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# Follow-up Evaluation 2 Years After ACL Reconstruction With Bone–Patellar Tendon–Bone Graft Shows That Excessive Tibial Rotation Persists

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# Follow-up Evaluation 2 Years After ACL Reconstruction With Bone Patellar Tendon–Bone Graft Shows That Excessive Tibial Rotation Persists

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**Objective:** To investigate in vivo if the increased tibial rotation found in anterior cruciate ligament (ACL)-deficient patients before surgery is restored 2 years after the reconstruction, during 2 high-demanding activities.

**Design:** Prospective follow-up study.

**Setting**: A gait analysis laboratory.

**Participants:** Nine subjects with unilateral ACL rupture, reconstructed with a bone–patellar tendon–bone (BPTB) graft, and 10 healthy control subjects.

**Interventions:** All the ACL-deficient patients underwent a unilateral ACL reconstruction after preconstruction data acquisition.

**Main Outcome Measurements**: Using a 6-camera motion analysis system, kinematics were collected as subjects (1) descended from a stair and, after foot contact, pivoted on the landing leg at 90°; and (2) jumped from a platform, landed with both feet on the ground and, after foot contact, pivoted on the right or left leg at 90° in a similar fashion. The dependent variable examined was the maximum range of motion of tibial rotation during the pivoting period.

**Results:** For both activities, no significant differences were found between the control healthy knee and the intact knee of the patient group before and 2 years after the ACL reconstruction. Significant differences were found between the control healthy knee and the affected knee of the patients group for both activities, both before and 2 years after the ACL reconstruction.

**Conclusion:** The increased tibial rotation found in the ACL deficient knees was not restored with reconstruction using a BPTB graft, even 2 years postoperatively. The authors propose that this excessive tibial rotation over time may lead to further deterioration of the knee resulting from abnormal loading at areas of the cartilage that are not commonly loaded in a healthy knee.

**Key Words:** ACL reconstruction, bone–patellar tendon–bone autograft, gait analysis, osteoarthritis, pivoting, tibial rotation

The anterior cruciate ligament (ACL) is a dynamic structure with unique anatomic properties and it consists of 2 major bundles—the anteromedial (AM) and posterolateral (PL)—each of which contributes in a different fashion in knee joint stability.[1] ACL reconstruction aims to restore these unique structural features and their resulting physiology. However, few studies provide long-term clinical evidence that current surgical techniques are successful in restoring knee kinematics. Additionally, orthopedic surgeons only judge the success of their operations subjectively, measuring clinical stability via static procedures and in terms of anterior tibial translation only (ie, KT-1000).[2] These measures cannot assure us that knee function is fully restored dynamically.[3] Furthermore, such measures do not provide information on the level of rotational stability achieved after ACL reconstruction. In vitro research has shown that the ACL is important in maintaining rotational stability.[4] However, it is unclear whether current surgical techniques restore rotational stability in vivo.[5,6]

Using optoelectronic systems, Georgoulis et al[7] and recently Andriacchi et al[8] found increased tibial rotation in ACL-deficient patients during low-demanding activities such as walking. ACL reconstruction partially restored tibial rotation to normal levels during walking.[7] However, it is unknown whether tibial rotation is restored during activities more demanding than walking. If differences exist in such higher demanding activities, it is also unknown if they persist longitudinally (ie, 2 years after the reconstruction).

Our purpose was to investigate in vivo if the increased tibial rotation found in ACL-deficient patients before surgery is restored 2 years after reconstruction during 2 high-demanding activities: landing from a jump and subsequently pivoting, and descending from a stairway and subsequently pivoting. This protocol required the patients to perform activities with increased translational and rotational loads. Stair descending and landing were used because it has been reported that they produce increased sagittal knee translations.[9] We combined these tasks with pivoting, practically imitating sports activities (ie, basketball). Thus, we evaluated the function of the graft in response to both anterior translational and rotational tibial loads. We hypothesized that normal levels of tibial rotation will eventually be restored 2 years postoperatively.

## METHODS

### Subjects

Nine men with ACL rupture (mean age, 27± 3 years; mean mass, 75± 6 kg; mean height, 1.79± 0.05 m) comprised the patient group. These subjects were examined before and 2 years after an ACL reconstruction with a bone–patellar tendon–bone (BPTB) autograft (operated by the senior author, A.G.). ACL reconstruction was performed subacutely at an average of 4 months (range, 2–7 months) after injury. Ten healthy gender-, age-, height-, and mass-matched subjects who had never suffered any kind of orthopedic or neurologic condition also volunteered as control subjects (mean age, 28± 4 years; mean mass, 74± 5 kg; mean height, 1.76± 0.04 m).

All patients had unilateral ACL tears, confirmed by MRI and arthroscopy. In 3 patients, meniscal damage was also found during the arthroscopic reconstruction, but in all cases the level of involved meniscus damage was much less than 25%.[10] All patients underwent the same rehabilitation protocol, starting from the first postoperative day with the use of passive exercises. Return to sports was permitted 24 weeks after reconstruction, provided that the patients had regained adequate thigh muscle strength and acceptable performance in sportspecific tests in addition to the restored static stability.[11,12] During data collection no clinical evidence of knee pain was found in the reconstructed subjects and they all had resumed competitive sports activities. During the clinical evaluation, Tegner and Lysholm scores were obtained, and anterior tibial translation was evaluated using the KT-1000 arthrometer (MEDmetric Corporation, San Diego, CA, USA).[2]

### Instrumentation–Procedures

A 6-camera optoelectronic system (Peak Performance Technologies, Inc., Englewood, CO, USA) was used to capture (50 Hz) the movements of 15 reflective markers placed on the selected bony landmarks of the lower extremities and pelvis using the model of Davis et al[13] (Fig. 1). The subjects performed 2 different activities: (1) descending from a stair and subsequent pivoting, and (2) landing from a platform and subsequent pivoting (Fig. 2). The height of the platform used for landing was 40 cm and it was designed according to James et al.[14] The stairway was constructed according to Andriacchi et al.[15]

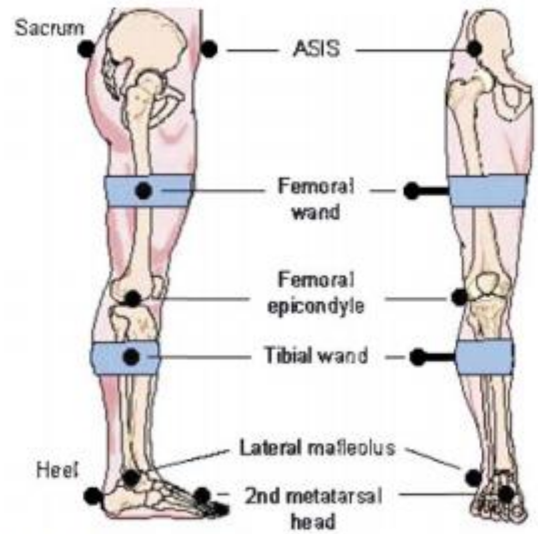


**FIGURE 1.** The retroreflective marker set required for the motion data collection tests (model by Davis et al[13]). This is a minimal configuration for a 3-dimensional analysis of gait.

During the first activity, the subjects descended the stairway at their own pace. The descending period was concluded on initial foot contact with the ground. After foot contact, the subjects were instructed to pivot (externally rotate) on the landing (ipsilateral) leg at 90° and walk away. While pivoting, the contralateral leg swung around the body (as it was coming down from the stairway) and the trunk was oriented perpendicular to the stairway. During the second activity, the subjects folded their arms across their chest and then jumped from the platform and landed with both feet on the ground. After foot contact, the subjects were instructed to pivot (externally rotate) on the right or left (ipsilateral) leg at 90° and walk away, in a similar fashion to the first activity. The pivoting period was identified from initial foot contact with the ground of the ipsilateral leg, until touchdown of the contralateral leg. Each subject performed each activity with both legs for 6 trials.

To validate our procedures[16] regarding video capture of skin markers, an additional trial was recorded for each subject in anatomic position. This trial was used as reference for the calculation of the anatomic angles. This calibration allowed correction of subtle misalignment of the markers that define the local coordinate system. It also provided a definition of 0° for all segmental movements in all planes.

**Data Reduction**

Marker identification and angular displacement calculations were conducted using the Peak Motus (Peak Performance Technologies, Inc.) and Matlab (Mathworks Inc., Natick, MA, USA) software. Spot-checking calibration assessment revealed a maximum 3-dimensional (3D) SD error in marker reconstruction of 0.303 mm. Anthropometric measurements were combined with 3D marker data from the anatomic position trial to provide positions of the joint centers and to define anatomic axes of joint rotations.[13]

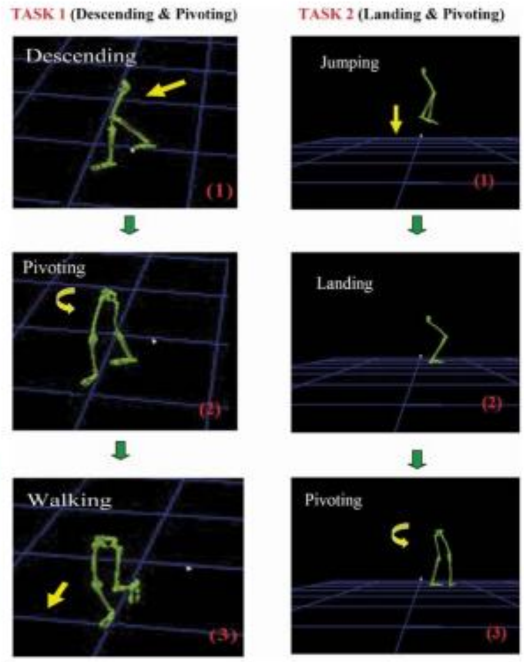


FIGURE 2. A stick figure mimicking the 2 activities performed. For task 1, the subjects descended the stairway at their own pace. The descending period was concluded on initial foot contact with the ground. After foot contact, the subjects were instructed to pivot on the landing leg at 90° and walk away from the stairway. While pivoting, the contralateral leg swung around the body (as it was coming down from the stairway) and the trunk was oriented perpendicularly to the stairway. For task 2, the subjects jumped off the platform and landed with both feet on the ground. After foot contact, the subjects pivoted (externally rotated) on the right or left (ipsilateral) leg at 90° and walked away from the platform. While pivoting, the contralateral leg swung around the body and the trunk was oriented perpendicularly to the platform.

The position of the markers provided the 3D segmental angles. The convention used for calculating knee rotations was based on Grood et al.[17] The dependent variable used was the range of motion of tibial rotation during the pivoting period of the 2 examined tasks (Fig. 3). The selection of the range of motion as the dependent variable eliminated possible errors reported in the literature[18] and used absolute measures (ie, maximum).

A dependent t-test between the left and right sides within the control group revealed no significant differences ($P<0.05$) for this variable for both activities. Thus, the right side was selected as the representative. Independent t-tests were then used to examine differences between the control healthy knee and both knees of the patient group as ACL deficient and as ACL reconstructed for both activities.

A 2-factor fully repeated analysis of variance was also performed for each activity to identify differences within the patient group. The first factor was the time of evaluation of the patient group (as ACL deficient, and 2 years after as ACL reconstructed). The second factor was the leg of the patient group (the healthy [intact] knee vs the affected knee). The level of significance was set at $a=0.05$.

## Ethical Considerations

All subjects gave consent for participation, according to the university institutional review board procedures. The original copy of consent was maintained in the investigators' files, and a copy was given to the subject at the time of consent. All subjects' physicians were in agreement with the testing protocol.

## Results

### Clinical Findings

Negative Lachman and pivot shift tests in the ACL- reconstructed subjects indicated that the static knee joint stability was regained. All 9 subjects resumed fully their preinjury level of sports participation. Only 1 subject reported mild limitations and occasional swelling after prolonged exercise. Before the reconstruction, the median Lysholm score was 64 points (range, 58–80 points) and the Tegner score was 4 points (range, 3–6 points). Two years after surgery, the median Lysholm score was 96 points (range, 92–97 points) and the Tegner score was 8 points (range, 8–9 points). For the control subjects, the median Lysholm score was 99 points (range, 96–100 points) and the Tegner score was 8 points (range, 8–9 points). KT-1000 testing revealed side-to-side differences of 3 mm or less 2 years after reconstruction. Specifically, KT-1000 results revealed that the mean difference between the anterior tibial translation of the reconstructed and intact sides was 1.5 mm (range, 1–2 mm) for the 134-N test and 1.7 mm (range, 1–2 mm) for the maximum manual test. Between the deficient and the intact sides, the mean difference for each test was 3.5 mm (range, 3–7 mm) and 4.5 mm (range, 3–9 mm) respectively.

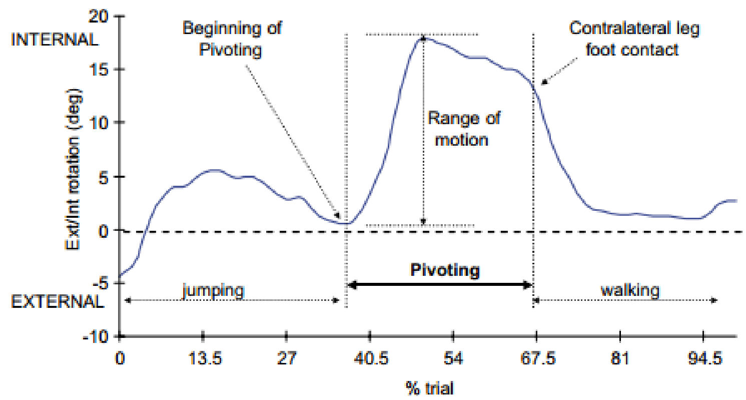


**FIGURE 3.** A typical tibial internal/external rotation curve during the period under study for a full "stride" from a representative healthy subject. The difference between the maximum and the minimum tibial rotation during the pivoting period is indicated. This difference was used as the dependent variable in this study.

## Gait Analysis Findings

### Comparisons With the Control Group

No significant differences were found between the control knee and the intact contralateral knee of our patient group as ACL deficient for both activities. Similar results were found when this comparison was conducted 2 years after the ACL reconstruction (Figs. 4, 5).

Significant differences were found between the control knee and the ACL-deficient knee in the patient group for both activities ($P = 0.007$ for descending stairs and pivoting, and $P = 0.004$ for landing and pivoting; Figs. 4, 5). Similar results were found when this comparison was conducted 2 years later in the patient group as reconstructed ($P = 0.017$ for descending stairs and pivoting, and $P = 0.006$ for landing and pivoting; Figs. 4, 5).

### Comparisons Within the Patient Group

Significant differences were found for the leg factor during landing and pivoting ($P<0.001$) as well as during descending stairs and pivoting ($P<0.001$), but not for the time of evaluation factor. These results showed that the increased tibial rotation that existed in the ACL-deficient knee when compared with the intact knee remained excessive even 2 years after reconstruction (Figs. 4, 5).

## Discussion

The principal finding of the current study was that the increased tibial rotation present in the ACL-deficient knees remained excessive 2 years after reconstruction, during high-loading activities such as immediate pivoting after landing and after descending stairs. During these activities, anterior and rotational loads were applied at the knee through these combined movements. The ACL reconstruction with a BPTB graft did not restore normal knee function regarding tibial rotation during these 2 high-loading activities, 2 years after the surgery. This result was verified with comparisons conducted with both the intact contralateral knees of our patient group and with healthy control knees. Furthermore, we found that tibial rotation of the intact knee of our patient group was similar with those recorded from the control healthy group. This result was expected, because these knees did not present any structural alterations.

Our findings provide support to other in vivo research work. [5-8] Specifically, Brandsson et al[19] examined 11 patients with unilateral ACL rupture. They performed continuous radiostereometric exposures (2–4 exposures/ second) while the patients ascended an 8-cm-high platform, and they found that the tibia was more externally rotated on the injured side. In another study by the same group,[5] they examined 9 patients preoperatively and 1 year after ACL reconstruction using the same methodology (2–4 exposures/second) and protocol. They found that tibial rotation was not significantly different after the reconstruction compared with the preoperative measurements. In the current study, we verified these findings in even more demanding activities, which included a pivoting movement, and we progressed to identify whether the findings persisted even 2 years postoperatively.

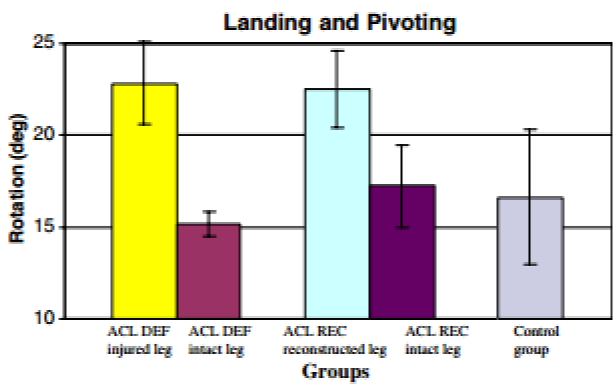


**FIGURE 4.** Group mean and SD values for maximum range of motion of the tibial internal–external rotation during the pivoting period for the landing and pivoting activity.

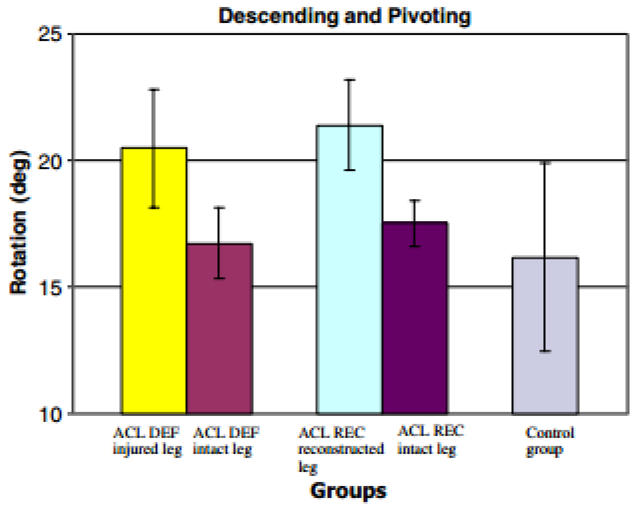


**FIGURE 5.** Group mean and SD values for maximum range of motion of the tibial internal–external rotation during the pivoting period for the descending and pivoting activity.

Our results give also support to findings from in vitro research in which the biomechanical efficiency of the ACL reconstruction has been questioned.[20–22] These studies revealed that ACL reconstruction was successful in limiting anterior tibial translation in response to an anterior tibial load, but was insufficient to control a combined rotatory load of internal and valgus torque. However, in vitro studies are limited because they cannot reproduce neuromuscular activity. As reported in the literature, neuromuscular adaptations can significantly affect dynamic function, and subjects with ACL reconstruction use such adaptations during gait and other activities.[23,24] Therefore, the importance of a dynamic evaluation as it was conducted in the current study to assess the efficiency of an ACL reconstruction is unquestionable.

A possible explanation for the presence of abnormal tibial rotation, even 2 years after an ACL reconstruction, is the absence of restoration of the actual ACL anatomy. As mentioned previously, each ACL bundle contributes to different aspects of stability and stresses.[1] Current reconstruction techniques with a BPTB graft seem to replicate mostly the AM bundle and ignore the PL. In the natural ACL, there is functional cooperation between the two bundles[1] ; each bundle has a different tension pattern. Such anatomic complexity does not seem to be reproduced by current procedures.

Recently, studies using animal models[25] have documented advantages of a 2-bundle reconstruction over a single bundle with respect to the ligament's structure both morphologically and functionally. Yagi et al[22] have also demonstrated in vitro that we could have better biomechanical results with an anatomic reconstruction procedure with 2 bundles than with the single-bundle reconstruction, which approximates mostly the AM bundle. Similar results have been reported in humanmodels[26] as well. In a 2-year follow-up study with a 2-bundle procedure in 54 patients, Muneta et al[26] demonstrated good anterior stability with no serious complications. This technique, however, has not been investigated in vivo, so future research work using external loading conditions similar to ones used in the current study should be performed to determine dynamically the advantages of the 2-bundle reconstruction.

An additional explanation for our findings is that the preferred femoral tunnel placement for a reconstruction with a BPTB is at the 11-o'clock position. This placement is designed to reproduce mostly the AM bundle. Thus, because the graft is placed near the center of rotation of the knee, it may be unable to resist rotational loads resulting from the lack of a sufficient moment arm. This is why several surgeons use a more lateral femoral tunnel (even as far as the 9-o'clock position) to increase the moment arm.[27] In the patients examined in the current study, radiographic examination postoperatively showed that the femoral tunnel was placed between the 10 and the 11-o'clock positions. However, we currently perform ACL reconstructions in which the femoral tunnel is placed in an even more oblique position. Therefore, in our future investigations we plan to examine in vivo whether the change in femoral tunnel positioning can affect tibial rotation.

The results of the current study also provide with an interesting theoretical proposition regarding the development of future pathology at the ACL-reconstructed knee. We propose that the excessive tibial rotation found in an ACL-reconstructed knee even 2 years postoperatively could degenerate soft tissues (ie, cartilage), resulting in osteoarthritis. We theorize that because current ACL reconstruction procedures cannot replicate exactly normal ACL anatomic complexity, they cannot restore normal tibiofemoral kinematics at the knee joint, leading to pathologic movement patterns. Additionally, we propose that such alterations in the rotational movements of the articulating bones of the knee could result in the application of loads at areas of the cartilage that are not commonly loaded in a healthy knee. These areas resulting from lack of sufficient cartilage may not be able to withstand the newly introduced loading and, over time, the end result could be knee osteoarthritis. However, our proposition needs to be further explored via both in vivo and in vitro studies.

Our results, though, should be viewed in light of the general gait analysis limitations,[16] even though gait analysis is widely accepted nowadays and is considered a well-established and reliable method.[28,29] Specifically, a known drawback of gait analysis is related to the movement of skin markers and their ability to predict bone movements. However, in the current study we minimized interoperator error by having the same clinician place all the markers and acquire all the anthropometric measurements. In addition, the absolute 3D marker reconstruction error of the system was very low (maximum SD, 0.303 mm; calibration space, approximately 8 $m^3$ ). We also used a standing calibration procedure to correct for subtle misalignment of the markers that define the local coordinate system and to provide a definition of 0° for all segmental movements in all planes. Additionally, we incorporated 2 different control subjects (the intact contralateral leg of our patient group and a separate healthy control group) to ensure the existence of differences in our dependent variable. Lastly, we assumed that because the same instrumentation was used for all subjects, the level of measurement noise would be consistent for all subjects and that any differences could be attributed to changes within the system itself.

## Conclusion

In conclusion, our findings revealed that even 2 years after ACL reconstruction, dynamic knee function in terms of excessive tibial rotation was not restored. Based on these results we can claim that a dynamic evaluation of the reconstructed knee under loading conditions that have both rotational and translational components should be performed to identify possible advantages and disadvantages of different surgical procedures, whether it is the graft material or the tunnel positioning. Such in vivo studies should complement in vitro research work to obtain a complete scientific basis of the functional abilities of the ACL-reconstructed knee.

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