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Differences in tibial rotation during walking in ACL reconstructed and healthy contralateral knees

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Abstract

This study tested the hypotheses that in patients with a successful anterior cruciate ligament (ACL) reconstruction, the internal-external rotation, varus-valgus, and knee flexion position of reconstructed knees would be different from uninjured contralateral knees during walking. Twenty-six subjects with unilateral ACL reconstructions (avg 31 yrs, 1.7 m, 68 kg, 15 female, 24 mo past reconstruction) and no other history of serious lower limb injury walked at a self-selected speed in the gait laboratory, with the uninjured contralateral knee as a matched control. Kinematic measurements of tibiofemoral motion were made using a previously-described point-cluster technique. Repeated-measures ANOVA ($\alpha=0.017$) was used to compare ACL-reconstructed knees to their contralateral knees at four distinct points during the stance phase of walking. An offset towards external tibial rotation in ACL-reconstructed knees was maintained over all time points (95% CI $2.3 \pm 1.3^\circ$). Twenty-two out of twenty-six individuals experienced an average external tibial rotation offset throughout stance phase. Varus-valgus rotation and knee flexion were not significantly different between reconstructed and contralateral knees. These findings show that differences in tibial rotation during walking exist in ACL reconstructed knees compared to healthy contralateral knees, providing a potential explanation why these patients are at higher risk of knee osteoarthritis in the long-term.

Keywords

anterior cruciate ligament; knee kinematics; osteoarthritis; walking; reconstruction

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CONFLICT OF INTEREST

The authors do not have any conflicts of interest to declare.

INTRODUCTION

ACL rupture is an injury that most often occurs during sports activities (Arendt et al., 1999; Boden et al., 2000; Miyasaka et al., 1991) and is associated with a much greater likelihood of developing premature knee osteoarthritis (OA) (Daniel et al., 1994; Kannus and Jarvinen, 1989; Lohmander et al., 2004; Maletius and Messner, 1999). For example, in a population of female soccer players who suffered ACL ruptures at an average age of 19 years, Lohmander et al. (2004) found that 51% of the injured knees showed radiographic knee OA just 12 years after injury (at age 31), compared to only 7% of the uninjured contralateral knees. This study also showed no significant difference in the incidence of radiographic knee OA between ACL reconstructed knees and ACL deficient knees, suggesting that this surgical procedure is unable to alter the long-term prognosis of OA in this population.

In the ACL-injured patient, abnormal knee motion has been observed (Andriacchi and Dyrby, 2005; Georgoulis et al., 2003; Li et al., 2006) before clinical signs of degenerative changes, which are typically observed many years later (Daniel et al., 1994; Kannus and Jarvinen, 1989; Lohmander et al., 2004; Maletius and Messner, 1999). It has been suggested based on data from both humans and animals (Andriacchi et al., 2006; Andriacchi and Mundermann, 2006; Andriacchi et al., 2004; Brandt et al., 1991; Liu et al., 2003; Pond and Nuki, 1973; Yoshioka et al., 1996) that abnormal kinematics associated with ACL deficiency could be a cause of these degenerative changes.

The purpose of ACL reconstruction is to restore the function of the ACL in the joint. However, reconstructive techniques have been primarily focused on restoring the static anterior-posterior (AP) translation stability while the native ACL constrains not only AP translation but also internal-external (IE) rotation (Fu et al., 2000). Accordingly, it has been shown during various static and dynamic activities that the motion of the reconstructed knee remains abnormal when compared to the contralateral knee or to healthy control knees (Papannagari et al., 2006; Tashman et al., 2007; Woo et al., 2002; Yoo et al., 2005). These *in vivo* and *in vitro* studies have shown a shift towards external rotation in the reconstructed knee of approximately 1.9° during simulated motion and downhill running (Tashman et al., 2007; Yoo et al., 2005) and a shift towards varus rotation of 1.3° in the reconstructed knee during downhill running (Tashman et al., 2007). While these studies suggest that tibiofemoral motion is altered during these specific activities, it still remains unknown whether the same outcome occurs during walking.

Overground walking is an especially relevant activity to study in a population at risk for knee OA because it is the most common weight-bearing activity of daily living. In fact, many individuals after suffering an ACL injury and reconstruction reduce their activity level from the most strenuous sports in favor of less demanding activities (Ferrari et al., 2001). In addition, there are specific biomechanical characteristics of walking that have been associated with the initiation and progression of knee OA (Andriacchi and Mundermann, 2006), and the loading at the knee varies substantially for different activities of daily living (Andriacchi et al., 2005; Nagura et al., 2002). While the peak loads during walking might be lower than other activities, the clinical evidence suggest that the cyclic accumulation of damage over many years due to daily walking may be the most relevant to understanding the etiology of OA (Miyazaki et al., 2002; Prodromos et al., 1985). In addition, it has been shown that routine clinical testing (e.g. KT-1000) based on non-ambulatory conditions is not predictive of the long term clinical outcomes for ACL injured or reconstructed patients (Hyder et al., 1997; Pollet et al., 2005; Sernert et al., 1999). Thus, it is important to consider the walking mechanics of patients following ACL reconstruction when examining the factors that influence premature knee OA in this population.

The purpose of this study was to identify the differences in tibiofemoral motion between ACL reconstructed knees and healthy contralateral knees during the stance phase of overground walking. We tested the hypothesis that in patients with a successful ACL reconstruction (based on clinical testing) that the internal-external (IE) rotation, varus-valgus (VV), and knee flexion position of the reconstructed knee would be different from the uninjured contralateral knee during the stance phase of walking.

METHODS

Twenty-six subjects with unilateral ACL reconstructions and no other history of serious lower limb injury (avg 31 yrs old, 1.7 m, 68 kg, 14 left legs, 15 females, 24 months past reconstruction, range 7-65 months past reconstruction) participated in this study after providing IRB-approved informed consent. The uninjured contralateral knees of the subjects served as matched controls. For purposes of this study we accepted patients that had a successful single-bundle ACL reconstruction based on clinical exam (negative Lachmann's test and KT-1000 side-side difference < 5mm) (Daniel et al., 1985; Rupp et al., 2001), self-reported history of knee stability, and MRI irrespective of the type of reconstruction technique, since the hypothesis was designed to test the relationship between knees with clinical stability and walking mechanics. As a result, there were twelve subjects with allografts (nine Achilles, one bone-patellar-bone, and two soft tissue allograft) and fourteen subjects with autografts (ten bone-patellar-bone and four hamstrings tendons). We excluded subjects with damage to >25% of the meniscus, clinical instability of the reconstructed knee, a history of other serious ligamentous injury to either lower limb, or a history of surgical procedures performed on either lower limb.

Data collection for tibiofemoral motion during walking was performed according to a previously-described protocol (Andriacchi et al., 1998; Dyrby and Andriacchi, 2004). Subjects performed several trials of walking at their self-selected normal walking speed for each leg, until three successful trials had been collected. The previously-described point-cluster technique (Andriacchi et al., 1998; Dyrby and Andriacchi, 2004) which uses a redundant set of twenty-one skin-based reflective markers, was used to estimate three rotations of the tibia with respect to the femur during the gait cycle. This method has previously been validated using a subject with an external fixation device (average orientation error of 0.370° on shank segment) (Alexander et al., 2001) and with simulated data (Alexander et al., 2001; Andriacchi et al., 1998). Femoral and tibial anatomical standing reference trials were collected with additional markers on the medial femoral condyle, medial tibial plateau, and medial malleolus. These three markers were removed for the walking trials. Subjects walked over a force plate (Bertec, Columbus OH) embedded in the floor to enable the identification of the stance phase. Marker motion data and force data was collected at 120Hz using an opto-electronic motion capture system (Qualisys, Gothenberg, Sweden), and custom software was used to estimate tibiofemoral motion.

The motion of the knee was determined by relating the motion of the marker clusters to anatomical coordinate systems based upon palpable bony landmarks. Details of the axes orientations of the femoral and tibial anatomical coordinate systems have been described previously (Figure 1) (Andriacchi et al., 2003; Andriacchi et al., 2005; Dyrby and Andriacchi, 2004). The IE rotation of the tibia relative to the femur was measured by projecting the medial-lateral (ML) femoral axis onto a plane created by the AP and ML axes fixed in the tibia. VV rotation of the tibia relative to the femur was measured by projecting the ML femoral axis onto a plane created by the superior-inferior and ML axes fixed in the tibia. Flexion was measured by projecting the AP femoral axis onto a plane created by the superior-inferior and AP axes fixed in the tibia. The reported IE rotation and VV rotation measurements are expressed relative to the subject's standing tibiofemoral reference position by subtracting off the standing reference

values from those measured during the walking trials. There was no significant difference in the standing reference IE rotation (0.2° , $p = 0.77$) or VV rotation (0.4° , $p = 0.26$) values between the ACL reconstructed and contralateral knees, confirming that this normalization procedure did not introduce any systematic bias into the data.

Analysis of the data was performed at four distinct times in the stance phase: foot strike, midstance, terminal extension, and toe off. Midstance was defined as the local maximum of the knee flexion angle during the first half of stance, while terminal extension was defined as the local minimum of the knee flexion angle during the second half of stance. For each trial, these four time points were identified for IE rotation, VV rotation, and knee flexion. The data were then averaged for all trials of each leg to give one value for each of the three kinematic parameters of interest at the four time points for both the ACL reconstructed and contralateral legs. A repeated-measures ANOVA with two within-subjects factors (SPSS GLM Repeated Measures, SPSS Inc., Chicago, IL) was used to test the hypotheses that these kinematic parameters were different between reconstructed and healthy contralateral knees. The two factors used were the knee status (reconstructed vs. contralateral) and the time point (foot strike, midstance, terminal extension, and toe off). A Bonferroni-corrected α level of 0.017 was used in the ANOVA to account for the analysis of three kinematic parameters.

RESULTS

For IE rotation, the ANOVA showed a significant pairwise difference between reconstructed and contralateral knees ($p < 0.01$) (Figure 2), and that the difference towards external tibial rotation in the reconstructed knees was maintained over the four instances during the stance phase (foot strike $2.9 \pm 4.6^\circ$; midstance $3.0 \pm 4.4^\circ$; terminal extension $2.2 \pm 4.5^\circ$; toe off $1.3 \pm 4.3^\circ$). Averaging the difference values over all of stance phase for each knee gives the offset, or average difference, between the reconstructed and contralateral knees for each subject (Figure 3). The distribution of individual subjects' average IE rotation offset over stance phase shows that twenty-two out of twenty-six (85%) individuals experienced an external rotation offset (Figure 3); the average offset for the population was 2.3° of external rotation with a 95% confidence interval of $[1.0^\circ, 3.7^\circ]$.

Knee flexion showed no significant difference between reconstructed and contralateral knees, although there was a significant interaction effect between injury status and time point ($p < 0.01$) (Figure 2C). VV rotation showed no significant difference between reconstructed knees ($p > 0.10$) (Figure 2B).

DISCUSSION

The results of this study supported the hypothesis that the IE rotation of the ACL-reconstructed knees was significantly different from contralateral knees throughout stance phase (Figure 2), but they did not support the hypotheses that V-V rotation and knee flexion would be different between reconstructed and contralateral knees. These results suggest that this procedure is not entirely successful at restoring normal kinematics, which may explain why patients are at much higher risk of knee OA in the long term (Lohmander et al., 2004; von Porat et al., 2004).

An important consideration when interpreting the results of this study and others that have found similar rotational offsets in ACL reconstructed and deficient subjects over a range of activities (Andriacchi and Dyrby, 2005; Defratre et al., 2006; Georgoulis et al., 2003; Papannagari et al., 2006; Tashman et al., 2007) is whether a small rotational offset can trigger degenerative processes in the cartilage. Several studies of cartilage morphology have shown topological variations in collagen structure and chondrocyte morphology within the weight-bearing area of the cartilage (Appleyard et al., 1999; Bullough et al., 1985; Clark, 1991; Quinn

et al., 2005; Thambyah et al., 2006), suggesting that a small shift in position may place loads on cartilage with very different ability to withstand that load. As shown in Figure 3, fifteen of twenty-six subjects had an offset greater than 2°. It may be that those with the largest offsets have the greatest risk. Fourteen of twenty-six subjects were observed to have a difference in external rotation greater than 5° at one or more of the four stance phase time points. A computational model of degeneration due to altered stresses on the cartilage has shown that a 5° rotational shift may be enough to cause accelerated degeneration of the cartilage (Andriacchi et al., 2006). These histological and computational results taken together with the finding of a rotational offset in a substantial percentage of these patients suggest that a relatively small threshold of rotational change may be clinically relevant for the development of OA. It was beyond the scope of this study to estimate actual articular contact location changes in each subject, so it is only possible to speculate on the consequences of this rotational shift on cartilage stresses. Estimating subject-specific articular contact patterns during walking remains an important future goal for understanding the development of OA in this population.

The finding of no significant difference in VV rotation between reconstructed and contralateral knees was contrary to previously reported results during downhill running, where reconstructed knees were found to have more varus rotation (Tashman et al., 2004; Tashman et al., 2007). This difference most likely is due to the fact that walking is a much less stressful activity than downhill running. However, the statistical power of this study to identify differences in VV rotation was quite low due to large variability across subjects in this variable, so further study of VV rotation during walking in this population may be warranted.

The external rotation offset observed in this study was very consistent across subjects, with 85% of the subjects showing a more externally rotated tibia relative to the contralateral knee. This result is consistent with the external rotation offset observed *in vivo* during downhill running (Tashman et al., 2007) and *in vitro* under simulated muscle loads (Yoo et al., 2005) in ACL reconstructed knees. However, this observed external tibial rotation offset was in the opposite direction compared to that observed in ACL deficient knees *in vivo* during walking (Andriacchi and Dyrby, 2005; Georgoulis et al., 2003). Given that the ACL graft's femoral insertion is in the lateral condyle while the tibial insertion is centered in the medial-lateral direction, over-tensioning of the graft can lead to a more externally rotated tibia, as has been observed in cadaver knees (Brady et al., 2007). Additionally, the intra-articular placement of the femoral and tibial graft tunnels has been shown to influence the *in-vitro* rotational stability of the ACL reconstructed knee (Loh et al. 2003, Scopp et al. 2004). It is also possible that this external rotation offset arises as a neuromuscular adaptation during the rehabilitation process. Further investigation of these factors is necessary to explain the development of the observed rotational alteration.

It is important to note that all the subjects in this study were considered similar if they had clinical stability based on clinical exam, irrespective of the surgical technique or time post-surgery. This assumption was confirmed by verifying that there was no significant effect ($p > 0.05$) of graft type or time post-surgery on the kinematic variables of interest prior to pooling the subjects. While this study was not designed to evaluate specific surgical techniques, the consistent finding of a rotational offset during walking following different methods of clinically successful reconstruction suggests that conventional surgical techniques are inadequate for the restoration of normal ambulatory kinematics. Additionally, the results suggest that routine clinical examination might not be sufficient to detect differences in ambulatory function. In the future, examining current methods of reconstruction and rehabilitation to determine if they influence secondary knee motions during ambulation may be very helpful in improving our understanding of how we might improve these methods to bring the reconstructed knee's kinematics closer to normal. For example, the double-bundle ACL reconstruction, which attempts to recreate both the anteromedial and posterolateral bundles, has been shown to

improve rotational kinematics in cadaver studies (Gabriel et al., 2004; Yagi et al., 2002), although it remains to be seen if these improvements carry over to walking. In addition, future examination of the evolution of kinematic changes over time past surgery may provide additional insight into the improvement of surgical technique and rehabilitation protocols.

When interpreting the results of this study, one must consider the use of the contralateral limb as a control rather than a healthy limb from a matched subject as it is possible that the kinematics of the contralateral limb are also affected by the ACL injury and reconstruction. However, the decision to use the contralateral knee as the control is supported by previous findings that observed no alteration in the 6-DOF kinematics of contralateral knees of ACL injured subjects relative to healthy control knees (Kozanek et al., 2008). Additionally, the contralateral limb is universally used as a control for quantitative knee laxity measurements such as the KT-1000 (Daniel et al., 1985) since joint laxity has substantial inter-subject variations and thus kinematics associated with laxity changes are best evaluated with an intra-subject control. In this study, we did not record limb dominance for our subjects. Bilateral differences in the knee joint motion due to limb dominance before ACL injury may have magnified or diminished the differences due to ACL reconstruction. However, the even distribution of ACL reconstructions (14 right, 12 left) and consistent results (22 out of 26 demonstrated an external tibial rotation offset of the reconstructed knee) suggest that the effect of limb dominance was minimal.

A limitation of this study is its use of a skin-based marker system to estimate tibiofemoral kinematics. All skin-based marker systems suffer from the fact that what is being measured is the motion of the skin and soft tissue overlying the bone, rather than the bones themselves. Although the error estimates of the point cluster method appear to be quite good (Alexander et al., 2001), comparisons to the current study must be considered in light of the fact that the error estimates were based on one subject, the pins of the external fixator could limit skin motion, and only errors associated with the markers placed on the shank were estimated. Other techniques using cine-MRI (Barrance et al., 2006), fluoroscopy (Defrate et al., 2006; Papannagari et al., 2006) or high speed radiography (Tashman et al., 2004; Tashman et al., 2007) that can image the bones directly have the potential to be more accurate at examining tibiofemoral motion. However, these imaging-based techniques are not able to examine overground walking because of the limitations of a small field of view, occlusion of one knee by the other in the radiographic images, and quasi-static motion for fluoroscopy (Defrate et al., 2006; Papannagari et al., 2006). It is believed that OA is a disease involving the gradual, accumulation of damage that results in degradation of the articular cartilage (Andriacchi and Mundermann, 2006), so it is very important to study activities that at-risk individuals engage in most often. Therefore, as described above, studying tibiofemoral motion and loading during walking is critical to understanding the development of OA. Skin-marker based motion analysis remains the only feasible way to study tibiofemoral motion during overground walking at present, so the acceptance of the larger error associated with skin markers is a compromise that must be made (Andriacchi and Mundermann, 2006).

The results of this study clearly show that differences in IE rotation exist in ACL reconstructed knees compared to uninjured contralateral knees, even during the most common daily weight-bearing activity of walking. The connection between this difference in secondary motion and the onset of OA remains to be shown experimentally, but if this relationship can be proven it should serve as a strong motivation to improve treatments to restore normal secondary knee motion and help these patients avoid future OA.

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Figure 1.
Determination of tibiofemoral joint angles. Adapted from Andriacchi et al., 2005.

Figure 2.

Differences in (A) tibial axial rotation, (B) tibial varus-valgus rotation, and (C) knee flexion between ACL-reconstructed knees and uninjured contralateral knees. Ensemble average curves for the two groups are shown, with error bars displaying 95% confidence intervals of each group at four selected time points during stance: foot strike, mid stance, terminal extension, and toe off. ACL reconstructed tibias were significantly more externally rotated than contralateral knees ($p < 0.01$).

Figure 3.

Average offset in axial tibial rotation position of reconstructed knees during stance relative to the contralateral knee, one point per subject. The shaded area in denotes the 95% confidence interval of the mean. Axial rotation showed a statistically significant offset of 2.3° (p<0.01).