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Tibiofemoral Joint Kinematics of the Anterior Cruciate Ligament-Reconstructed Knee During a Single-Legged Hop Landing

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Background: Abnormal 3-dimensional tibiofemoral joint kinematics have been identified in anterior cruciate ligament-reconstructed knees during functional gait tasks, which is suggested to directly affect risk of knee osteoarthritis. However, the extent to which similar high-risk abnormalities are present during more demanding maneuvers, such as single-legged hopping, is largely unknown.

Hypothesis: When performing a single-legged forward hop landing, the reconstructed knee will demonstrate altered sagittal, frontal, and transverse plane kinematics compared with the contralateral limb.

Study Design: Controlled laboratory study.

Methods: High-speed biplane radiography was used to quantify bilateral 3-dimensional tibiofemoral joint kinematics in 9 subjects with unilaterally reconstructed anterior cruciate ligaments (mean time after surgery, 4 months) during 3 single-legged, forward hop landing trials. Mean subject-based initial foot contact and maximum stance (0-250 ms) values were calculated for each kinematic variable. Two-tailed paired *t* tests were subsequently applied to examine for the main effect of limb (reconstructed vs contralateral).

Results: The reconstructed knees exhibited significantly greater extension ($P = .04$), external tibial rotation ($P = .006$), and medial tibial translation ($P = .02$) than the contralateral knees at initial contact. Reconstructed knees underwent significantly greater maximum flexion ($P = .05$), maximum external tibial rotation ($P = .01$), and maximum anterior tibial translation ($P = .02$). No significant differences existed between limbs for initial contact ($P = .65$) or maximum adduction-abduction ($P = .55$).

Conclusion: Tibiofemoral joint kinematics of the anterior cruciate ligament-reconstructed knee are significantly different from those of the uninjured contralateral limb during a single-legged hop landing. This altered kinematic profile, in conjunction with the large impact loads associated with hopping, may further contribute to the risk of posttraumatic knee osteoarthritis.

Clinical Relevance: Returning to sports involving dynamic single-legged landings at 4 months after anterior cruciate ligament reconstruction surgery may contribute to accelerated knee joint degeneration.

Keywords: anterior cruciate ligament; reconstruction; joint kinematics; osteoarthritis; hopping

Anterior cruciate ligament (ACL) rupture is a common sports injury, representing a significant source of pain, disability, and medical expense. A high percentage of ACL ruptures occur in young, healthy athletes during sports activity.[1,10] In addition to extensive short-term trauma and loss of play, approximately 50% of all ACL ruptures lead to osteoarthritis within 10 to 20 years after the incident injury.[30] Consequently, it is not uncommon for posttraumatic osteoarthritis to afflict persons as young as 30 years old.[41] For patients of such a young age, successful treatment options are limited, often necessitating cessation of strenuous activity.[21]

Surgical reconstruction is the current standard of care for a ruptured ACL in physiologically young, physically active persons. The primary goal of ACL reconstruction is the restoration of normal joint kinematics.[13] Indeed, during "low-demand" gait tasks such as level-ground walking, ACL-reconstructed knees have been found to demonstrate tibiofemoral joint kinematics similar to those of matched

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TABLE 1
Subject Characteristics[a]

Subject No.	Age, y	Sex	Height, in	Weight, lb	Graft Type	Additional Procedures
1	27	M	75	210	HD	Medial meniscal repair
2	22	F	64	155	HS	Partial lateral meniscectomy
3	19	F	67	150	HD	None
4	17	M	66	150	HD	Medial meniscal repair
5	22	M	66	172	HD	Medial/lateral menisci repairs
6	23	F	68	150	HS	None
7	52	M	70	194	AD	None
8	49	M	72	170	AD	Partial medial meniscectomy
9	28	M	71	190	HD	Partial lateral meniscectomy

[a]HD, hamstring tendon autograft double-bundle technique; HS, hamstring tendon autograft single-bundle technique; AD, allograft double-bundle technique.

control knees.[20] Previous research suggests, however, that this goal may not be readily achieved for more demanding tasks, such as those that incorporate rapid deceleration and/or pivoting. For example, during single-legged hopping and single-legged vertical drop landing, ACL-reconstructed knees were found to undergo significantly different knee flexion motion than the uninjured contralateral knees.[22,52,54] Furthermore, Papannagari and colleagues[35] reported that ACL-reconstructed knees underwent significantly more anterior tibial translation and external tibial rotation while performing a single-legged lunge than the healthy contralateral knee. Similarly, during downhill treadmill running, ACL-reconstructed knees have been reported to demonstrate significantly more adduction and external rotation of the tibia relative to the femur than the uninjured contralateral knees.[49] These data strongly suggest that ACL reconstruction fails to restore normal joint kinematics during dynamic movement tasks. Moreover, it has been suggested that abnormal knee joint kinematics play a critical role in the initiation and progression of knee osteoarthritis.[6,9,18]

Patients who elect to undergo surgical reconstruction of a torn ACL most often choose this treatment option because they wish to return to preinjury activity levels, which are typically high.[45] Therefore, it is important to determine the extent to which normal kinematics are restored during movements relevant to this particular patient population. Single-legged hop landings are synonymous with the demanding jumping and cutting movements of high-level competitive sports, such as soccer and basketball.[42] Moreover, single-legged hopping induces larger vertical ground-reaction forces than walking, running, or lunging.[2,22,32,38,54] Although it is likely that the high forces placed on the knee joint by single-legged hopping elicit further kinematic differences between ACL-reconstructed and uninjured contralateral knees,[39] accurate 3-dimensional (3D) kinematic data to support this notion do not exist.

Therefore, the objective of this study was to use dynamic radiostereophotogrammetric analysis (RSA; accuracy, ±0.1 mm[46,48,49]) to evaluate 3D tibiofemoral joint kinematics in patients with unilateral ACL reconstruction during the landing phase of a single-legged hop. On the basis of previous studies of the ACL-reconstructed knee during dynamic motions,[22,35,49] we hypothesized that the reconstructed knee would demonstrate altered sagittal, frontal, and transverse plane kinematics compared with the uninvolved limb.

MATERIALS AND METHODS

Subjects

We enrolled 9 recreational athletes (6 men and 3 women) who were undergoing primary arthroscopic reconstructive surgery to repair a unilateral ACL rupture (Table 1). Based on previous data comparing ACL-reconstructed and uninvolved limb kinematics for downhill running,[49] we estimated that to achieve 80% power with an alpha level of 0.05, a minimum of 7 subjects would be required. Inclusion criteria were (1) no history of surgery to either limb and (2) no damage to the injured limb other than the ruptured ACL and minor meniscal tears requiring removal of no more than one third of the radial width of the meniscus. All subjects who matched the inclusion criteria and who were undergoing surgery by one of the participating surgeons were contacted to participate in the study. Mean subject age was 28.8 ± 12.8 years. Mean time from injury to surgery was 9.6 ± 9.5 months. Mean time from surgery to testing was 4.4 ± 0.7 months. We obtained informed consent from all subjects, and the appropriate institutional review board for human subject research approved the study protocol.

Surgical Reconstruction

The ACL reconstruction surgery was performed by 1 of 2 surgeons (P.A.K. and T.R.L.). Graft type was not restricted and included single-bundle hamstring tendon autograft (n = 2), double-bundle hamstring tendon autograft (n = 5), and double-bundle allograft (n = 2). For the single-bundle reconstructions, the femoral graft tunnel was drilled using a transtibial guide. For the double-bundle surgeries, the posterolateral femoral tunnel was drilled through an accessory medial portal and the anteromedial femoral tunnel was placed using a transtibial guide. Interference screw fixation was used in all cases. During the ACL reconstruction procedure, the surgeon inserted small tantalum spheres (1.6-mm diameter) into the distal femur and proximal tibia of both limbs using a cannulated drill.[48] The sphere placement was such that each bone contained 3 noncollinear spheres with a minimum 2-cm separation between spheres. The surgeon did not attempt to place the spheres at specific anatomical landmarks. The tantalum spheres served as internal markers for the dynamic RSA procedure employed in this study. This method has been used extensively and reported in previous studies by our research group.[4,5,47-49]

Testing Procedures

After surgery, all subjects completed the standard rehabilitation protocol of our institution. The rate of rehabilitation was dictated by the patient's progress. Laboratory testing took place once the physician cleared the subject to return to light sports activity, typically 4 to 5 months after surgery. We used dynamic RSA to assess 3D tibiofemoral joint kinematics from biplane radiographic images acquired during the landing phase of a single-legged forward hop. The biplane x-ray system contains 2 x-ray gantries that are configured with their beam paths intersecting at 60° in a plane parallel to the floor. Each gantry contains a 100-kW pulsed x-ray generator (CPX 3100CV; EMD Technologies, Quebec, Canada), a 30-cm image intensifier (Shimadzu AI5765HVP, Kyoto, Japan), and a high-speed digital video camera (Phantom IV, Vision Research, Wayne, New Jersey). This experimental approach has been used in previous studies of knee function and is capable of measuring in vivo joint motion to an accuracy of within ±0.1 mm.[46,49]

Subjects were positioned in the biplane x-ray system so that the knee of interest would remain in the system's 3D imaging volume throughout the landing phase of a single-legged forward hop. Subjects were required to complete 3 successful 0.5-second forward hop trials for each leg. To perform a successful hop, the subject was required to stand on 1 leg and, at his or her discretion, to jump forward over a 4-cm high obstacle and land at a distance of 30 cm in front of the takeoff position. The subject landed on the takeoff leg and was required to maintain this position for as long as possible. The 0.5-second data collection period was initiated when the subject was in flight before landing and included at least 250 ms of the postimpact phase. While in the air, the subject broke the plane of an optoelectric switch (RadioShack, Fort Worth, Texas), which triggered the biplane x-ray system to begin recording. Radiographs were generated using an exposure of 90 kVp and 160 mA, with the digital radiographic images collected at 170 Hz.

On the same day as laboratory testing, subjects underwent bilateral CT imaging of the tibiofemoral joint. The CT field of view was approximately 28 × 28 cm, slice thickness ranged from 0.6 to 1.25 mm, and in-plane resolution was approximately 0.55 mm per pixel. The 3D bone models of the distal femur and proximal tibia of each knee joint were reconstructed from the CT images, as previously described in detail.[46] First, the 3D center of each implanted tantalum bead was located within the CT volume to within the nearest one-half slice in the CT image stack and to within the nearest pixel within the slice (ImageJ 1.32 J, National Institutes of Health, Bethesda, Maryland). Next the tibia and femur were manually segmented from surrounding tissues. After segmentation, custom software was used to perform feature-based interpolation to create the reconstructed 3D bone model.

Measuring Tibiofemoral Joint Motion

Custom software tracked the 2-dimensional position of each tantalum bead from each of the biplane x-ray images throughout all trials. The 2-dimensional positions were combined to reconstruct the 3D position of each bead,[43] and these positions were subsequently low-pass filtered using a sixth-order zero-lag Butterworth digital filter with a 20 Hz cutoff frequency. Subject-specific local anatomical coordinate systems were created for both the femur and tibia as previously described in detail.[46] The origin of the femoral coordinate system was defined as the 3D point halfway between the center of the medial and lateral femoral condyles. Similarly, the origin of the tibial coordinate system was defined to be the 3D point located halfway between the most medial and lateral aspects of the tibial plateau. Rotations of the tibia relative to the femur were defined with respect to the bone-fixed coordinate systems, and calculated using body-fixed axes in the order flexion-extension, adduction-abduction, and internal-external rotation.[49] Neutral rotations (zero values) were defined as the position where the tibial and femoral coordinate systems were aligned. Anteroposterior and mediolateral displacements of the tibia relative to the femur were also quantified using the position vector from the femoral anatomical origin to the tibial anatomical origin.

Statistical Analysis

For each successful hopping trial, the initial foot contact value and maximum value within the first 250 ms of stance were quantified bilaterally for the 3 rotational and 2 translational kinematic variables described earlier. This interval was selected as it captures the primary loading phase of the knee (ie, achievement of maximum knee flexion angle and peak ground-reaction force and a return toward full extension) during this task. Mean subject-based values for each of these measures were subsequently determined. Two-tailed paired t tests were used to examine for the main effect of limb (reconstructed vs contralateral) on each of these dependent measures. An alpha level of 0.05 was used to denote statistical significance.

RESULTS

A number of kinematic differences were observed between the reconstructed and uninvolved limbs for the single-legged hopping task. Specifically, the reconstructed limb

TABLE 2
Means and Standard Deviations for All Dependent Variables Examined[a]

Dependent Variable	Initial Contact Recon	Initial Contact Contra	Maximum Recon	Maximum Contra
Knee flexion, deg	19.08 ± 8.64[b]	26.04 ± 9.60[b]	38.92 ± 10.85[b]	47.69 ± 8.14[b]
Knee adduction (+) / abduction (−), deg	0.87 ± 0.91	0.65 ± 1.76	1.28 ± 1.92	0.94 ± 2.26
Internal (+) / external (−) tibial rotation, deg	0.61 ± 4.30[b]	6.02 ± 4.59[b]	4.84 ± 6.28[b]	9.84 ± 5.70[b]
Lateral (+) / medial (−) tibial displacement, mm	0.89 ± 1.47[b]	2.51 ± 1.30[b]	1.16 ± 1.70	2.65 ± 1.34
Anterior (+) / posterior (−) tibial displacement, mm	9.89 ± 4.14	9.40 ± 4.34	12.00 ± 3.67[b]	10.48 ± 4.21[b]

[a]Recon, reconstructed limb; Contra, uninjured contralateral limb.
[b]$P \leq .05$, side difference.

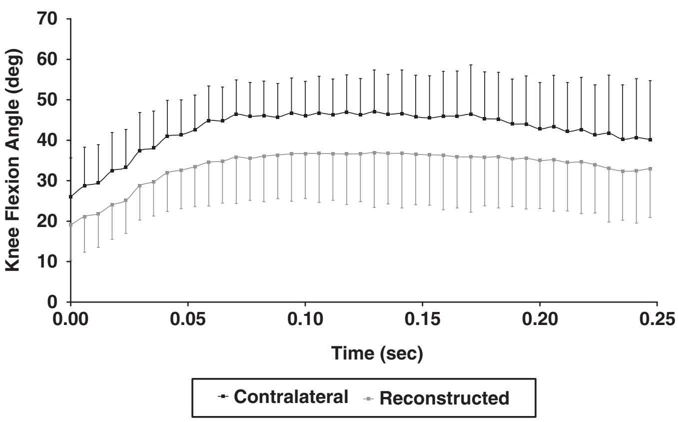

Figure 1. Mean knee flexion angle as a function of time after initial contact. For visual clarity, unidirectional positive and negative standard deviations are represented for the contralateral and reconstructed limbs, respectively. The reconstructed knee was significantly less flexed at initial contact ($P = .04$).

was significantly ($P = .04$) less flexed than the healthy limb at initial contact (Figure 1). Similarly, maximum knee flexion was significant ($P = .05$), with the reconstructed limb exhibiting a smaller maximum flexion angle than the contralateral limb (Table 2).

The reconstructed limb was found to be consistently more adducted than the contralateral limb throughout the landing phase (Figure 2), but the differences were not found to be statistically significant for either initial contact ($P = .65$) or maximum ($P = .55$) angles (Table 2).

The reconstructed limb was less internally rotated throughout the first 250 ms of ground contact (Figure 3), with significantly smaller initial contact ($P = .006$) and maximum ($P = .01$) angles being observed (Table 2)

Bilateral limb differences were evident in mediolateral tibial displacements at initial contact, with the reconstructed limb demonstrating significantly ($P = .02$) less lateral displacement at this time point compared with the contralateral limb (Figure 4 and Table 2). Statistical differences were not observed between limbs, however, for maximum mediolateral displacement values ($P = .08$) (Table 2).

Bilateral limb differences were observed in anteroposterior tibial displacement measures, with the reconstructed limb eliciting significantly ($P = .02$) larger maximum anterior tibial displacement compared with the contralateral limb (Table 2). Although this trend was observed across the entire stance phase, no significant differences were evident between limbs for anteroposterior displacement at initial contact ($P = .23$) (Figure 5 and Table 2).

DISCUSSION

The objective of this study was to determine the extent to which ACL reconstruction may promote 3D kinematic differences between the reconstructed and contralateral (uninjured) limbs during a single-legged hop landing. On the basis of previous studies of the ACL-reconstructed knee during dynamic motions,[22,35,49] we hypothesized that the reconstructed knee would demonstrate altered sagittal, frontal, and transverse plane kinematics compared with the uninvolved limb. As predicted, the reconstructed tibia remained in a more extended, externally rotated, and anteriorly displaced position relative to the femur throughout the hop landing. Significant differences also were evident for mediolateral displacement, while no significant differences occurred for adduction-abduction angle.

The 30-cm forward hopping task provided a reasonably challenging yet safe landing movement for assessing bilateral kinematic differences that were reflective of the athletic ability of the subjects, as well as consistent with the physical constraints of the biplane x-ray system. All subjects were familiar with the hopping task from their postsurgical rehabilitation routine.[24,33] The single-legged hopping task is highly relevant to the athletic demands placed on ACL-reconstructed knees when the patients return to sports activity after surgery.[54] Therefore, we believe that identification of bilateral differences in tibiofemoral joint kinematics during performance of this task is pertinent to elucidating the role of joint mechanics in the development of knee osteoarthritis in this population.

We found that the reconstructed knee was consistently more extended throughout the single-legged hop landing. This observation agrees with previous studies investigating

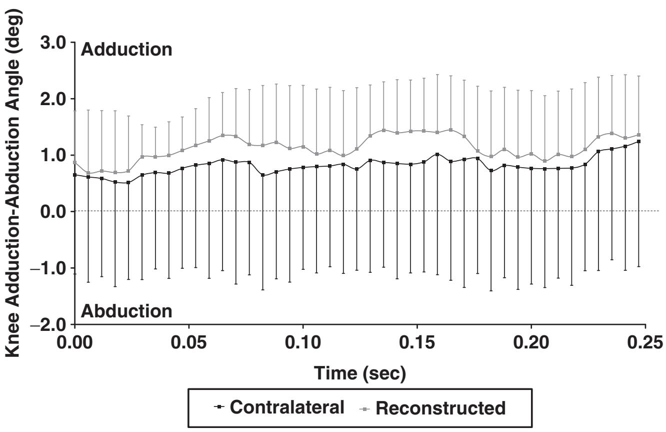

Figure 2. Mean knee adduction-abduction angle as a function of time after initial foot contact. For the vertical axis, positive values indicate adduction and negative values indicate abduction. Unidirectional positive and negative standard deviations are represented for the reconstructed and contralateral limbs, respectively. No significant differences in adduction-abduction angle were detected between limbs at initial contact ($P = .65$).

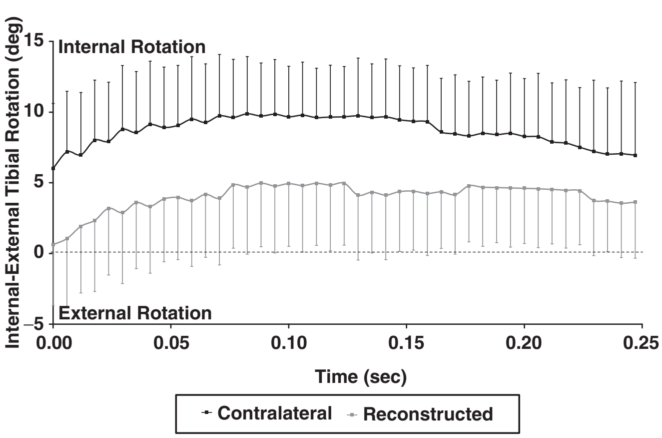

Figure 3. Mean internal-external tibial rotation as a function of time after initial foot contact. For the vertical axis, positive values indicate internal rotation and negative values represent external rotation. Unidirectional positive and negative standard deviations are represented for the contralateral and reconstructed limbs, respectively. The reconstructed tibia was significantly more externally rotated at heel strike ($P = .006$).

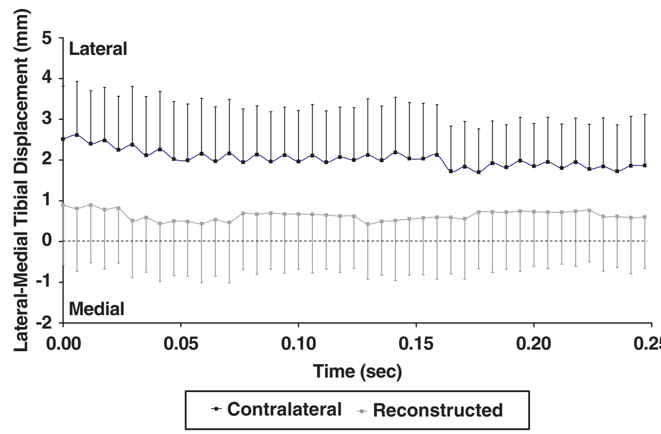

Figure 4. Mean mediolateral tibial displacement relative to the femur as a function of time after initial foot contact. For the vertical axis, positive values indicate lateral translation and negative values indicate medial translation. Unidirectional positive and negative standard deviations are represented for the contralateral and reconstructed limbs, respectively. The reconstructed tibia was positioned significantly less laterally at heel strike ($P = .02$).

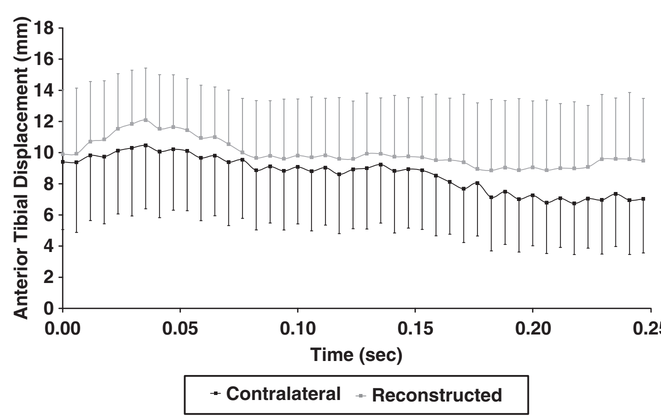

Figure 5. Mean anterior tibial displacement relative to the femur as a function of time after initial foot contact. Unidirectional positive and negative standard deviations are represented for the reconstructed and contralateral limbs, respectively. No significant difference was detected between limbs at initial contact ($P = .23$).

single-legged hopping knee mechanics in patients with ACL-deficient and ACL-reconstructed knees.[22,39,42,54] A more extended landing posture may be a strategy that patients with ACL-deficient or ACL-reconstructed knees use to achieve greater knee stabilization, particularly in the presence of increased anteroposterior laxity, as seen in this study.[42,53] Increased extension may also be necessary to prevent knee collapse that may otherwise occur during the deceleration phase because of a relatively weak opposing quadriceps force, a common occurrence following ACL injury.[23,25,34] Because we did not measure muscle strength in the current study, however, we can only speculate to the plausibility of this relationship. It should be noted also that, although a minimum jump height was enforced using an obstacle that was 4 cm high, the height of the single-legged hop was not controlled for in the experimental protocol. Therefore, it is possible that the peak hop height achieved by the uninjured limb was larger than the peak height achieved by the injured limb, which would require more energy to be absorbed at impact and more knee joint flexion in the uninjured limb. However, because the task was a forward hop over a relatively small distance rather than a vertical hop, we believe that jump height differences would be relatively minor.

No significant differences in knee adduction were detected in this study, contrary to our hypothesis. Previous studies using identical techniques[49] compared reconstructed and healthy contralateral limbs during downhill running and found the reconstructed limb to be significantly more adducted (mean difference, 1.32°). This difference is much larger than the between-limb differences noted in the present study (0.22° and 0.34° for initial contact and maximum knee adduction angle, respectively). It is commonly proposed that the reconstructed knee has increased knee adduction motions or loads during walking and running gait, increasing risk of osteoarthritis through an altered cartilage loading pattern.[8,17,49] Our current results, however, suggest that at least for single-legged hopping, substantial modifications in cartilage loading patterns via an altered knee abduction-adduction profile are not as likely.

In this study we found that internal-external tibial rotation of the ACL-reconstructed limb did not match that of the uninjured limb during a single-legged hop landing. Specifically, the reconstructed knee was significantly more externally rotated both at initial contact and at maximum internal-external rotation. Tashman and colleagues[49] found similar results when they evaluated 3D knee kinematics during downhill treadmill running using the same techniques as the current study. Further, this bilateral kinematic discrepancy continued to manifest at both 5 and 12 months after surgery. Ristanis et al[40] similarly found that ACL-reconstructed knees had greater axial tibial rotation than healthy control knees during 2 separate tasks: a jump landing followed by a 90° pivot turn and a stair descent followed by a 90° pivot turn. Interestingly, however, Georgoulis and colleagues[20] found no significant differences in stance-phase axial rotation between reconstructed and contralateral knees during level-ground walking. Therefore, it seems plausible that altered internal-external knee rotation patterns may occur in the ACL-reconstructed knee only during more demanding dynamic landing and pivoting tasks, where extreme axial loading states are known to manifest.[12,31] If altered knee internal-external rotations contribute to the risk of osteoarthritis initiation and/or progression, as has been proposed, then the single-legged hop may indeed be a task where this risk is exacerbated.[6,7,44]

It is interesting to note that the current study included 7 subjects who had undergone double-bundle ACL reconstruction surgery, a technique that is believed to better restore healthy internal-external rotation patterns.[55] A post hoc comparison between the single- and double-bundle subjects found no substantial differences in any kinematic variable, including internal-external rotation angles. However, the sizes of the single- and double-bundle subgroups were too small to provide adequate statistical power for this analysis. These double-bundle reconstructions were also performed with the femoral anteromedial tunnel drilled using a transtibial technique, typically resulting in a nonanatomical anteromedial tunnel position high in the femoral notch. More recent double-bundle techniques employ a medial portal drilling approach to place the femoral graft tunnels over the native insertions of the ACL bundles.[37] Kinematics after this anatomical double-bundle reconstruction procedure are currently under investigation.

This study determined that the reconstructed knee experienced larger peak anterior tibial translation than the contralateral knee by an average of 1.52 ± 1.55 mm. Previous studies have reported similar results for walking, double-legged squatting, and single-legged lunging.[11, 29, 35] Papannagari et al[35] found that reconstructed knees translated approximately 2.9 mm more at full extension and 2.2 mm more at 15° of knee flexion when compared with the uninvolved limb for a quasistatic weightbearing single-legged lunge. Logan and colleagues[29] investigated sagittal plane kinematics during quasistatic squatting using open MRI and similarly determined that the anterior tibial position of the involved knee was greater at 0°, 20°, 45°, and 90° of knee flexion. As the ACL is the primary restraint to anterior tibial translation, one of the primary goals of ACL reconstruction is to return anterior laxity, and hence the anteroposterior translational profile, to within the limits of the uninjured knee.[13,16] Our results support the notion that this goal may not be readily achieved using the surgical techniques employed for this study,[3,11,35] which represent commonly used surgical procedures.[13,56]

The reconstructed tibia was more medially translated than the contralateral tibia at initial contact, with this discrepancy being maintained over the first 250 ms of stance. Li and colleagues[27] similarly found that the tibiofemoral contact patterns of ACL-deficient knees during a single-legged weightbearing lunge were consistent with a medial shift of the tibia. Previous research has also shown that the ACL resists medial tibial translation, again suggesting that this medial tibial shift in the reconstructed limb may stem from an ACL graft that is unable to properly restrain knee joint motion.[26,28,36]

The results of this study demonstrate that bilateral differences in tibiofemoral kinematics exist following ACL reconstruction, even for patients who have been cleared to return to light sports activity. These findings may lend insight into the high incidence of early knee osteoarthritis that is common in this patient population.[30,41] Hop landings are representative of the demanding sports activities that many patients with ACL-reconstructed knees perform on a regular basis.[42,45] These activities elicit larger impact-induced joint forces than other movements that have been previously studied in the ACL-reconstructed knee (eg, walking).[2,22,32,38,54] Thus, when a hop landing is performed with the knee in a more extended position, it is likely that the articular cartilage and other surrounding joint tissues are subjected to much higher compressive loads than would be experienced within the uninjured and comparatively more flexed knee.[42]

In the current study, we determined an average difference in external tibial rotation angle between the reconstructed and contralateral knees of 5.41° and 5.00° for initial contact and peak values, respectively. Andriacchi and colleagues[6] have demonstrated that a 5° internal rotational offset of the tibia leads to accelerated cartilage thinning in a finite element model of the tibiofemoral joint. Therefore, it is plausible that an external rotational shift of similar magnitude, particularly when coupled with a more extended knee position, could lead to similar cartilage changes.

In the present study, the reconstructed knee also showed altered anteroposterior and mediolateral displacements of the tibia relative to the femur. As with a rotational offset, it is likely that these changes alter the manner in which the articular cartilage is loaded.[7,18] The greater anterior displacement of the tibia seen in this study likely creates a posterior shift in the femur's contact location on the tibial plateau. Ironically, a posterior shift in the femur's location of contact on the tibia has been associated with greater cartilage thinning on the anterior tibial plateau.[7] In other words, a decrease in load may be associated with cartilage thinning. In contrast, Li and colleagues[28] have found that shifts in mediolateral tibial position in the ACL-deficient knee shift the point of tibial contact in the medial compartment closer to the medial tibial spine, where cartilage degeneration frequently presents in the ACL-deficient knee. These contradictory findings—that is, that cartilage degeneration occurs in regions where loads are believed to increase or decrease—suggest that the relationship between cartilage loading and cartilage degeneration is highly complex and not well understood. Regardless of the specific mechanism that relates cartilage degeneration and mechanical loading, patients with ACL-reconstructed knees who perform a demanding activity such as hopping may be altering the cartilage loading patterns in a manner that is sufficient to initiate the development of osteoarthritis.[9]

The data from this study also suggest that the manifestation of bilateral kinematic differences appears to be task-specific. In this study, single-legged hopping elicited significant differences in all examined degrees of freedom, except adduction of the tibia relative to the femur. However, in a study of knee kinematics during downhill running[49] that evaluated a similar population using identical methods, significant differences were noted only in the angles of tibial adduction and tibial external rotation. Similarly, Bush-Joseph et al[15] found that sagittal plane kinematics were not significantly different between patients with ACL-reconstructed knees and healthy matched controls for light activities such as walking, but that kinematic profiles did indeed diverge for higher demand activities. Consequently, it is important for future studies aimed at assessing the efficacy of specific ACL reconstruction techniques to assess knee function during high-level activities that are consistent with the goals of the young, athletic patient.

The strength of this study lies in the high accuracy of the methods used to quantify tibiofemoral kinematics. Dynamic RSA eliminates errors due to skin motion associated with surface marker-based techniques, thus allowing for the 3D, dynamic measurement of in vivo knee motion to an accuracy of within ± 0.1 mm.[46] To our knowledge, no prior study has assessed 3D tibiofemoral kinematics during single-legged hopping with this level of accuracy. However, we also acknowledge limitations to this study. In particular, we adopted the uninjured contralateral knee as the control population for the reconstructed knee. Although this method has been employed in several previous studies to examine motion of the ACL-injured knee,[27,29,35] comparisons between injured and contralateral limbs must be made cautiously, given the potential for intraindividual variability and the possibility that the incident injury or surgery may have produced bilateral neuromuscular changes.[14,51] Nonetheless, on the basis of recent work suggesting that intersubject variability exceeds intrasubject variability with regard to tibiofemoral joint morphometric dimensions[19] and gait mechanics,[50] we believe that the use of the uninvolved limb as the control population was justified. Additionally, the sample size was small, and we did not control for surgeon, meniscal injury, graft type, sex, age, rate of rehabilitation, or activity level, although all subjects were recreational athletes. Therefore, extrapolation of these results to the general ACL-reconstructed population must be made with caution. Regardless, the development of posttraumatic osteoarthritis is neither confined to a single reconstructive procedure nor to a single patient demographic. Because this group of subjects represents a typical subset of those with ACL-reconstructed knees and statistically significant trends were consistent across subjects despite the apparent heterogeneity, we are confident in our results.

In conclusion, patients who have undergone unilateral ACL reconstruction perform a single-legged hop landing with significantly different tibiofemoral joint motion in the reconstructed knee as compared with the contralateral knee. This task is a common sports movement that elicits large ground-reaction forces and places substantial demands on the knee joint. For patients with ACL-reconstructed knees who are returning to sports activity, performing this task with the potentially altered knee kinematics demonstrated in this study could result in deleterious consequences for articular cartilage health. Future investigations will be necessary to determine the extent to which this kinematic profile alters the normal loading pattern of the tibiofemoral joint. Additionally, it is important to determine the mechanisms underlying bilateral kinematic differences after ACL reconstruction and to evaluate the ability of clinical interventions, such as a more anatomical graft tunnel placement, to reduce these changes.

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