in patients after ACLR.[3,6] Kinematic magnetic resonance imaging (MRI) has been developed to noninvasively quantify 3-dimensional (3D) joint kinematics.[7,8] It was previously reported that combined tibiofemoral registration with automatic definition of the posterior femoral condyle and diaphysis axes allows for improved knee kinematic quantification with excellent in vivo reproducibility.[9,10] Nevertheless, little information is known about the mechanisms that may lead to increased knee joint laxity after ACLR.

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The current literature highlights evaluation of landing mechanics during standardized jump tasks as a screening tool for risk of anterior cruciate ligament (ACL) injury.[11] Several studies have reported asymmetrical landing strategies among patients after ACLR.[12,13] In addition, limb symmetries after ACLR were suggested as predictive factors of subsequent ACL injury and knee osteoarthritis development. The observed asymmetrical biomechanical pattern has often been proposed to arise from quadriceps strength deficits in the involved leg, with ACLR patients with increased strength deficits exhibiting the largest asymmetries in sagittal knee joint biomechanics.[14,15] However, these biomechanical studies were cross-sectional in nature, and the longitudinal changes in landing mechanics in ACLR patients have yet to be investigated. Moreover, little information is available regarding the relation between knee joint laxity and landing biomechanics. Therefore, it is of great interest to the orthopaedic community to determine whether longitudinal changes in landing mechanics are associated with longitudinal changes in knee joint laxity.

The purposes of this study were to investigate the longitudinal changes in landing mechanics and knee kinematics for patients both before and 3 years after ACLR and to investigate the association between changes in landing mechanics and magnetic resonance (MR) knee kinematics. We hypothesized that landing mechanics would be altered after ACLR and that altered landing mechanics after ACLR would influence knee laxity and clinical outcomes.

Methods

Subjects

This study was approved by our university's institutional review board (No. 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 45 subjects who had MRI data obtained before ACLR and had landing biomechanics assessed 6 months after ACLR. The exclusion criteria for this study were (1) concomitant ligamentous injuries that needed surgical treatment; (2) a history of inflammatory or primary osteoarthritis; (3) previous knee surgery or a nonoperatively treated ACL, meniscal, or cartilage injury; and (4) an abnormal contralateral knee. Subjects were excluded from follow-up if they declined to receive ACLR or if meniscal repair was required (n = 2) because they would undergo a different rehabilitation protocol and have weight-bearing requirements. Rerupture cases that occurred during the observational period were also excluded (n = 4). A total of 6 patients were lost to follow-up from 6 months (first drop-landing test) to 3 years after ACLR, and 2 patients could not sufficiently perform the drop-landing test at 3 years. Table 1 summarizes the subjects' demographic characteristics. All ACLRs were performed by 1 of 3 board-certified, fellowship-trained orthopaedic surgeons (including C.B.M.) at a single institution (University of California, San Francisco) using either hamstring autograft (n = 22) or soft-tissue allograft (i.e., posterior tibialis or hamstring) (n = 9). Graft choices regarding 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 using anteromedial portal drilling. All patients underwent the same fixation method with suspensory femoral fixation and interference tibial fixation.

Table 1. Demographic Data of ACLR Patients (N = 31)

	Data
Male/female sex, n	17/14
Age, yr	31.3 (7.8)
BMI	23.5 (2.2)
Time from injury to baseline, wk	9.3 (6.7)
Time from injury to surgery, wk	10.3 (7.8)
Graft type, n	
Hamstring autograft	22
Posterior tibial allograft	8
Hamstring autograft	1

NOTE. Data are presented as mean (standard deviation) unless otherwise indicated.

ACLR, anterior cruciate ligament reconstruction; BMI, body mass index.

All patients participated in a standard postoperative ACL rehabilitation program at our sports medicine clinic. Immediate postoperative recovery emphasized controlling pain and swelling and regaining motor control. The operative knee was kept in a hinged knee brace at all times; the brace was locked in extension while walking until quadriceps control and normal gait were achieved (partial weight bearing with crutches for 3 weeks). The primary focus for the first 6 weeks was on 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 permitted at 6 to 8 months, as long as the patient had achieved appropriate functional milestones.

All ACLR patients returned at 6 months and 3 years after ACLR for follow-up visits consisting of MRI and biomechanical assessments. Power analysis was performed to detect 10% differences in MR kinematic measurements at 3 years between the ACLR and contralateral limbs with a power of 80% at a significance level of .05. Thirty subjects were needed, and we over-recruited for this study in consideration of dropouts.

All ACLR patients were asked to fill out the Knee Injury and Osteoarthritis Outcome Score (KOOS) at all testing time points to obtain self-reported measures of knee-related pain, symptoms, activities of daily living, sports and recreation function, and quality of life.[16] In addition, all ACLR patients filled out the Marx activity rating scale at all testing time points to quantify the patients' physical activity level.[17]

Landing Analysis

Three-dimensional position data were recorded using a 10-camera motion capture system (Vicon, Oxford, England) at a sampling rate of 250 Hz. Ground reaction force (GRF) data were collected using 2 embedded force platforms (Advanced Mechanical Technology, Watertown, MA) at a sampling rate of 1,000 Hz. A marker set consisting of 41 retroreflective markers was used to collect 3D position data. 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 L5-S1 joint. Thigh and shank tracking was performed using rigid clusters consisting of 4 markers each that 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 3 markers placed on the shoe heel 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.

The drop-jump task, as previously described,[11] 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 participant was 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 in which the participant stepped off the platform as opposed to jumping off or lowering himself or herself down, landed with both feet simultaneously with 1 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 7-segment musculoskeletal model in the Visual3D program (C-Motion, Germantown, MD) consisting of the pelvis and bilateral thighs, shanks, 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.[18] Local joint coordinate systems were created, and an unweighted least squares method was used to describe segment position and orientation.[19] Lower-extremity joint kinematics was resolved using a Cardan rotation sequence of X-Y′-Z″,

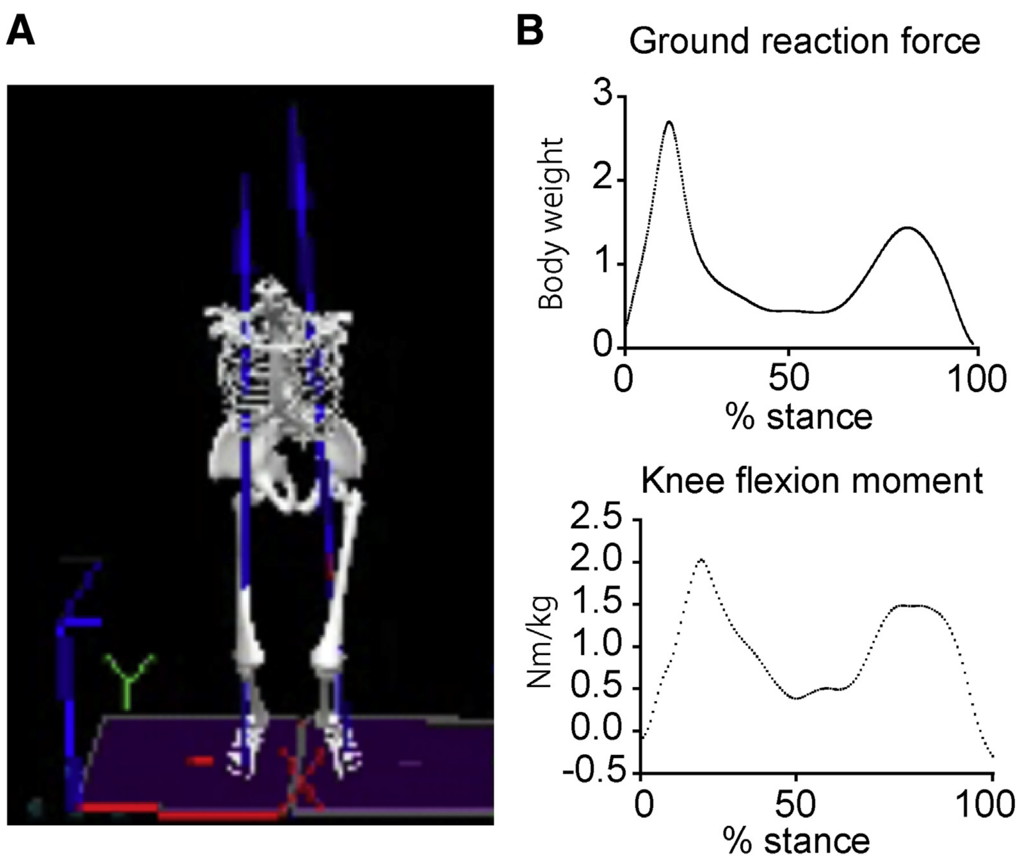

Fig 1. (A) Drop landing. (B) Vertical ground reaction force normalized by body weight and knee flexion moment during stance phase of drop-landing task.

representing the medial-lateral, anterior-posterior, and superior-inferior directions (Fig 1A). All joint angles were normalized to the standing calibration trial. GRF data were normalized to the participant's body weight. The external sagittal-plane knee joint moment was normalized to each participant's body mass (in newton meters per kilogram). Knee flexion and adduction angles and moments were considered positive. All data were analyzed during the landing phase of the task (stance phase). The stance phase of the task was defined as initial contact to toe off (vertical ground reaction force [vGRF] > 20 N) and was time normalized to 101 points (Fig 1B). Knee joint kinematic and kinetic variables of interest for this study included the peak knee flexion angle (KFA), peak knee abduction angle, peak external knee flexion moment (KFM), and peak knee abduction moment. In addition, the peak ipsilateral vGRF and contralateral vGRF during the stance phase were determined and used to calculate the limb symmetry index (LSI = Peak ipsilateral vGRF/Contralateral vGRF × 100%). Side-to-side differences (SSDs) were calculated by subtracting the value of the contralateral knee from that of the ACLR knee. These variables were computed for each trial, and the average value for 3 successful trials was used for statistical analyses. These biomechanical evaluations were performed by 4 authors (T.S., Z.C., M.A.S., and R.B.S.).

MR Image Acquisition

Sagittal T2 fast spin echo images of both knee joints were acquired on a 3-T MR scanner (GE Healthcare, Waukesha, WI) with a quadrature transmit and 8-channel receive knee coil (In Vivo, Orlando, FL), as previously described.[3] The imaging parameters included the following: repetition time, 4,000 milliseconds; echo time, 48.16 milliseconds; number of averages, 2; field of view, 16 cm; slice thickness, 1.5 mm; matrix size, 512 × 512; pixel size, 0.31 × 0.31 mm^2; and acquisition time, 2 minutes 24 seconds. The knee was first scanned in extension, followed by scanning at approximately 40° of flexion.[10] In both positions, the lower extremity was axially loaded with 25% of the participant's body weight using a low-friction pulley system (Fig 2A).[10,20] The compressive load used in this study was sufficient to produce a result (anterior subluxation of the tibia in extension) similar to that seen in full weight bearing with dual-plane fluoroscopy, as previously described.[21]

Kinematic MRI Analysis

MR-based tibiofemoral biomechanics was calculated using kinematic quantification methods previously described and shown to have good reproducibility (Fig 2B).[3,10,20] Tibial and femoral segmentations of the baseline contralateral (uninjured) knee were used to establish the coordinate systems for the respective bones. An iterative closest-point registration technique was then used to fit the 3D cloud of points obtained from segmentations of the injured side and follow-up scans. Tibial position in the anteroposterior direction was defined as the distance between the tibial and femoral coordinate system origins (circles in Fig 2C), with the more positive number indicating an anteriorly translated tibia. The SSD was calculated by subtracting the contralateral-side measurement from the injured-side measurement. These MR kinematic evaluations were performed by 4 authors (T.S., Z.C., M.S.T. and X.L.).

Statistical Analysis

Paired *t* tests with Bonferroni correction were used to compare limb differences in landing biomechanics and MR-based kinematics. Repeated-measures 1-way analyses of variance were used to examine the effect of

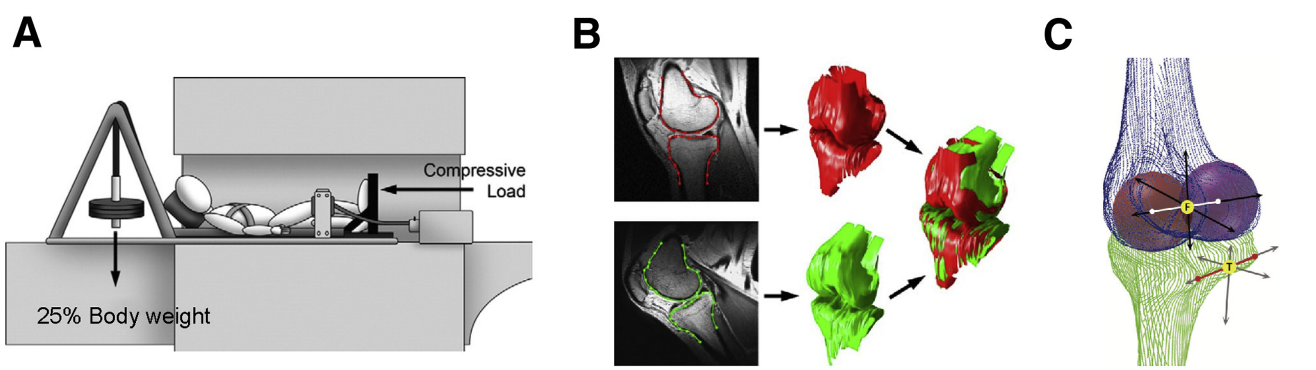

Fig 2. (A) Experimental setup. Weights are hung behind the patient in the magnetic resonance imaging system, and a set of pulleys and a loading plate transfer the force into a compressive load at the foot. The phased-array paddle coil is attached to the medial and lateral sides of the knee, and a knee-positioning plate provides feedback to help ensure a consistent angle of knee flexion. (B) Image analysis process. Sagittal images of the tibia and femur in an extended position (top) and flexed position (bottom) were segmented, and all slices were combined to obtain 3-dimensional shapes. The shapes of the tibiae were matched, and the motion of the femur relative to the tibia was analyzed. (C) Coordinate systems used to analyze kinematics of femur and tibia. The centers of spheres fit to the femoral condyles were used to quantify femoral condyle locations, and the most posterior points on the medial and lateral sides of the tibial plateau were used to define the tibial coordinate system.

Table 2. KOOS and Marx Activity Scores at Baseline, 6 Months After ACLR, and 3 Years After ACLR

	Preoperatively	6 mo After ACLR	3 yr After ACLR
KOOS			
Pain	78.9 (16.3)	81.1 (11.2)	90.0 (10.5)*†
Symptoms	69.8 (20.3)	68.6 (12.1)	82.1 (12.5)*†
Activities of daily living	85.9 (13.3)	91.3 (7.7)	96.0 (7.0)*†
Sports	59.4 (26.7)	64.3 (18.1)	85.3 (13.2)*†
Quality of life	47.2 (28.3)	46.1 (14.7)	72.0 (16.9)*†
Marx activity scale score	7.0 (3.5)	4.7 (4.0)	7.5 (3.7)†

NOTE. Data are presented as mean (standard deviation).
ACLR, anterior cruciate ligament reconstruction; KOOS, Knee Injury and Osteoarthritis Outcome Score.
*Statistically significant difference compared with baseline.
†Statistically significant difference compared with 6 months.

time on subjects' self-reported outcomes, landing biomechanics, and kinematics. When a significant main effect of time was noted, post hoc Bonferroni tests were conducted for pair-wise comparison. Linear regression models adjusted for age, sex, and body mass index were built to determine the associations between changes in biomechanical parameters, KOOS values, and MR-assessed kinematics within the ACLR patients. All statistical analyses were performed using SPSS Statistics software (version 23.0; IBM, Armonk, NY) with the significance level set at .05.

Results

Survey Results

ACLR patients reported improvements in the KOOS pain, symptoms, sports, and quality-of-life subscores from the 6-month to 3-year time point (Table 2). As expected, ACLR patients exhibited reduced Marx scores from before surgery to 6 months, yet they showed an improvement in Marx scores from 6 months to 3 years.

Landing Mechanics

ACLR patients exhibited lower peak vGRF of the ipsilateral limb at 6 months and 1 year compared with the contralateral limb, but they showed a gradual increase and achieved similar peak vGRF to the contralateral limb at 3 years after surgery. ACLR patients exhibited a lower peak KFM and KFA of the ipsilateral knee at 6 months and 1 year compared with the contralateral knee, but they showed a gradual increase and achieved a similar peak KFM and KFA to the contralateral knee at 2 years and 3 years. No interlimb differences in frontal-plane knee joint mechanics were noted (Table 3).

Tibiofemoral Alignment (Anteroposterior Direction)

Tibial position was significantly more anterior on the injured side than on the contralateral side at baseline, 6 months, and 3 years in ACLR subjects (Fig 3A). The mean estimated SSD of the anterior tibial position was significantly higher ($P < .05$) at 3 years after surgery compared with 6 months (Fig 3B).

Correlations Between Changes in Landing Characteristics and KOOS

Among ACLR subjects, an increase in the LSI of peak vGRF from 6 months to 3 years was associated with an increase in KOOS pain and sports scores from 6 months to 3 years (Fig 4A). An increased SSD in peak KFM was associated with an increase in KOOS pain and quality-of-life scores from 6 months to 3 years (Fig 4B).

Correlations Between Changes in Landing Characteristics and MRI-Assessed Kinematics

Among ACLR subjects, changes in the SSD in peak KFM from 6 months to 3 years were associated with changes in the SSD in anterior tibial translation from 6 months to 3 years ($\beta = 0.483$, $P = .018$) (Fig 5A). In addition, patients with a lower peak ipsilateral KFM compared with the contralateral knee at 6 months showed an increase in knee joint laxity from 6 months to 3 years after ACLR ($\beta = -0.448$, $P = .021$) (Fig 5B).

Discussion

The results of this study showed that drop-landing mechanics and patient-reported outcome measures recover 3 years after surgery. Surgery seeks to restore knee kinematics, but this study confirms previous work showing that anterior knee laxity still frequently exists postoperatively.[22] Although the improvement in drop-landing mechanics is correlated with the improvement

Table 3. Longitudinal Biomechanical Analysis During Landing From 6 Months to 3 Years

	6 mo	3 yr
Peak vGRF normalized by body weight		
ACLR (dominant)	1.28 (0.28)*	1.75 (0.45)†
Contralateral	1.76 (0.48)	1.65 (0.31)
Peak KFM, Nm/kg		
ACLR	1.37 (0.41)*	1.81 (0.42)†
Contralateral	2.00 (0.30)	1.93 (0.47)
Peak KFA, °		
ACLR	84.3 (14.2)*	89.3 (11.8)*
Contralateral	87.5 (14.3)	91.1 (12.3)
Peak knee abduction moment, Nm/kg		
ACLR	0.30 (0.19)	0.41 (0.28)
Contralateral	0.32 (0.20)	0.39 (0.20)
Peak knee abduction angle, °		
ACLR	6.23 (5.38)	7.07 (5.56)
Contralateral	4.42 (5.08)	7.11 (6.51)

NOTE. Data are presented as mean (standard deviation).
ACLR, anterior cruciate ligament reconstruction; KFA, knee flexion angle; KFM, knee flexion moment; vGRF, vertical ground reaction force.
*Statistically significant difference compared with contralateral.
†Statistically significant difference compared with 6 months after ACLR.

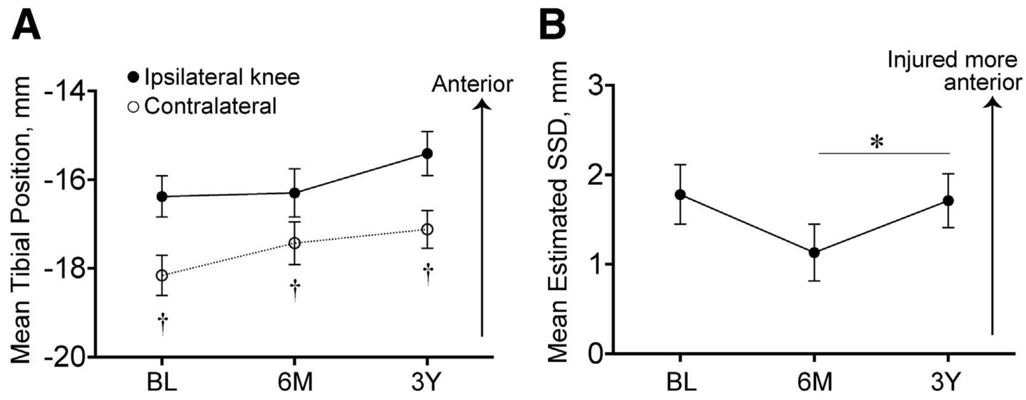

Fig 3. (A) Mean tibial position of injured and contralateral sides at each time point in anterior cruciate ligament reconstruction subjects. Daggers indicate $P < .05$ versus contralateral side. (B) Mean estimated side-to-side difference (SSD) in tibial position in anterior cruciate ligament reconstruction patients. The asterisk indicates $P < .05$. (BL, baseline; 6M, 6 months; 3Y, 3 years).

in patient-reported outcome measures from 6 months to 3 years, the improvement in drop-landing mechanics is correlated with increased joint knee laxity. Considering that patients with a lower peak ipsilateral KFM compared with the contralateral knee at 6 months showed an increase in knee joint laxity from 6 months to 3 years after ACLR, the findings of this study imply that these patients started with abnormal landing mechanics with a low KFM, leading to changes in joint kinematics and resulting in gradually increased laxity[23,24] while they continued through rehabilitation and their mechanics improved.

The results of this study are consistent with those of previous work that assessed 1-year longitudinal changes in peak ipsilateral vGRF in ACLR patients during a drop-jump task and showed lower kinetics in the ACLR knee compared with the contralateral knee.[25] This study showed that the peak ipsilateral vGRF and KFM increased from 6 months to 3 years among ACLR patients and a corresponding increase in the LSI of peak vGRF and SSD of peak KFM occurred within this period as well. Moreover, this study showed that recovery of interlimb asymmetry was associated with improvements in KOOS values from 6 months to

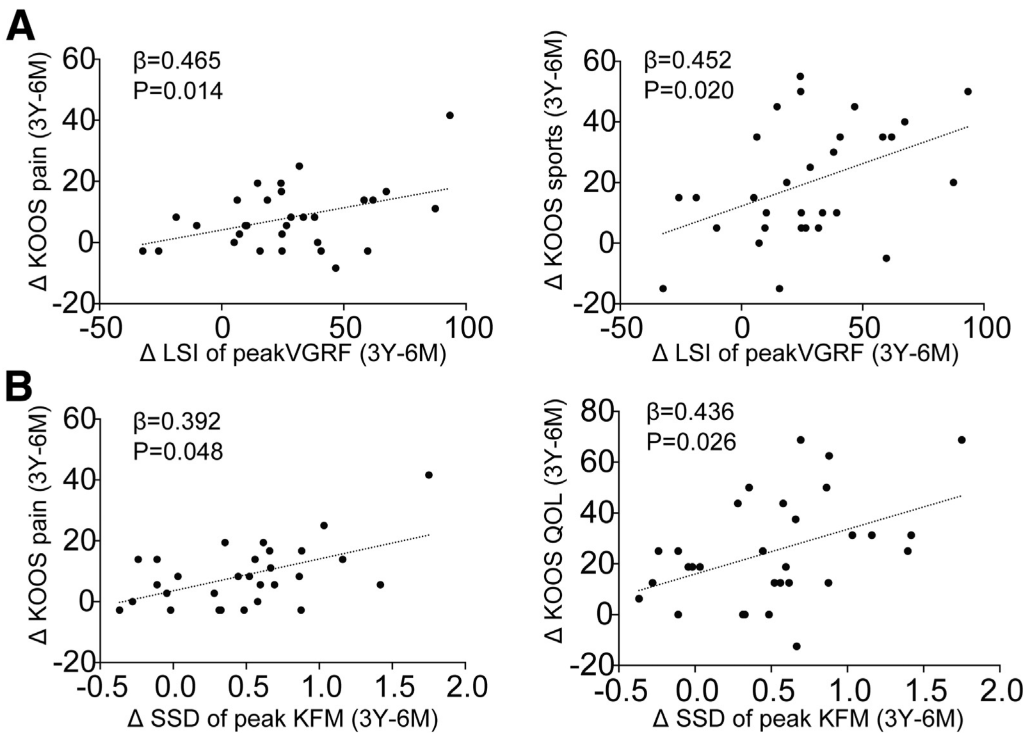

Fig 4. (A) Correlations between change in limb symmetry index (LSI) of peak vertical ground reaction force (VGRF) and change in Knee Injury and Osteoarthritis Outcome Score (KOOS) from 6 months (6M) to 3 years (3Y) in anterior cruciate ligament reconstruction patients. (B) Correlations between change in side-to-side difference (SSD) in peak knee flexion moment (KFM) and change in KOOS from 6 months (6M) to 3 years (3Y) in anterior cruciate ligament reconstruction patients. (QOL, quality of life.)

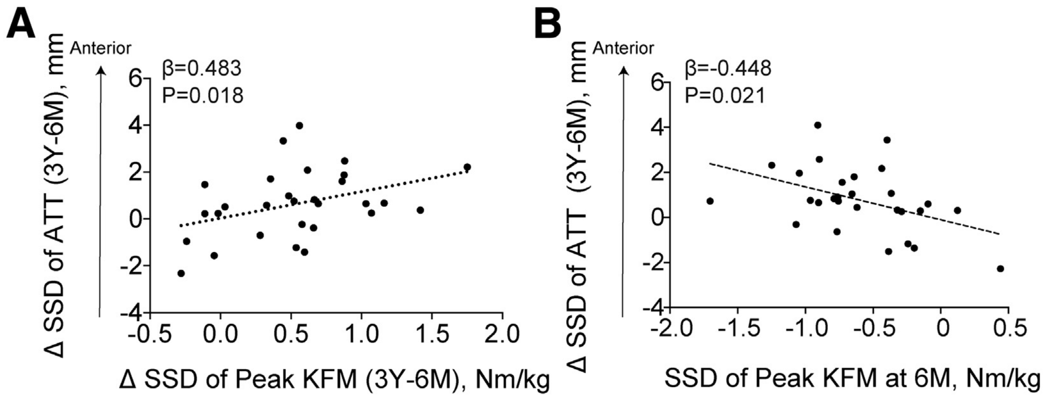

Fig 5. (A) Correlation between change in side-to-side difference (SSD) in peak knee flexion moment (KFM) and change in SSD in anterior tibial translation (ATT) from 6 months (6M) to 3 years (3Y) in anterior cruciate ligament reconstruction group. (B) Correlation between SSD of peak KFM at 6 months (6M) and change in SSD in ATT from 6 months (6M) to 3 years (3Y).

3 years after ACLR, suggesting that lower-extremity joint kinetics during a drop-landing task may be related to patient-reported outcomes after ACLR. These results support a recent study showing that after ACLR, young athletes with asymmetries in knee kinetics at the time of return to sports showed decreased self-reported function 2 years later.[26] In addition, the restoration of knee joint kinetic and movement symmetry after ACLR is an important goal to optimize knee function and is recommended as an objective criterion to allow return to sports.[27,28] Given that ACLR patients tend to be younger active individuals, more dynamic testing other than gait analysis may be appropriate to look at the impact of abnormal mechanics during activities on knee function. Limb asymmetry evaluated by a drop-landing test could be a potential biomarker to evaluate each patient's rehabilitation protocol after ACLR and predict the future clinical outcome.

This study showed that changes in sagittal-plane knee joint kinetics during a landing task were related to an increase in anterior tibial translation. This result is consistent with the findings of a previous study looking at a healthy population during a landing task that showed that joint laxity was associated with internal knee extensor moments and flexion angles.[29] However, this finding is contrary to the results of a recent small (N = 17) cross-sectional study that did not find any correlations between differences in drop-jump mechanics and knee joint laxity in a short duration (9 months).[22] The discrepancy in conclusions between our study and the report of Meyer et al.[22] could be explained by differences in follow-up times. It is interesting to note that our patients with larger SSDs in peak KFM 6 months after ACLR tended to exhibit larger increases in anterior tibial translation from 6 months to 3 years after ACLR. Therefore, the peak KFM during a landing task can be an important biomechanical parameter during the early postoperative period in predicting knee joint laxity after ACLR. This is an important finding because patients tend to increase their activity 6 months after ACLR. We should consider a different return-to-play protocol for patients who still have significant abnormal landing mechanics at 6 months.

Limitations

The main limitations of this study were that the sample size of ACLR patients was small and the types of grafts were not homogeneous. Despite the small sample size, the longitudinal nature of this study provides a unique approach to determining and understanding the associations of landing joint mechanics and knee joint laxity. In addition, the drop-landing task is a more demanding task compared with 25% body weight loading during kinematic MRI. Moreover, all patients in this study underwent a single-bundle anatomic ACLR, and therefore, our findings may be limited to this surgical technique. Finally, in this study, we did not investigate the graft tunnel placement and enlargement that have been reported to have an association with knee joint laxity.[30]

Conclusions

Although landing mechanics and clinical outcomes recovered in patients with ACLR in this study, anteroposterior translation failed to be restored at 3 years after surgery. In addition, patients who have low KFMs in early stages could have greater anteroposterior laxity.

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