# In Vivo Kinematics of the Knee After Anterior Cruciate Ligament Reconstruction

## A Clinical and Functional Evaluation

Ramprasad Papannagari, MS, Thomas J. Gill, MD, Louis E. DeFrate, ScD, Jeremy M. Moses, MD, Alex J. Petruska, PT, SCS, and Guoan Li,* PhD
*From the Bioengineering Laboratory, Department of Orthopaedics, Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts*

**Background:** Recent follow-up studies have reported a high incidence of joint degeneration in patients with anterior cruciate ligament reconstruction. Abnormal kinematics after anterior cruciate ligament reconstruction have been thought to contribute to the degeneration.

**Hypothesis:** Anterior cruciate ligament reconstruction, which was designed to restore anterior knee laxity under anterior tibial loads, does not reproduce knee kinematics under in vivo physiological loading conditions.

**Study Design:** Controlled laboratory study.

**Methods:** Both knees of 7 patients with complete unilateral rupture of the anterior cruciate ligament were magnetic resonance imaged, and 3D models were constructed from these images. The anterior cruciate ligament of the injured knee was arthroscopically reconstructed using a bone–patellar tendon–bone autograft. Three months after surgery, the kinematics of the intact contralateral and reconstructed knees were measured using a dual-orthogonal fluoroscopic system while the subjects performed a single-legged weightbearing lunge. The anterior laxity of both knees was measured using a KT-1000 arthrometer.

**Results:** The anterior laxity of the reconstructed knee as measured with the arthrometer was similar to that of the intact contralateral knee. However, under weightbearing conditions, there was a statistically significant increase in anterior translation of the reconstructed knee compared with the intact knee at full extension (approximately 2.9 mm) and 15° (approximately 2.2 mm) of flexion. In addition, there was a mean increase in external tibial rotation of the anterior cruciate ligament–reconstructed knee beyond 30° of flexion (approximately 2° at 30° of flexion), although no statistical significance was detected.

**Conclusion:** The data demonstrate that although anterior laxity was restored during KT-1000 arthrometer testing, anterior cruciate ligament reconstruction did not restore normal knee kinematics under weightbearing loading conditions.

**Clinical Relevance:** Future reconstruction techniques should aim to restore function of the knee under physiological loading conditions.

**Keywords:** anterior cruciate ligament (ACL) reconstruction; in vivo kinematics; KT-1000; anterior laxity; clinical stability

Surgical reconstruction of the ACL is evaluated clinically by its ability to restore anterior stability compared with that of the intact contralateral knee under anterior tibial loads.[8,36] Although high initial success rates have been reported in the literature,[5,36] long-term patient follow-up studies have reported a high incidence of degenerative changes,[13,24] abnormal knee laxity,[28,31,34] the need for a revision surgery,[17,33] and anterior knee pain.[4,7,14] The precise mechanisms contributing to these postoperative complications are unknown.

Abnormal knee kinematics have been thought to be one of the possible reasons for long-term development of degenerative changes after ACL reconstruction.[6,18] Previous biomechanical studies of ACL reconstruction have focused on restoring anterior stability in response to anterior tibial loads. However, many researchers have suggested that after ACL reconstruction, knee joint kinematics are not restored

*Address correspondence to Guoan Li, PhD, Director, Bioengineering Lab, MGH/Harvard Medical School, 55 Fruit St, GRJ 1215, Boston, MA 02114 (e-mail: gli1@partners.org).

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under functional loading conditions.[15,29,32,38] For example, in an in vitro robotic experiment, Yoo et al[38] reported that after ACL reconstruction, knee joint kinematics were not restored under simulated physiological loads. Li et al[21] reported elevated graft forces compared with the intact ACL in knees in which anterior stability was restored. Similarly, several studies have reported altered kinematics after ACL reconstruction compared with the intact contralateral knees during in vivo activities.[15,29,32] However, few studies have directly compared the results of a clinical screening test (such as the Lachman test) with the kinematics measured from functional activities such as in vivo weightbearing flexion.

In this study, we hypothesized that ACL reconstruction, which was designed to restore anterior knee laxity, does not reproduce anterior tibial translation and internal tibial rotation under in vivo physiological loading conditions. The objectives of this study were to evaluate the anterior stability of ACL-reconstructed patients using a joint arthrometer (KT-1000 arthrometer, MEDmetrics, San Diego, Calif) and to investigate in vivo knee kinematics of these patients during weightbearing flexion using a combined dual-orthogonal fluoroscopic and MRI technique. Intact contralateral knees of the same patients were used as controls.

## MATERIALS AND METHODS

Seven subjects (aged 19-38 years) with complete unilateral rupture of the ACL (documented by clinical examination and MRI), no injuries to other knee ligaments and cartilage, and minimal injuries to the menisci participated in this study. Patients with injury to the meniscus were included in this study because it was difficult to find ACL patients with no damage to the meniscus, and it is difficult to precisely quantify meniscus damage without arthroscopic examination. However, the status of each patient's meniscus was documented at the time of subsequent ACL reconstruction surgery. Two patients had no significant damage to the meniscus, 1 patient had a partial-thickness tear of the lateral meniscus, and the remaining 4 patients had injuries requiring partial removal of the lateral meniscus (10%, 15%, 30%, and 40% removal of the lateral meniscus). Subjects had been injured within a mean of 6.5 ± 11.6 months of testing and had intact contralateral knees. The protocol of the study was explained in detail, and each subject signed a consent form approved by our institutional review board.

Before ACL reconstruction surgery, both the ACL-deficient and intact contralateral knees of each subject were scanned using a 1.5-T scanner (GE, Milwaukee, Wis) and a fat-suppressed 3D spoiled gradient-recalled sequence. The MR scan spanned a field of view of 16 × 16 cm. Sagittal plane images separated by 1 mm with a resolution of 512 × 512 pixels were acquired. These images were used to construct a 3D anatomical model of the knee using a solid modeling software (Rhinoceros, Robert McNeel & Associates, Seattle, Wash). The images were placed in parallel planes separated by 1 mm, and the contours of the femur and tibia were manually digitized. These contours were then meshed to create surface models of the femur and tibia. A 3D anatomical model of the knee of a typical patient is shown in Figure 1A.

### Surgical Technique

The subjects underwent arthroscopic surgical reconstruction of the ACL of the injured knee. All surgeries were performed by one orthopaedic surgeon (TJG). A diagnostic arthroscopy was performed before graft placement. During surgery, the status of each patient's menisci was documented. Reconstruction was performed in a standard fashion using a 10-mm bone–patellar tendon–bone autograft. A 10-mm tibial tunnel was drilled using a 55° guide (Linvatec-Conmed, Largo, Fla) centered at a point 7 mm anterior to the PCL on the downslope of the medial tibial spine. A 10-mm femoral tunnel was drilled using a 6-mm femoral offset guide (Arthrex, Naples, Fla) centered at the 10:30 o'clock position for right knees (1:30 for left). The graft was passed in retrograde fashion, and the femoral and tibial bone blocks were secured with titanium interference screws (Guardsman, Linvatec-Conmed). The femoral screw length was 25 mm and was placed with the knee in maximal flexion. The tibial screw length was 30 mm. The graft was fully tensioned with the knee in full extension. Screw diameter was determined based on graft-tunnel fit. Examination confirmed that there was no notch impingement, and cycling of the knee revealed less than 2 mm of graft motion in all cases.

### Clinical Stability Testing

Three months after surgery, the patient was called back for the follow-up study. The clinical stability testing was performed first. The subject lay supine on a bed and was tested using the KT-1000 arthrometer. A physical therapist (AJP) with extensive experience with this device performed all of the joint laxity measurements. The ACL-reconstructed knee was flexed to 20°, and the laxity of the knee was measured under 15 lb, 20 lb, 30 lb, and maximum anterior loads. Similarly, the laxity of the intact contralateral knee was measured.

### Measurement of In Vivo Weightbearing Kinematics

The kinematics of the intact contralateral and ACL-reconstructed knees were measured during weightbearing flexion using the dual-orthogonal fluoroscopic system[23] (Figure 1B). The subjects were imaged simultaneously from both fluoroscopes as they performed a quasi-static lunge. The subjects were imaged at full extension and 15°, 30°, 60°, and 90° of flexion. This procedure was repeated for both the intact contralateral and the reconstructed knees.

Next, a virtual fluoroscopic system was created in a 3D modeling software (Rhinoceros) to reproduce the geometry of the fluoroscopic testing system[23] (Figure 1C). The fluoroscopic images were placed in orthogonal planes, and the anatomical knee model was imported into the virtual fluoroscopic system. The model was then adjusted in 6 degrees of freedom until its projections matched the outlines of the bones in the fluoroscopic images. Thus, the 6 degrees of freedom in vivo knee position was reproduced using the 3D anatomical knee model. This procedure was repeated for each position of each knee of each subject. This system has an accuracy of less than 0.1 mm in measuring tibiofemoral

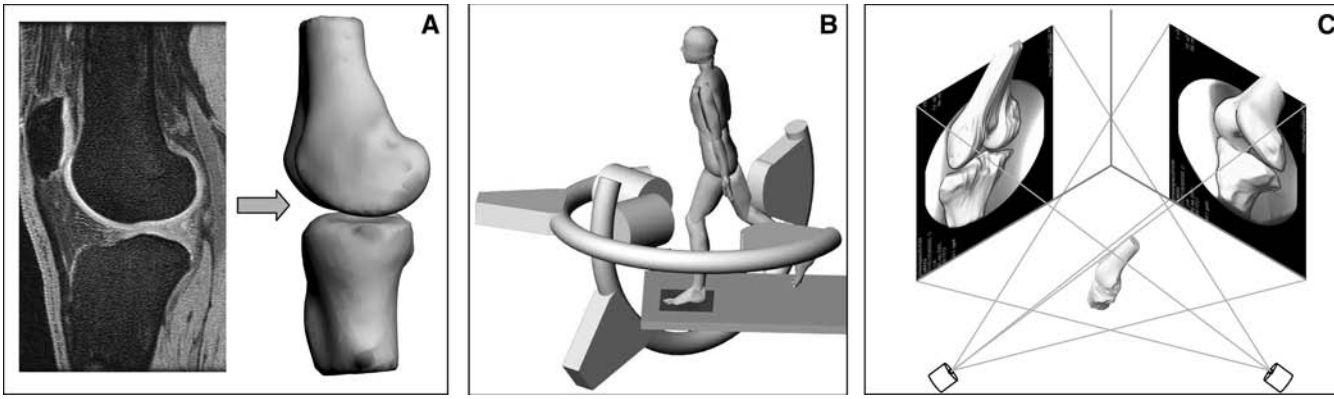


**Figure 1.** A, 3D anatomical model of the knee joint constructed from the MRI. B, a subject performing a single-legged weightbearing lunge inside the dual-orthogonal fluoroscopic system. C, a virtual fluoroscopic system built in the solid modeling software to reproduce the geometry of the dual-orthogonal fluoroscopic system. The anatomical model of the knee is imported into the virtual fluoroscopic system and manipulated in 6 degrees of freedom until its projections match the contours of the bones on fluoroscopic images.

joint kinematics.[10,23] The in vivo kinematics of the ACL-reconstructed and intact contralateral knees were measured from the series of knee models.

## Data Analysis

A coordinate system was then created on both knees of each subject to quantify the kinematics from each series of matched models (Figure 2). To reduce the variability due to differences in coordinate systems, the right knee of each patient was mirrored to create 2 left knees using the solid modeling software. The 2 knee models of each patient were then aligned, and the coordinate systems were created on both knees simultaneously.

The long axis of the tibial shaft was drawn first. Next, axes were drawn perpendicular to the long axis of the tibia: an anteroposterior axis and a mediolateral axis. These axes intersected at the center of the tibial plateau to form a Cartesian coordinate system. Next, 2 axes were drawn on the femur: the long axis of the femur and the transepicondylar line. Translation was defined as the motion of the midpoint of the transepicondylar line relative to the tibial coordinate system.[27] Femoral translations were then converted to tibial translations, to report our data in a manner consistent with previous studies in the sports medicine literature.

The rotations of the knee were measured in a fashion similar to that described by Grood and Suntay.[16] Flexion was defined as the angle between the long axes of the femur and tibia, projected onto the sagittal plane of the tibia (Figure 2). Internal-external rotation was defined as rotation about the long axis of the tibia.

## Statistical Methods

A repeated-measures analysis of variance was used to detect statistically significant differences in the in vivo kinematics of ACL-reconstructed and intact contralateral knees. Specifically, anterior laxity under the anterior tibial load and anteroposterior translation and internal-external rotation under weightbearing loads were compared at each flexion angle. Differences were considered statistically significant at $P < .05$. If no statistical significance was detected between reconstructed and intact contralateral knees, a power analysis was performed to ensure that the statistical tests had sufficient power.

# RESULTS

## Clinical Stability Testing

KT-1000 arthrometer testing showed that the mean difference in anterior laxity between the reconstructed and intact contralateral knee was less than 1.0 mm under 15, 20, and 30 lb of anterior load (Figure 3). Under the 15 and 20 lb of loads, the ACL-reconstructed knee showed similar laxity compared with the contralateral knee. Under maximum anterior load, the intact knee had a laxity of $7.2 \pm 3.1$ mm, compared with a laxity of $8.1 \pm 1.8$ mm for the reconstructed knee. The laxity of the reconstructed knee was 0.9 mm more than that of the intact contralateral knee. These differences were not statistically significant ($P > .05$). These data have 99% power in detecting differences of 3 mm in anterior laxity. Differences of less than 3 mm in anterior laxity are considered clinically to be a successful reconstruction.[8]

## In Vivo Weightbearing Kinematics

*Anteroposterior Translation.* The tibiae of both the intact and reconstructed knees translated anteriorly with increasing flexion (Figure 4). Positive values correspond to an anterior position of the tibia relative to the femur, and negative values correspond to a posterior position. At full extension, the tibiae of the intact and reconstructed knees were $4.1 \pm 1.5$ mm

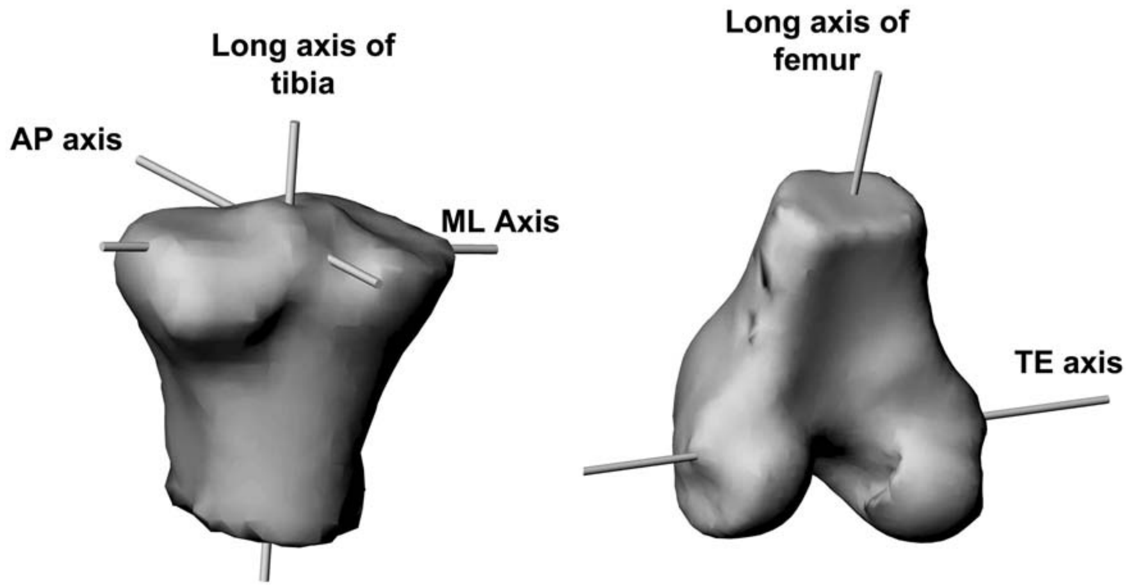


**Figure 2.** The tibial and femoral coordinate systems used to quantify knee kinematics. AP, anteroposterior; ML, mediolateral; TE, transepicondylar line.

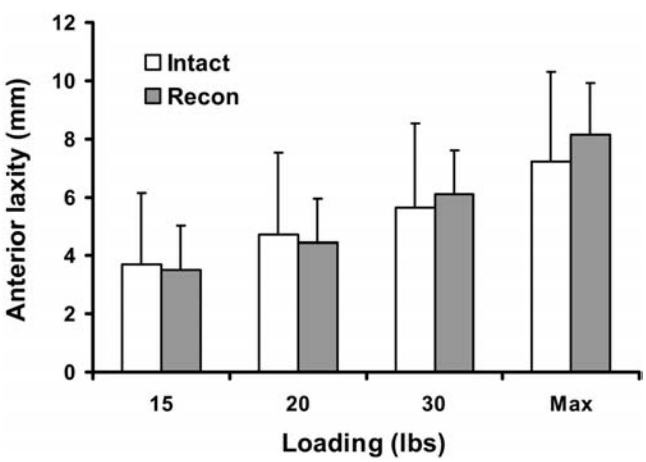


**Figure 3.** The anterior laxity of the reconstructed knee compared with that of the intact knee measured using KT-1000 arthrometer as a function of anterior tibial load.

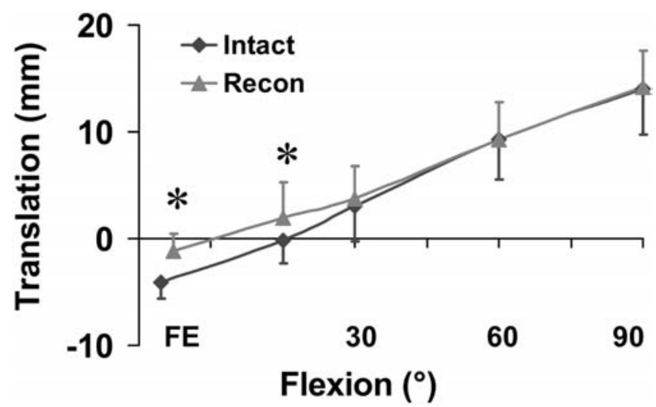


**Figure 4.** Tibial translations of the intact and reconstructed knees during single-legged weightbearing flexion. Positive values denote anterior tibial translation. $^{*}P < .05$.

and 1.2 ± 1.6 mm posterior to the center of the femur, respectively. At 15° of flexion, the tibiae of the intact and reconstructed knees translated to –0.2 ± 2.1 mm and 2.0 ± 3.3 mm, respectively. The tibia of the reconstructed knee was significantly anterior to that of the intact contralateral knee at full extension and 15° of flexion ($P < .05$). Beyond 15° of flexion, there was minimal difference between the intact and reconstructed knees.

*Internal-External Rotation.* The tibiae of the intact and reconstructed knees rotated internally with increasing flexion (Figure 5). At full extension, the tibiae of the intact and reconstructed knees were externally rotated relative to the femur by 5.4° ± 7.6° and 2.7° ± 5.9°, respectively. Beyond full extension, knees with ACL reconstruction had less internal tibial rotation compared with the intact knee. For example, at 30° of flexion, the tibia of the reconstructed knee was externally rotated by 1.9° compared with the intact knee. No statistically significant differences in tibial rotations were detected between the reconstructed and intact contralateral knees ($P > .05$). The power analysis indicated that these data only had approximately 30% power in detecting differences of 2° between intact and ACL-deficient knees.

## DISCUSSION

The success of current treatments of ACL injury has typically been evaluated by measuring the ability of the reconstruction to restore normal knee laxity under anterior tibial loads.[1,2,5,36] A reconstruction that restores the anterior laxity of the injured knee to within 3 mm of the intact

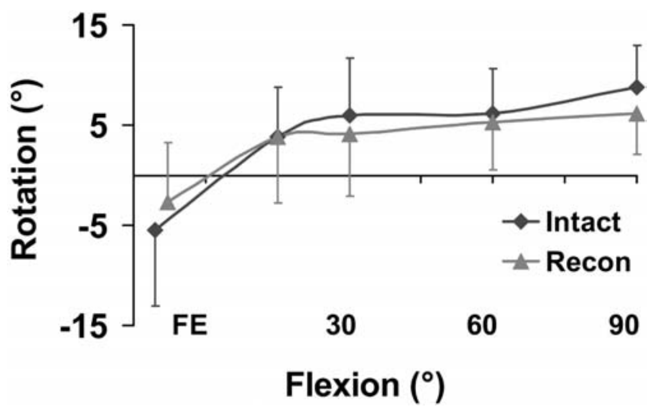


**Figure 5.** Tibial rotations of the intact and reconstructed knees during single-legged weightbearing flexion. Positive values denote internal tibial rotation.

knee as measured using the KT-1000 arthrometer has been considered normal or nearly normal.[8,9] Few studies have examined knee kinematics under both the passive anterior tibial load and active functional loads.[15,29,32] This study evaluated the kinematic behavior of ACL-reconstructed knees 3 months after surgery during both clinical examination and weightbearing flexion.

Contemporary ACL reconstruction, using either a bone–patellar tendon–bone graft or a hamstring graft, has been shown to restore anterior stability under anterior tibial loads.[3,26,37] However, its ability to restore knee kinematics under functional loading conditions has not been well documented.[36,38] Yoo et al[38] recently evaluated ACL reconstruction using a robotic testing system under both anterior tibial loads and simulated muscle loads. They reported that although anterior tibial translation was satisfactorily restored under anterior loads, there was a significant external rotation of the tibia compared with the intact knee under simulated physiological loads. Tashman et al[32] studied 6 patients after ACL reconstruction (with patellar tendon or hamstring tendon grafts) during running using high-speed biplane radiography. They found that although anterior tibial translation was similar, the reconstructed knee was externally rotated compared with the intact knee by approximately 3.8°. Nordt et al[29] have also reported increased external tibial rotation after ACL reconstruction using computed tomography. Ristanis et al[30] reported that ACL reconstruction may not restore tibial rotation during a combined descending and pivoting movement, although normal anterior tibial translation was reproduced.

In this study, the in vivo kinematics of the ACL-reconstructed knee were compared with the kinematics of the intact knee during weightbearing flexion 3 months after reconstruction. During testing, none of the patients had difficulty performing the experimental protocol. The anterior laxity of the reconstructed knee was clinically evaluated using a KT-1000 arthrometer under anterior tibial loads and compared with that of the intact knee. The bilateral differences were less than 1.0 mm on average. These data had 99% power in detecting a 3-mm difference in anterior laxity. A difference of less than 3 mm in anterior laxity has been described as a stable knee by Daniel et al.[8] However, the kinematics of the knees with ACL reconstruction were significantly different from those of the intact knee during in vivo functional activities. The anterior tibial translation of the reconstructed knee was significantly more than that of the intact knee at full extension and 15° of flexion. On average, ACL-reconstructed knees had less internal tibial rotation beyond 15° of flexion, although no statistically significant differences in internal rotation were detected. This may be because of the small sample size used in this study. Our data currently have only approximately 30% power to detect changes of 2° in tibial rotation. However, this study and other reports in the literature[29,30,32] suggest that the ability of an ACL reconstruction to restore anterior laxity under anterior tibial loads does not indicate that knee behavior is restored under more complex in vivo loading conditions.

Patient follow-up studies have reported a high incidence of joint degeneration after ACL reconstruction.[12,13,19,24,25] Approximately 10% to 50% of ACL-reconstructed knees have abnormal knee laxity,[14,28,34] and up to 31% of patients have a second operation within 5 years of the first one.[14] Furthermore, prospective studies have reported no difference in the rate of osteoarthritis (based on radiographic evaluation) between patients with ACL reconstruction and those treated nonoperatively.[13,24,35] Recent reports have suggested that ACL reconstruction does not prevent the development of osteoarthritis and that more research is needed to investigate the long-term effects of ACL injury and reconstruction.[11,24]

Although many factors may be responsible for the poor long-term results of ACL reconstruction (eg, traumatic injuries to other tissues of the joint), abnormal knee joint kinematics have been thought to be one mechanism contributing to joint degeneration. Most contemporary ACL reconstruction surgeries have been designed to restore normal anterior knee laxity.[1,2,5,36] However, both in vitro and in vivo studies have indicated that ACL reconstruction might not reproduce the complex biomechanical function of the ACL and may cause abnormal joint motion when the knee is subjected to in vivo loading conditions.

The altered joint kinematics observed after ACL reconstruction could change articular cartilage contact patterns. In the normal knee, the articular cartilage contact was found in regions with thicker cartilage on both the tibial and femoral cartilage layers.[22] The increased anterior tibial translation at low flexion angles and altered tibial rotation may shift the articular contact locations away from the thicker cartilage, thus altering the contact mechanics of the joint. Further investigation is necessary to determine the effect of altered tibial translation and rotation on cartilage contact biomechanics during in vivo knee function.

In vitro studies have noted that increased external tibial rotation elevated the peak contact pressures in the patellofemoral joint.[20] Therefore, the reduced internal tibial rotation (or increased external tibial rotation) after ACL reconstruction observed in these in vivo studies may also contribute to patellofemoral joint complications. Therefore, consistently restoring tibial rotation after ACL reconstruction surgeries might help to prevent degeneration of the patellofemoral joint.

There are several limitations in the current study. This study evaluated the patient kinematics only at 3 months after surgery. By this time, patients may not have returned fully to their normal daily activities (eg, sports). In the future, patients should be followed up at various time intervals to investigate the change in kinematics over time. This might also provide insight into the relationship between altered kinematics and joint degeneration. Patients with ACL reconstruction using other graft materials (such as hamstrings tendon) should be investigated. Furthermore, 7 patients were investigated in this study. A larger patient population should be included in future studies to increase statistical power, so that the effects of ACL reconstruction on tibial rotation can be investigated. Future studies should also measure knee kinematics during other functional activities such as gait.

In conclusion, current ACL reconstruction techniques restored anterior laxity to within clinically satisfactory levels in response to anterior tibial loads. However, reconstruction might not restore knee joint kinematics under in vivo activities. These data suggest that although a reconstruction might restore anterior stability in response to anterior tibial loads, it might not reproduce knee 6 degrees of freedom kinematics under functional loading conditions, such as weightbearing flexion. Future ACL reconstructions should aim to restore knee kinematics under in vivo loading conditions.

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