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Dynamic Function of the ACL-reconstructed Knee during Running

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Little is known about the three-dimensional behavior of the anterior cruciate ligament (ACL) reconstructed knee during dynamic, functional loading, or how dynamic knee function changes over time in the reconstructed knee. We hypothesized dynamic, in vivo function of the ACL-reconstructed knee is different from the contralateral, uninjured knee and changes over time. We measured knee kinematics for 16 subjects during downhill running 5 and 12 months after ACL reconstruction (bone-patellar tendon–bone or quadrupled hamstring tendon with interference screw fixation) using a 250 frame per second stereoradiographic system. We used repeated-measures ANOVA to ascertain whether there were differences between the uninjured and reconstructed limbs and over time. We found no differences in anterior tibial translation between limbs, but reconstructed knees were more externally rotated and in more adduction (varus) during the stance phase of running. Anterior tibial translation increased from 5 to 12 months after surgery in the reconstructed knees. Anterior cruciate ligament reconstruction failed to restore normal rotational knee kinematics during dynamic, functional loading and some degradation of graft function occurred over time. These abnormal motions may contribute to long-term joint degeneration associated with ACL injury and reconstruction.

The primary goals of treatment after anterior cruciate ligament (ACL) injury are the restoration of lost function, the reduction or elimination of knee instability, and the prevention of long-term joint degeneration. Modern ACL reconstruction procedures use graft constructs with high initial strength[37] and are arguably successful for meeting the first two goals over the short term.[46] However, the graft cannot replicate the complex geometry of the original ligament,[6] which may contribute to altered kinematics and ACL length-flexion patterns in the reconstructed knee.[52] Also, biologically driven changes in the implanted graft can substantially reduce graft strength after implantation. In animal models, histological and biochemical changes occur in the graft for a year or more after implantation[2] with related changes in mechanical properties.[34] Reductions in graft failure loads of 50% to 89% and stiffness of up to 87% (relative to the contralateral intact ACL) have been reported a year or more after reconstruction.[7,34] Thus, there is reason to believe the function of the ACL graft may change over time. The effects of these factors on in vivo knee function and long-term joint health are not well understood, especially during functional, stressful loading situations.

Altered mechanics of the ACL-injured/reconstructed knee may increase the risk for long-term joint degeneration. Animal models have shown a clear connection between mechanical instability and progressive osteoarthritis (OA).[11,38,40] Human ACL injury is associated with a high incidence of radiographic knee OA, with sclerosis, osteophytes and/or joint space narrowing present in 53% to 70% of patients 5 to 10 years after injury.[19,31,56] The goal of ACL reconstruction surgery is to reproduce the function of the original ligament, to restore stability and function, and reduce the risk of subsequent OA. Though the surgery may effectively restore short-term function, it does not appear effective for preventing OA. In a review of five previous studies, radiographic evidence of OA was found in from 13% to 65% of patients 3 to 12 years after ACL reconstruction.[22] Similar or higher incidences of knee OA has been reported in ACL-deficient individuals who have undergone ligament reconstruction compared with those who

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have not.[18,20,30,54] Despite criticisms of these studies (retrospective, uncontrolled, possible selection bias between patients who choose surgical reconstruction versus those who do not), to date there is no clear evidence of a long-term protective effect from the procedure. Though other factors may contribute to OA development in the reconstructed joint (such as possible damage to other tissues at the time of injury), failure of the reconstruction to restore and maintain normal knee kinematics could be an important contributor to progressive cartilage degeneration.

The effectiveness of ACL reconstruction for restoring normal knee function has been difficult to quantitatively assess. Static tests of anterior tibial displacement in response to an applied anterior force suggest abnormal anterior tibial motion (typically 5–10 mm) after ACL loss, which returns to near-normal levels after ACL reconstruction,[17,28,32,47,53] and increased rotational laxity (internal-external tibial rotation) in ACL-deficient knees.[27] However, static stability measures have not correlated with any known measure of functional outcome for ACL-injured subjects before or after reconstruction.[8,15,24,44,48] Conventional motion analysis studies (video and surface markers) are insufficient for studying in-depth knee kinematics and ligament function because of motion of the skin relative to underlying bones,[12,41,50] and algorithms for reducing skin motion artifact[1,13,49] have yet to be validated for activities such as running and jumping where there are high peak accelerations and decelerations. Dynamic magnetic resonance imaging (MRI) and computed tomography (CT) methods show promise,[42,45] but are limited by low frame rates and environments too restrictive for most dynamic, weightbearing activities.

Radiographic imaging offers a minimally invasive alternative for knee motion assessment. Use of biplane radiographic film methods (radiostereophotogrammetric analysis or RSA) for three dimensional (3D) studies of static bone position has been well established,[28,43] with precision reported in the ± 10 to 250 μm range.[26] We have developed a dynamic RSA system for accurate assessment of dynamic joint motion. This system (in detail elsewhere)[51] is well suited for dynamic knee motion measurement, with 3D accuracy of ± 0.1 mm and rates up to 1000 frames/s. Using this approach we previously reported preliminary findings (the first six subjects) tested 4 to 6 months after surgery[52] and found anterior tibial translation was similar for the reconstructed and uninjured limbs. However, reconstructed knees were more externally rotated (tibia relative to femur) on average by 3.8 ± 2.3° across all subjects. Reconstructed knees were also more adducted (in greater varus), by an average of 2.8 ± 1.6°. Though the sample size was small, these differences were consistent across all subjects.

We sought to confirm whether these findings applied in a larger population with longer followup (1 year after surgery, by which time most subjects had returned to full activity including sports participation) and whether there were any changes in dynamic knee function over time. We hypothesized previously identified early kinematic differences between reconstructed and contralateral (uninjured) limbs would remain substantial at 1 year. We also hypothesized there would be differences in kinematics of the reconstructed knee between the early and 1-year followup tests related to changes in the mechanical function of the ACL graft.

MATERIALS AND METHODS

We prospectively recruited subjects between the ages of 16 and 50 years undergoing unilateral, primary arthroscopic ACL reconstruction.[52] Exclusion criteria included any prior substantial injury to the contralateral limb and substantial damage to other knee structures in the ACL-injured limb (subjects with minor meniscal tears, requiring removal of no more than ⅓ of the radial width of the meniscus, were not excluded). All nonexcluded patients undergoing ACL reconstruction by one of the three participating surgeons (DC, PK, KA) were asked to participate in the study. Sixteen subjects with 1-year followup data available were included in this analysis. There were six women and 10 men, of mean age 35 years (range, 24–48 years), and minimum time of 1 month from injury to surgery (mean, 17 months; range, 1–121 months). One subject was reconstructed 10 years after the injury; excluding that subject the mean time from injury to surgery was 10 months (Table 1). Autografts were used in all cases; graft material was bone-patellar tendon-bone for seven subjects and tripled/quadrupled hamstrings tendon for 9 subjects.

Interference screw fixation was used in all cases but two of the hamstring grafts, where a cross-pin system was used for femoral fixation. During the ACL reconstruction procedure, tantalum spheres (1.6-mm diameter) were inserted into the distal femur and proximal tibia of both limbs using a cannulated drill. These markers provided high-accuracy radiographic targets for RSA. Three noncollinear markers were inserted into each bone, to enable full six degree-of-freedom tracking. Informed consent was obtained from all enrolled subjects, and the protocol was approved by the Henry Ford Health System Institutional Review Board for human subject research.

Static knee laxity was also assessed (using a KT-1000 arthrometer [MEDmetric Corp, San Diego, CA, USA] at 89 N anterior force), and correlated with the maximum value for Functional Graft Length from the dynamic measurements. Subjective knee function and activity level were also evaluated with the Cincinnati Knee Ligament Rating System[36] (sports activity level, ability to participate in sports, functional assessment rating scale and rate of pain/swelling/giving way; based on a 0% to 100% scoring system with 100% being maximum function/minimum pain). Arthrometer measurements and subjective evaluations were performed at the time of each xray kinematic study, as described below.

TABLE 1. Subject Characteristics

Subject	Age	Gender	Graft Type	Additional Procedures	Time Injury to Surgery (months)	KT-1000 Difference (mm)	Cincinnati Knee Score 1 Year Postsurgery (4 scales)
1	48	F	Ham	Partial lateral meniscectomy	18	1	75/50/80/20
2	39	M	Ham	Partial medial meniscectomy	9	N/A	85/80/100/100
3	41	M	Ham	Medial meniscus repair	1	4.5	95/100/100/100
4	42	F	PT	Partial lateral meniscectomy	24	1	85/100/80/100
5	34	F	PT	Partial med/lat meniscectomy	4	0.5	95/100/100/100
6	41	M	PT	Partial med/lat meniscectomy	5	3.5	95/60/80/80
7	37	F	Ham	None	4	N/A	80/80/100/80
8	40	M	Ham	None	24	−1	85/100/100/100
9	40	F	Ham	Medial meniscus repair	2	2.5	80/100/100/100
10	34	M	Ham	None	30	1	95/100/100/100
11	39	F	PT	None	121	−1.5	95/80/100/100
12	27	M	PT	None	3	0	80/100/100/100
13	25	M	PT	Partial lateral meniscectomy	2	−0.5	85/80/100/100
14	29	M	Ham	Partial medial meniscectomy	6	1	80/100/100/100
15	27	M	PT	None	10	1.5	95/80/100/80
16	24	M	Ham	Partial medial meniscectomy	12	1.5	90/100/100/80

Ham = hamstring tendon; PT = bone-patellar tendon-bone; N/A = not available

We performed kinematic testing as soon as possible after the subject completed his or her rehabilitation program and was cleared by the surgeon for return to light sports activities. This time was typically 4 to 6 months (mean 5 months). Moderate-speed downhill running was selected as the activity for study because it is more stressful on the ACL than level-ground running.[29] In addition to placing greater mechanical demands on the knee than walking, running also eliminates the double-support phase and reduces the effects of compensation from the contralateral limb. It can be performed in a controlled, repeatable fashion within the laboratory environment, and is unlikely to put the individual at risk for injury. A moderately slow running speed (jog) was selected to insure all subjects would be able to perform the task. All subjects were able to perform the downhill running task without difficulty, with no obvious limping or asymmetry, at both the 5- and 12-month tests. Testing was performed at 2.5 m/s on a standard treadmill (Model L8, 46 × 152 cm belt, Landice Corp. Randolph, NJ, USA) with the rear supports elevated 25 cm to provide a 10° downward slope (Fig 1). For each trial, kinematic data was collected from shortly before footstrike through mid-stance for one step of the test leg (approximately 0.5 s duration), using an electronic timer system and an accelerometer strapped to the shank to detect footstrike.

Knee kinematics were assessed with dynamic RSA, a technique for determining 3D kinematic information from stereo-pair radiographic images of musculoskeletal tissue with implanted high-contrast markers.[43] We have applied this technique to the study of dynamic knee movement by replacing radiographic film with high-speed digital imaging. The dynamic RSA system consisted of two gantries (each containing a 150 kW xray source, 30 cm image intensifier and 250 frame/s digital video system), configured to provide two beams parallel to the ground with an inter-beam angle of 60° (Fig 1). This system is capable of tracking implanted markers with accuracy of approximately ± 0.1 mm, as previously described.[51] For a typical marker configuration (three markers, at least 20 mm between markers), this corresponds to rigid-body kinematics errors of approximately ± 0.2 mm and 0.3 degrees. Xray studies were performed using a biplane 90 kVp, 100 mA, 0.5 s exposure, delivering an estimated effective radiation dose of 200 mR per trial (total of 2.4 R for all of the running trials for the 5 and 12-month tests). This amount of radiation exposure is similar to a single clinical knee CT scan.

We calculated rotations of the tibia relative to the femur using body-fixed axes in the order (flexion/extension, adduction/abduc-

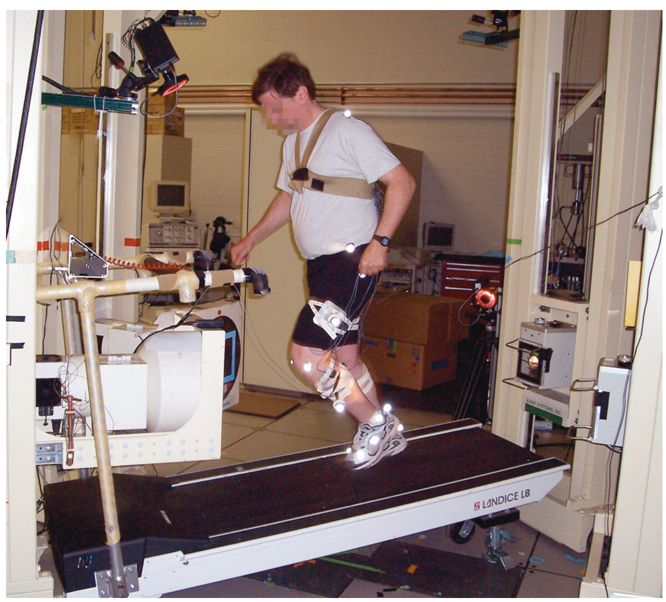

Fig 1. A subject is shown running downhill on a treadmill in the High-Speed Biplane Radiographic System. Images were acquired simultaneously at 250 frames/s for the two views (60° separation).

tion, internal/external rotation) corresponding to the rotational component of the Joint Coordinate System originally described by Grood and Suntay.[23] Transformations between implanted marker-based coordinates and anatomical axes/landmarks were determined from CT, as previously described.[51] Missing marker data, due to interference from implanted hardware or marker overlap, was filled in prior to kinematic analysis using cubic spline interpolation. Since long gaps (ie, greater than 1–2 frames) were rare and the sample rate was high relative to the frequency of movement, this had minimal impact on data interpretation. Prior to any kinematic analysis, the 3D marker coordinates for each trial were lowpass filtered using a bidirectional 6th-order Butterworth digital filter with a 20 Hz cutoff frequency. Displacements of the tibia relative to the femur (anteroposterior, mediolateral, and proximodistal) were measured from ACL (or graft) origin to insertion and expressed in an orthogonal anatomical coordinate system fixed to the tibia. We estimated graft origins and insertions by identifying the center of the tibial and femoral tunnels at the joint surface of 3D bone models generated from subject-specific CT scans. To minimize side-to-side variability, the same locations were used for the uninjured limb by mirror-imaging the reconstructed limb CT and coregistering it with the uninjured limb CT. Functional graft and ACL length was estimated as the instantaneous magnitude of the origin-to-insertion vector during the running task.

Rigid-body motions of the tibia relative to the femur were determined for each limb for each of six kinematic variables: flexion/extension, internal/external rotation, abduction/adduction (valgus/varus), mediolateral translation, anteroposterior translation, and functional graft length. For each subject, limb and test date, kinematic curves were aligned relative to footstrike and averaged across the 3 trials. Data from six time points during the period from footstrike to mid-stance (0, 0.02, 0.04, 0.06, 0.08, and 0.10 s after footstrike) were extracted from the 3-trial average, using an interpolating cubic spline if necessary.

Within-subject limb-to-limb differences and changes over time were evaluated with a 3-way repeated-measures ANOVA (SPSS GLM3, SPSS Inc, Chicago, IL, USA) with the design LIMB × TESTDATE × SAMPLETIME (LIMB = reconstructed versus contralateral; TESTDATE = 5 months versus 12 months after surgery; SAMPLETIME = six points from each trial, from 0 to 0.1 s after footstrike). Interactions between LIMB, TESTDATE, and SAMPLETIME were evaluated ($p = 0.10$ due to reduced power for detecting interactions).[33] If interactions were nonsignificant, then LIMB and TESTDATE effects were examined for overall differences. Where interactions were found, the groups were examined separately with post hoc ANOVAs (with Bonferroni adjustment for multiple comparisons) ($p = 0.05$ except for the interaction terms).

RESULTS

Clinically and functionally, the subjects were doing well 1 year after surgery, with mean scores on the Cincinnati Knee Ligament Rating System of 87%, 88%, 96%, and 90% (out of a maximum of 100%) on the sports activity, sports participation, function and pain/discomfort scales, respectively. Of the 48 separate scores (4 scales × 16 subjects), only three (from two different subjects) were less than 80%. Differences in KT-1000 arthrometer measurements between limbs 5 months after surgery were small (mean difference, +1.1 mm; range, –1.5–4.5), but with greater ($p = 0.029$) anterior tibial translation in the reconstructed knees. Arthrometer measurements were similar at 5 and 12 months.

Kinematics differed ($p = 0.014$) between reconstructed and uninjured limbs. We identified specific differences between limbs for rotational motion in the coronal and transverse planes (Fig 2). Across both test dates, reconstructed limbs were more ($p = 0.007$) adducted (in more

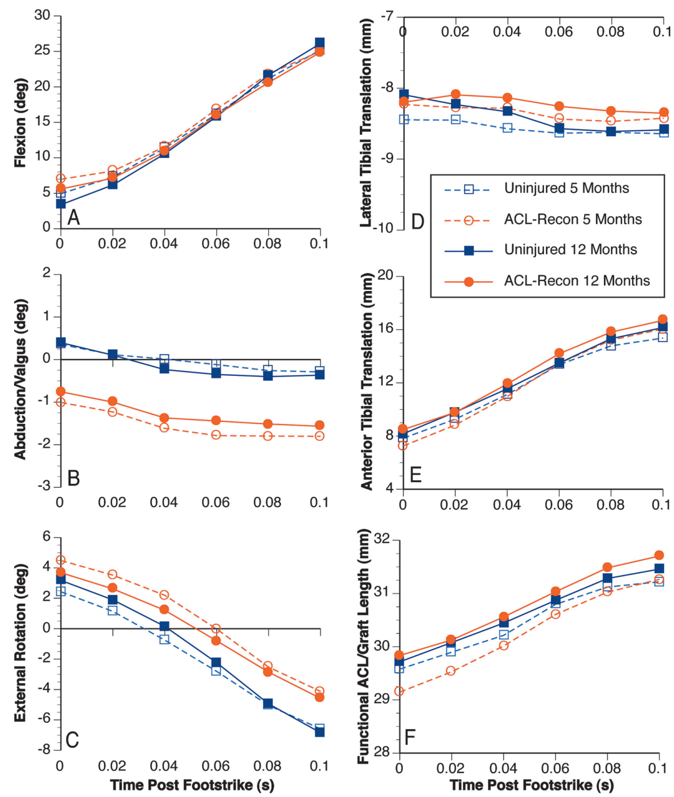

Fig 2A–F. Mean knee kinematics for 16 subjects were calculated for the period from early to mid-stance phase of downhill running. Data was collected continuously at 250 frames per second, but values were extracted every 20 ms for statistical analysis. Square symbols are ACL-reconstructed limbs; round symbols are contralateral (uninjured) limbs. Dashed lines (open symbols) are 5 months post surgery; solid lines (filled symbols) are 12 months post surgery. (A) Tibiofemoral rotations corresponding to the clinical planes of flexion/extension, (B) abduction/adduction and (C) external/internal rotation are presented. Translations of the tibia relative to the femur in the (D) anterior and (E) lateral directions are shown. (F) The functional length of the ACL (or graft), calculated as the 3D distance between the ligament/graft origin and insertion is shown.

varus; mean difference, reconstructed versus uninjured, 1.32°) and more externally rotated (mean difference, 1.94°; $p = 0.048$) (Fig 3). No differences were found between limbs for flexion/extension (mean difference, –0.9°), mediolateral translation (mean difference, 0.39 mm), anteroposterior translation (mean difference, 0.41 mm), or functional graft length (mean difference, 0.06 mm).

Knee kinematics in the reconstructed limb changed ($p = 0.006$) between the 5- and 12-month tests (Fig 4). Anterior tibial translation increased ($p = 0.002$) by a mean of 0.85 mm, with the greatest differences occurring during the impact and peak loading phase. Functional graft length was increased ($p < 0.001$) throughout stance by an average of 0.53 mm (1.91% of the standing ACL length in the intact limb). No differences were found between the 5-

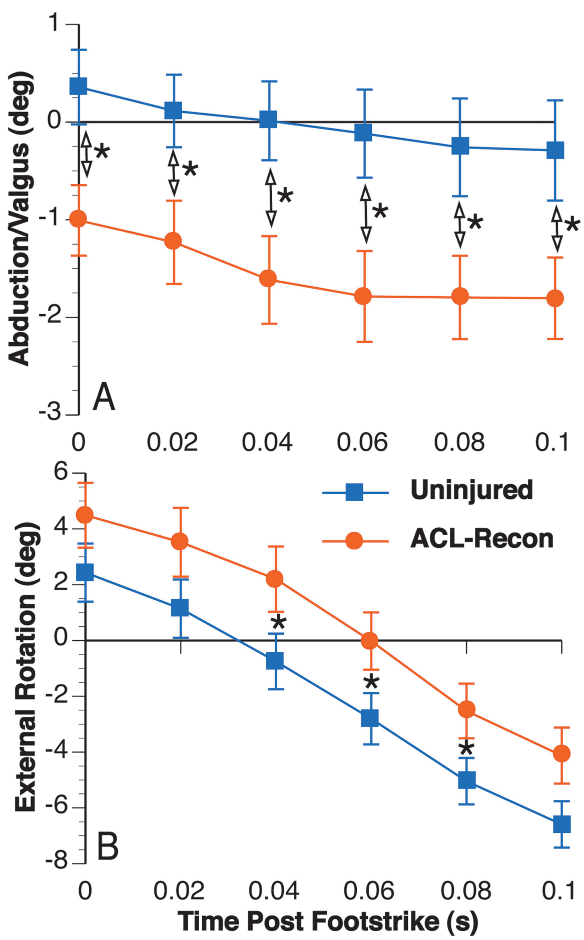

Fig 3A–B. Significant differences ($p < 0.05$; indicated by asterisks) between ACL-reconstructed knees (round symbols) and contralateral, uninjured knees (square symbols) were identified for (A) abduction/adduction and (B) internal-external rotation at five months after surgery. Differences in flexion/extension and all joint translations (not shown) were not significant. Vertical lines are ± 1 standard error.

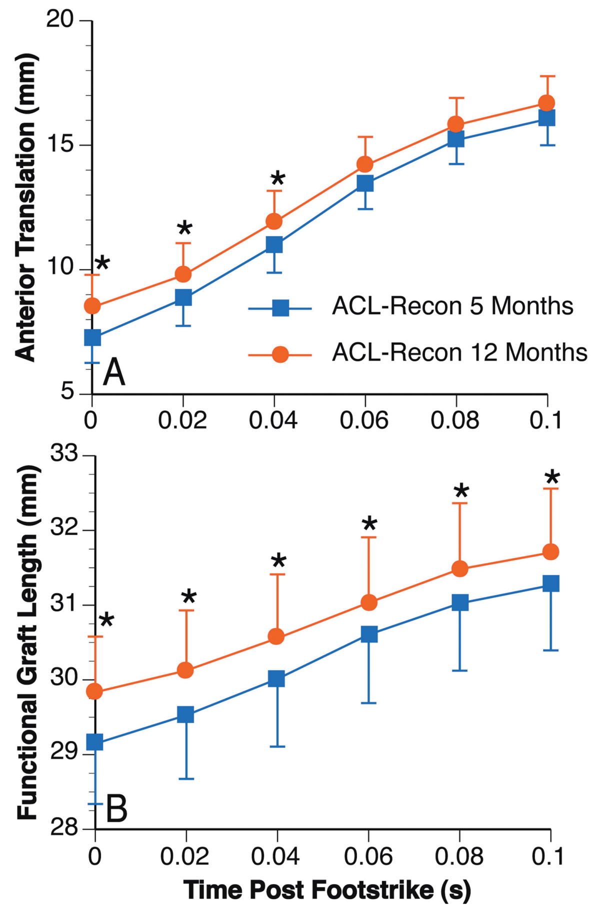

Fig 4A–B. Knee kinematics changed significantly (asterisks: $p < 0.05$) from 5 (square symbols) to 12 (round symbols) months after surgery. (A) Anterior tibial translation increased over time during early stance in ACL-reconstructed knees, and (B) functional graft length was significantly increased throughout early/mid stance. No significant changes over time were found in contralateral, uninjured knees. Vertical lines are ± 1 standard error.

and 12-month kinematics in the reconstructed limb for flexion/extension (mean change, –0.88°), abduction/adduction (mean change, +0.27°), internal-external rotation (mean change, –0.71°) or mediolateral translation (mean change, 0.13 mm). There were no changes between test dates in any of the measures for the contralateral, uninjured limbs.

DISCUSSION

We evaluated function of the ACL-reconstructed knee at two time points after surgery (approximately 5 and 12 months) during a dynamic, stressful functional task (downhill running). We hypothesized there would be differences between kinematics of reconstructed and contralateral (uninjured) limbs and kinematics of the reconstructed knee would change over time.

We note several limitations, including the heterogeneity of the subject population in regards to age, gender, surgeon, graft type (hamstring or patellar tendon), graft fixation, rate of rehabilitation, level of athletic activity, etc. Exploratory analyses revealed no effects (or even strong trends) of age, graft type, meniscal injury, surgery and/or testing timing, or functional scoring on knee kinematics. However, the sample size and statistical power were insufficient to detect such relationships reliably. Graft positioning was also not tightly controlled (though a coronal angle of 30° from vertical was targeted). These factors could influence some of the results reported here. However, the rotational differences between reconstructed and contralateral limbs were consistent in both direction and magnitude, even across this relatively diverse subject group. Changes over time were somewhat less consistent across subjects, and may be more dependent on surgical and subject-specific factors. This is an ongoing study, and data on all of the confounding variables listed above have been collected (excluding graft tension, which was not measured, but including graft positioning as determined from CT). As data from more subjects become available, it should be possible to investigate the influence of these confounding factors in a more robust manner.

This analysis was limited to a single activity. Running was selected as a reasonable compromise between the goals of physiologically stressing the knee/graft and avoiding placing subjects at risk for injury (especially at the early time point). Running is also an activity commonly performed by most athletically active individuals. Because dynamic behavior of the knee may be task-specific, these findings may not predict the behavior of the ACL-reconstructed knee for other movements (in particular, those involving very high forces and/or rotational torques).

Static, in vivo studies of knee rotation and displacement have often reported minimal differences between ACL-reconstructed and uninjured limbs.[10,35] However, static studies of knee stability typically test the behavior of the knee by applying a unidirectional (linear or rotational) load to measure the range of passive joint motion. The results of this study suggest even though ACL injury and reconstruction shifts the operating point of the joint, there is little or no associated increase in the range of motion, and the joint appears operating well within the limits of passive stability. Thus, load-displacement testing may not predict joint behavior during functional tasks, which may explain why static stability correlates poorly with patient function.[8,15,39,48]

There are few other studies assessing transverse and coronal-plane knee rotation in ACL-reconstructed and contralateral, uninjured knees during dynamic, functional tasks, and fewer still have reliably evaluated changes in 3D, dynamic function of the ACL-reconstructed joint over time. Gait studies using skin markers and video-motion analysis have reported greater internal tibial rotation in ACL-deficient knees compared with uninjured knees during walking[4] and running[55] and greater abduction in knees during running.[55] Though these rotational differences are in opposite directions to those reported in this study, they are not necessarily in conflict. It is possible ACL reconstruction might over-correct or over-constrain the joint, leading to kinematic differences in opposite directions than in ACL-deficient knees. However, similar gait studies have reported no differences between ACL-reconstructed and uninjured limbs.[21] Also, no differences were found in rotational motion between ACL-reconstructed and uninjured joints during a relatively slow weightbearing flexion task (deep knee bend) using a single-plane fluoroscopic technique.[25]

There are two likely explanations as to why the findings of this study differ from much of what has been published previously for ACL-reconstructed kinematics. First, the limb-to-limb differences identified, while potentially clinically important, are quite small and would be difficult to detect reliably with skin markers. Second, low-demand activities (including gait) may not stress the knee adequately to produce substantial instability even in ACL-deficient knees,[55] and smaller differences would be expected between ACL-reconstructed and uninjured knees. Thus, higher-stress tasks may be required to elucidate abnormalities in ACL-R knees.

Increases over time in static knee laxity have been previously observed after ACL reconstruction.[9] Histological, biochemical, and mechanical changes occur in the graft for a year or more after implantation,[2,34] and mechanical loading experienced by the graft during this weakened phase of remodeling may adversely affect graft properties.[16] However, the effects of graft changes on dynamic knee function have not been well characterized. We found no change in static laxity (via KT-1000) between the 5 and 12-month data, but functional graft length assessed during dynamic testing increased. There was also no correlation between KT-1000 laxity and maximum functional graft length during running at 5 or 12 months ($R^2 = 0.07$ and 0.005, respectively), suggesting static laxity is a poor predictor of dynamic joint stability. Static laxity testing evaluates only the "limit" of anterior tibial motion when the muscles are inactive, whereas dynamic studies instead assess the "functional motion envelope" describing knee motion during a muscle-driven task. There is little reason to believe these two disparate measures would be closely related.

It was expected an increase in functional graft length would be associated with changes in other kinematic measures, but changes between 5- and 12-month tests were identified only for anterior tibial translation. However, there are trends towards changes over time in the reconstructed knee for both abduction/adduction and internal-external rotation (particularly during early stance). Rotations in both planes are closer to those of the contralateral, uninjured limbs at 12 months than they were at 5 months after surgery. Exploratory analyses showed correlations between increased functional graft length and increased maximum internal rotation ($r = 0.70$; $p = 0.02$), greater mediolateral translation range ($r = 0.51$; $p = 0.042$), and maximum anterior translation ($r = 0.86$, $p < 0.001$). This raises the possibility graft elongation may to some extent be a compensatory adaptation to restore more normal joint kinematics, but more subjects and longer followup are required to determine if the trends seen here are clinically meaningful.

Questions remain as to the clinical importance of the differences in rotational motion between ACL-reconstructed and contralateral knees. Though small in absolute terms (averaging 1.32° adduction and 1.94° external rotation), these differences are relatively large percentages of the mean range of observed motion during the stance phase of running (approximately 25% for internal-external rotation and 120% for abduction/adduction relative to the average range of motion in the uninjured limbs). A qualitative assessment of these rotational changes on motion at the articulating surfaces of the tibiofemoral joint (provided by 3D animations of estimated joint contact regions[3]) indicated the shift towards adduction typically resulted from an increase in lateral compartment separation and a decrease in medial compartment separation, while the external tibial rotation shifted the tibial contact area primarily in the lateral compartment. If the medial compartment contact point was unchanged, a simple geometric analysis shows a 2° increase in external rotation would shift the lateral compartment tibial plateau contact area anteriorly by approximately 2 mm in a typical size joint. Similarly, assuming equal effects in both compartments, a 1.3° adduction would create a 0.6 mm loss of medial compartment separation and a 0.6 mm increase in lateral compartment separation.

Thus, even small rotational differences in tibiofemoral kinematics could substantially alter the location, pattern, and magnitude of stresses applied to cartilage and menisci, which could have important implications for long-term joint health. Knee adduction has been specifically linked to higher incidence and faster progression of knee OA,[14] and it has been hypothesized shifts in cartilage contact to areas less suitable for weightbearing caused by kinematic abnormalities subsequent to ligament damage, may contribute to OA initiation and/or progression.[5] Long-term followup of our patients is in progress, and may elucidate relationships between kinematic abnormalities and cartilage degeneration in the ACL-reconstructed knee. The results of these studies may help to guide the development of new or alternative treatment options for improving long-term joint health after ACL injury.

References

1. Alexander EJ, Andriacchi TP. Correcting for deformation in skin-based marker systems. *J Biomech*. 2001;34:355–362.
2. Amiel D, Kuiper S. Experimental studies on anterior cruciate ligament grafts: histology and biochemistry. In: Daniel DM, Akeson WH, O'Conner JJ, eds. *Knee Ligaments: Structure, Function, Injury, and Repair: Vol 1*. New York: Raven Press; 1990:379–388.
3. Anderst W, Tashman S. A method to estimate in vivo dynamic articular surface interaction. *J Biomech*. 2003;36:1291–1299.
4. Andriacchi TP, Dyrby CO. Interactions between kinematics and loading during walking for the normal and ACL deficient knee. *J Biomech*. 2005;38:293–298.
5. Andriacchi TP, Mundermann A, Smith RL, Alexander EJ, Dyrby CO, Koo S. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng*. 2004;32:447–457.
6. Arnoczky S. Biology of ACL reconstructions: what happens to the graft? *Instr Course Lect*. 1996;45:229–233.
7. Ballock RT, Woo S-Y, Lyon RM. Use of patellar tendon autograft for anterior cruciate ligament reconstruction in the rabbit: a long term histological and biomechanical study. *J Orthop Res*. 1989;7:474–485.
8. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Orthop Relat Res*. 1990;255:204–214.
9. Beynnon BD, Johnson RJ, Fleming BC, Kannus P, Kaplan M, Samani J, Renstrom P. Anterior cruciate ligament replacement: comparison of bone-patellar tendon-bone grafts with two-strand hamstring grafts: a prospective, randomized study. *J Bone Joint Surg Am*. 2002;84:1503–1513.
10. Brandsson S, Karlsson J, Sward L, Kartus J, Eriksson BI, Karrholm J. Kinematics and laxity of the knee joint after anterior cruciate ligament reconstruction: pre- and postoperative radiostereometric studies. *Am J Sports Med*. 2002;30:361–367.
11. Brandt KD, Myers SL, Burr D, Albrecht M. Osteoarthritic changes in canine articular cartilage, subchondral bone, and synovium 54 months after transection of the anterior cruciate ligament. *Arthritis Rheum*. 1991;34:1560–1570.
12. Cappozzo A, Canati F, Leardini A, Benedetti MG, Della Croce U. Position and orientation in space of bones during movement: experimental artifacts. *Clin Biomech (Bristol, Avon)*. 1996;11:90–100.
13. Cappozzo A, Capello A, Della Croce U, Pensalfini F. Surface marker cluster design criterial for 3-D bone movement reconstruction. *IEEE Trans Biomed Eng*. 1997;44:1165–1174.
14. Cerejo R, Dunlop DD, Cahue S, Channin D, Song J, Sharma L. The influence of alignment on risk of knee osteoarthritis progression according to baseline stage of disease. *Arthritis Rheum*. 2002;46:2632–2636.
15. Cross MJ, Wootton JR, Bokor DJ. Acute repair of injury to the anterior cruciate ligament: a long-term followup. *Am J Sports Med*. 1993;21:128–131.
16. Daniel DM. Principles of knee ligament surgery. In: Daniel DM, Akeson WH, O'Conner JJ, eds. *Knee Ligaments: Structure, Function, Injury, and Repair: Vol 1*. New York: Raven Press; 1990:11–29.
17. Daniel DM, Stone ML. KT-1000 anterior–posterior displacement measurements. In: Daniel DM, Akeson WH, O'Conner JJ, eds. *Knee Ligaments: Structure, Function, Injury, and Repair: Vol 1*. New York: Raven Press; 1990:427–447.
18. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the ACL-injured patient: a prospective outcome study. *Am J Sports Med*. 1994;22:632–644.

19. Fetto JF, Marshall JL. The natural history and diagnosis of anterior cruciate ligament insufficiency. *Clin Orthop Relat Res*. 1980;147:29–38.
20. Fink C, Hoser C, Benedetto KP. Development of arthrosis after rupture of the anterior cruciate ligament: a comparison of surgical and conservative therapy. *Unfallchirurg*. 1994;97:357–361.
21. Georgoulis AD, Papadonikolakis A, Papageorgiou CD, Mitsou A, Stergiou N. Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. *Am J Sports Med*. 2003;31:75–79.
22. Gillquist J, Messner K. Anterior cruciate ligament reconstruction and the long term incidence of gonarthrosis. *Sports Med*. 1999;27:143–156.
23. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng*. 1983;105:136–144.
24. Harter RA, Osternig LR, Singer KM. Long-term evaluation of knee stability and function following surgical reconstruction for anterior cruciate ligament insufficiency. *Am J Sports Med*. 1988;16:434–443.
25. Kanisawa I, Banks AZ, Banks SA, Moriya H, Tsuchiya A. Weight-bearing knee kinematics in subjects with two types of anterior cruciate ligament reconstructions. *Knee Surg Sports Traumatol Arthrosc*. 2003;11:16–22.
26. Karrholm J. Roentgen stereophotogrammetry: review of orthopedic applications. *Acta Orthop Scand*. 1989;60:491–503.
27. Karrholm J, Elmquist LG, Selvic G, Hansson LI. Chronic anteriolateral instability of the knee: a roentgen stereophotogrammetric evaluation. *Am J Sports Med*. 1989;17:555–563.
28. Karrholm J, Selvik G, Elmqvist LG, Hansson LI, Jonsson H. Three-dimensional instability of the anterior cruciate deficient knee. *J Bone Joint Surg Br*. 1988;70:777–783.
29. Kuster M, Wood G, Sakurai S, Blatter G. Downhill walking: a stressful task for the anterior cruciate ligament? A biomechanical study with clinical implications. *Knee Surg Sports Traumatol Arthrosc*. 1994;2:2–7.
30. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum*. 2004;50:3145–3152.
31. Lynch MA, Henning CA. Osteoarthritis and the ACL-deficient knee. In: Feagin JA, ed. *The Crucial Ligaments: Diagnosis and Treatment of Ligamentous Injuries About the Knee*. New York: Churchhill Livingstone; 1988:385–391.
32. Markolf KL, Kochan A, Amstutz HC. Measurement of knee stiffness and laxity in patients with documented absence of the anterior cruciate ligament. *J Bone Joint Surg Am*. 1984;66:242–253.
33. Maxwell SE, Delaney HD. *Designing Experiments and Analyzing Data*. Pacific Grove, CA: Brooks/Cole Publishing Co; 1990.
34. Newton PO, Horibe S, Woo SL-Y. Experimental studies on anterior cruciate ligament: autografts and allografts: mechanical studies. In: Daniel DM, Akeson WH, O'Conner JJ, eds. *Knee Ligaments: Structure, Function, Injury, and Repair: Vol 1*. New York: Raven Press; 1990:389–397.
35. Nordt WE III, Lotfi P, Plotkin E, Williamson B. The in vivo assessment of tibial motion in the transverse plane in anterior cruciate ligament-reconstructed knees. *Am J Sports Med*. 1999;27:611–616.
36. Noyes FR, Barber SD, Mooar LA. A rationale for assessing sports activity levels and limitations in knee disorders. *Clin Orthop Relat Res*. 1989;246:238–249.
37. Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS. Biomechanical analysis of human knee ligament grafts used in knee ligament repairs and reconstructions. *J Bone Joint Surg Am*. 1984;66:344–352.
38. O'Connor P, Oates K, Gardner DL, Middleton JFS, Orford CR, Brereton JD. Low temperature and conventional scanning electron microscopic observations of dog femoral condylar cartilage surface after anterior cruciate ligament division. *Ann Rheum Dis*. 1985;44:321–327.
39. Pollet V, Barrat D, Meirhaeghe E, Vaes P, Handelberg F. The role of the Rolimeter in quantifying knee instability compared to the functional outcome of ACL-reconstructed versus conservatively-treated knees. *Knee Surg Sports Traumatol Arthrosc*. 2005;13:12–18.
40. Pond MJ, Nuki G. Experimentally induced osteoarthrosis in the dog. *Ann Rheum Dis*. 1973;32:387–388.
41. Reinschmidt C, van den Bogert AJ, Nigg BM, Lundberg A, Murphy N. Effect of skin movement on the analysis of skeletal knee joint motion during running. *J Biomech*. 1997;30:729–732.
42. Rhoad RC, Klimkiewicz JJ, Williams GR, Kesmodel SB, Udupa JK, Kneeland JB, Iannotti JP. A new in vivo technique for three-dimensional shoulder kinematics analysis. *Skeletal Radiol*. 1998;27:92–97.
43. Selvik G. Roentgen stereophotogrammetric analysis. *Acta Radiol*. 1990;31:113–126.
44. Seto JL, Orofino AS, Morrissey MC. Assessment of quadriceps/hamstring strength, knee ligament stability, functional and sports activity levels five years after anterior cruciate ligament reconstruction. *Am J Sports Med*. 1988;16:170–180.
45. Sheehan FT, Zajac FE, Drace JE. Using cine phase contrast magnetic resonance imaging to non-invasively study in vivo knee dynamics. *J Biomech*. 1998;31:21–26.
46. Shelbourne K, Gray T. Anterior cruciate ligament reconstruction with autogenous patellar tendon graft followed by accelerated rehabilitation: a two- to nine-year followup. *Am J Sports Med*. 1997;25:786–795.
47. Shino K, Inoue M, Horibe S, Nakamura H, Ono K. Measurement of the anterior stability of the knee: a new apparatus for clinical testing. *J Bone Joint Surg Br*. 1987;69:608–613.
48. Snyder-Mackler L, Fitzgerald GK, Bartolozzi AR, Ciccotti MG. The relationship between passive joint laxity and functional outcome after anterior cruciate ligament injury. *Am J Sports Med*. 1997;25:191–195.
49. Spoor CW, Veldpaus FE. Rigid body motion calculated from spacial coordinates of markers. *J Biomech*. 1980;13:391–393.
50. Stagni R, Fantozzi S, Cappello A, Leardini A. Quantification of soft tissue artefact in motion analysis by combining 3D fluoroscopy and stereophotogrammetry: a study on two subjects. *Clin Biomech (Bristol, Avon)*. 2005;20:320–329.
51. Tashman S, Anderst W. In vivo measurement of dynamic joint motion using high speed biplane radiography and CT: application to canine ACL deficiency. *J Biomech Eng*. 2003;125:238–245.
52. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W. Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2004;32:975–983.
53. Torzilli PA, Greenberg RL, Hood RW, Pavlov H, Insall JN. Measurement of anterior-posterior motion of the knee in injured patients using a biomechanical stress technique. *J Bone Joint Surg Am*. 1984;66:1438–1442.
54. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Ann Rheum Dis*. 2004;63:269–273.
55. Waite JC, Beard DJ, Dodd CA, Murray DW, Gill HS. In vivo kinematics of the ACL-deficient limb during running and cutting. *Knee Surg Sports Traumatol Arthrosc*. 2005;13:377–384.
56. Youmans WT. The so-called "isolated" anterior cruciate ligament tear or anterior cruciate ligament syndrome: a report of 32 cases with some observation on treatment and its effect on results. *Am J Sports Med*. 1978;6:26–30.