

Excessive Tibial Rotation During High-Demand Activities Is Not Restored by Anterior Cruciate Ligament Reconstruction

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Purpose: Recent in vitro research has suggested that anterior cruciate ligament (ACL) reconstruction does not restore control of tibial rotation. The purpose of this study was to explore these findings in vivo and investigate rotational knee stability during landing and subsequent pivoting. Such an activity places higher demands on the knee, almost similar to those found during high-level sports. **Type of Study:** Case control series study. **Methods:** We assessed 11 patients who had undergone ACL reconstruction with the same arthroscopic technique using a bone–patellar tendon–bone graft, 11 ACL-deficient subjects who had sustained the injury more than 1 year prior to testing, and 11 matched controls. Kinematic data were collected (50 Hz) with a 6-camera optoelectronic system while the subjects performed the following task: they jumped off a 40-cm platform and landed on the ground. After foot contact, the subjects were instructed to pivot at 90° and walk away from the platform. The evaluation period was identified from initial foot contact with the ground with both legs, included the pivoting of the ipsilateral leg, and was completed on touchdown of the contralateral leg. **Results:** Significant differences were found between the reconstructed leg of the ACL group and the healthy control, and between the deficient leg of the ACL-deficient group and the healthy control. We also found no significant differences between the deficient leg of the ACL-deficient group and the reconstructed leg of the ACL reconstructed group. **Conclusions:** It was concluded that, under high-stress activities, ACL reconstruction may not restore tibial rotation to the previous physiological level, even though anterior tibial translation is restored. Future research on ACL reconstruction should focus on the development of new surgical procedures and/or grafts to address this problem. **Level of Evidence:** Level III. **Key Words:** Tibial rotation—ACL reconstruction—Gait analysis—Pivoting—Landing—Knee rotational instability—Anatomic tunnel placement.

The success level of an anterior cruciate ligament (ACL) reconstruction is often assessed in terms of anterior tibial translation, i.e., by use of the KT-

1000 arthrometer.¹⁻⁴ However, such measures cannot assure that knee joint function is restored dynamically.⁵⁻⁸ Furthermore, such measures do not provide us with information of the level of rotational stability achieved after an ACL reconstruction. In the last few years, there has been considerable research done in vitro on the effectiveness of ACL reconstructed knees in resisting both anterior and rotational loads.⁹⁻¹² These cadaveric studies reported that the current reconstruction procedures using bone–patellar tendon–bone (BPTB) or multiple (semitendinosus and gracilis) tendon grafts are successful in limiting anterior tibial translation but fail to restore rotational stability.¹⁰⁻¹² However, there is limited research that examines rotational stability during in vivo activities. Using optoelectronic systems, Andriacchi and Dyrby¹³ and Georgoulis et al.¹⁴ reported increased tibial rotation in

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Supported by the General Secretariat for Research and Technology of the Greek Ministry of Development, and the European Social Fund of European Union.

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0749-8063/05/2111-4317\$30.00/0
doi:10.1016/j.arthro.2005.08.032*

ACL-deficient patients during a low-demand activity such as walking. Regarding ACL reconstruction, a radiostereometric study by Brandsson et al.¹⁵ reported that tibial rotation did not change significantly during a step-up activity when compared with preoperative measurements. However, it is unknown if tibial rotation is restored in patients after ACL reconstruction when performing more stressful activities than walking and simple stepping up.

In this study, we investigated *in vivo* the maximum range-of-motion of tibial rotation during a high-demand activity that required landing from a jump and subsequently pivoting. Landing from a jump is a task that places higher demands on the knee than walking or simple stepping up.¹⁶ It is considered by many researchers^{17,18} to represent demands that are more comparable to those found during high-level sports. In the present study, this stressful activity was followed by subsequent pivoting to create rotational loads on the knee. The application of such loads on the knee can provide us with additional insights into the functional recovery after an ACL reconstruction. Therefore, the purpose of our study was to determine whether in a high-demand activity like landing and subsequent pivoting, tibial rotation would be restored after ACL reconstruction. We hypothesized that tibial rotation in ACL BPTB reconstructed knees will be larger when compared with contralateral intact knees. In addition, we hypothesized that no significant differences would exist in terms of tibial rotation between ACL-deficient knees and the ACL BPTB reconstructed knees.

METHODS

Subjects

Three groups were included in the study. Eleven male subjects (mean age, 27 ± 4 years; mean weight, 73 ± 7 kg; mean height, 1.78 ± 0.06 m) with ACL-reconstructed knees and 11 male subjects (mean age, 29 ± 5 years; mean weight, 76 ± 7 kg; mean height, 1.76 ± 0.09 m) with an ACL-deficient knee were evaluated. The ACL-deficient subjects had sustained an isolated unilateral ACL injury confirmed by magnetic resonance imaging and clinical evaluation by an orthopaedic surgeon. Their rupture was also confirmed arthroscopically later when they underwent ACL reconstruction. They had sustained the injury more than 1 year before testing (mean time, 24 ± 11 months). During this time, they all had a successful rehabilitation and they had resumed sports-related ac-

tivities using a knee brace. In addition, 11 healthy gender-, age-, height-, and mass-matched subjects who had never suffered of any kind of orthopaedic or neurologic condition also volunteered for the control group (mean age, 28 ± 4 yrs; mean mass, 74 ± 5 kg; mean height, 1.74 ± 0.04 m). The ACL-reconstructed subjects were tested 1 year, on average, after the ACL reconstruction.

In some instances, meniscal damage had also been present at the time of injury. In all cases, the level of involved meniscus damage was less than 25%. Subjects with more than 25% of meniscus damage, posterior cruciate or collateral ligament injury, symptomatic anterior knee pain, or objective instability at the latest follow-up examination (a positive pivot-shift test result, positive Lachman test result, and arthrometer side-to-side differences of >3 mm) were excluded from the study.¹⁹ All patients underwent the same rehabilitation protocol, including full range of motion training. Return to sports-related activities was permitted 24 weeks after reconstruction, provided that the patients had regained functional strength and stability. At the time of data collection, no clinical evidence of knee pain was found in the ACL-reconstructed subjects and all of them had resumed their daily living activities. All subjects' physicians were in agreement with the testing protocol and all subjects gave informed consent in accordance with university policies to participate in the study.

Before any data collection, a clinical evaluation was performed in all subjects. This evaluation was conducted for all subjects by the same clinician. For the ACL-reconstructed subjects, negative Lachman and pivot-shift test results indicated that the knee joint stability was regained. During this evaluation, both Tegner and Lysholm scores were obtained.²⁰ In addition, anterior tibial translation was evaluated using the KT-1000 knee arthrometer (MEDmetric, San Diego, CA) for both ACL-reconstructed, ACL-deficient, and healthy subjects.^{1,21} The measurements were performed using 134-N posterior–anterior external force at the tibia, as well as maximum posterior–anterior external force until heel clearance. Repeated anterior tractions were performed until a constant reading on the dial was registered.

Surgical Technique

All the subjects were operated on by the same orthopaedic surgeon (A.D.G.). They underwent arthroscopic-assisted ACL reconstruction using an autologous BPTB graft at an average of 11 months

(range, 2 to 22 months) after the injury. The drilling of the femoral tunnel was performed arthroscopically through the anteromedial approach, with the knee joint at 120° of flexion. The anteromedial approach increased our capability to place the graft in a more horizontal position, about 10 to 11 o'clock. This was not always easy using the transtibial technique, in which the drill is restricted by the axis of the tibial tunnel. The tibial tunnel was made in the center of the ACL footprint, avoiding the impingement in knee extension. The placement of the graft in the tunnel was with the cortical side of the bone plug and close to the over-the-top position. In the tibia, we turned the graft 90° , so the ligament was in a more anatomic placement in the tibial tunnel.^{22,23}

Fixation of the graft was performed with bioabsorbable interference screws on both the femur and tibia. Interference screws were inserted on the bone side of the bone plugs. After fixation to the femur, maximal tension was performed manually by pulling the graft from its tibial edge. Holding the knee in 20° of flexion and holding the graft tensioned as we described, we proceeded to the fixation on the tibia with the second interference screw. Radiographic assessment of the examined ACL-reconstructed knees indicated a femoral tunnel placement between the 10 and 11 o'clock positions. We preferred a more horizontal graft placement (close to the 10 o'clock position) because such a position is anatomically closer to the femoral insertion of the posterolateral bundle and, theoretically, should improve the rotatory stability of the reconstructed knee.^{10-12,24}

Instrumentation Procedures

A 6-camera optoelectronic system (Peak Performance Technologies, Englewood, CO) sampling at 50 Hz was used to capture the movements of 15 reflective markers placed on the selected bony landmarks of the lower limbs and the pelvis (Fig 1), using the model described by Davis et al.²⁵ All subjects were given enough time (10 minutes) to warm up and familiarize themselves with jumping from a 40-cm high platform and land on the ground with the same strategy each time.

Subjects were instructed to fold their arms across their chest and then jump from the platform and land as naturally as possible with both feet on the ground. Following foot contact, the subjects were instructed to pivot (externally rotate) on the right or left (ipsilateral) leg at 90° and walk away from the

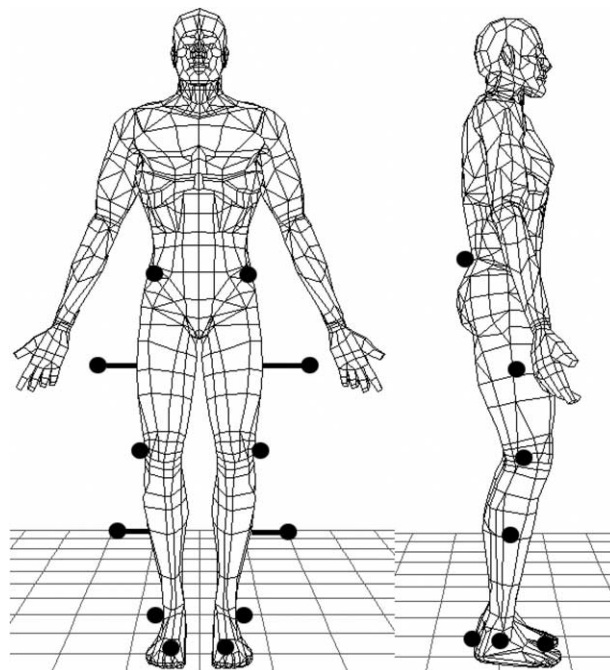


FIGURE 1. The retroreflective marker set required for the motion data collection tests (model as described by Davis et al.²⁵). This is a minimal configuration for a 3-dimensional analysis of gait.

platform. While pivoting, the contralateral leg was swinging around the body and the trunk was oriented perpendicularly to the platform. The subjects then continued to walk for at least 5 consecutive strides. None of the subjects reported any pain or discomfort during the experiment. Each subject performed at least 5 trials for both legs. Data collection was initiated at the top of the platform and was concluded as the subject completed pivoting. In the present study, the period that we evaluated was identified from initial foot contact with the ground with both legs, included the pivoting of the ipsilateral leg, and was completed on touchdown of the contralateral leg.

Furthermore, to validate our procedures and minimize errors reported in the literature^{26,27} regarding video capture of external skin markers, an additional trial was recorded with the subject in the anatomic position. The data from this trial were used as reference for the calculation of the anatomic angles. The subjects were instructed to stand in the anatomic position within a purpose-built mould with their feet parallel and 15 cm apart. This procedure allowed for correction of subtle misalignment of the markers that define the local coordinate system and provided a

definition of zero degrees for all segmental movements in all planes.

Data Analysis and Reduction

Marker identification and angular displacement calculations were conducted using the Peak Performance software (Motus 5; Peak Performance Technologies) and Matlab (Mathworks, Natick, MA). Spot checking calibration assessment revealed a maximum 3-dimensional standard deviation error in marker reconstruction of 0.303 mm. All data were smoothed using the cross-validated quintic spline.²⁸ Anthropometric measurements were combined with 3-dimensional marker data from the anatomic position trial to provide positions of the joint centers and define anatomic axes of joint rotations.²⁵ The position of the reflective markers during the movement provided the 3-dimensional segmental angles. The angular displacement of the tibial rotation was retained and the maximum and minimum points during the evaluation period were identified. These 2 points were subtracted to acquire the maximum range of motion for tibial rotation.

Statistical Analysis

Based on our hypothesis, the dependent variable examined in the present study was the maximum range of motion of tibial rotation during the identified evaluation period. A dependent *t* test between the left and right sides within the control group revealed no significant differences ($P = .64$) for this variable, and thus the left side was selected as the representative for the control group. Subsequently, a 1-way analysis of variance was performed between the 3 groups (ACL-deficient, ACL-reconstructed, and control) for the dependent variable with a Tukey test for post hoc comparisons. In addition, dependent *t* tests were used to compare the ACL-reconstructed leg with the contralateral intact leg within the ACL-reconstructed group, and the ACL-deficient leg with the contralateral intact leg within the ACL-deficient group. The level of significance was set at $P = 0.01$.

RESULTS

All subjects in the ACL-reconstructed group were satisfied with the outcome of surgery and resumed their pre-injury level of sports participation. Only 1 patient described mild limitations, especially after prolonged exercise. In addition, for the ACL-reconstructed subjects, the median Lysholm score was 91 (range, 85-96) and the Tegner score was 8 (range, 8-9)

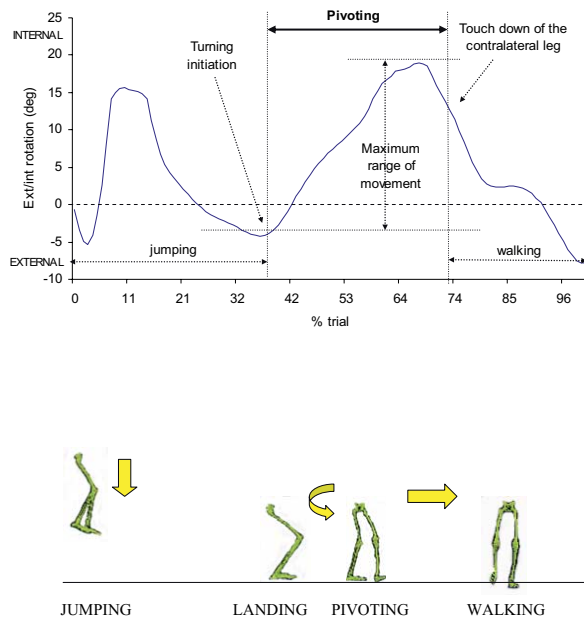


FIGURE 2. A tibial internal/external rotation curve from the entire period that kinematic data were collected. The curve is from an ACL-deficient subject, accompanied by a stick figure describing the task. Our study focus was the pivoting period, which is indicated on the curve. Within this pivoting period, we identified the maximum range of motion that is the difference between the maximum and minimum tibial rotation. The maximum range of motion, which is the dependent variable of our study, is also indicated in the graph.

after surgery. For the healthy controls, the median Lysholm score was 97 (range, 95-98) and the Tegner score was 8 (range, 8-9), and for the ACL-deficient subjects, the median Lysholm score was 69 (range, 50-81) and the Tegner score was 4 (range, 3-6). All the reconstructed subjects regained objective stability, with negative Lachman and pivot shift test results. KT-1000 results revealed that the mean difference between the anterior tibial translation of the reconstructed and intact sides in the ACL-reconstructed group was 1.5 mm (range, 1 to 2 mm) for the 134-N test and 1.7 mm (range, 1 to 2 mm) for the maximum manual test, and between the deficient and intact sides for the deficient group it was 3.5 mm (range, 3 to 7 mm) and 4.5 mm (range, 3 to 9 mm), respectively.

Typical curves of the tibial internal-external rotation during the evaluation period from a representative ACL-deficient and a healthy subject are shown in Figs 2 and 3, respectively. The calculated range of movement that was used as the dependent variable is also identified, along with time events for both the ipsilateral and the contralateral legs. No significant differences were found between the ACL-deficient knee and

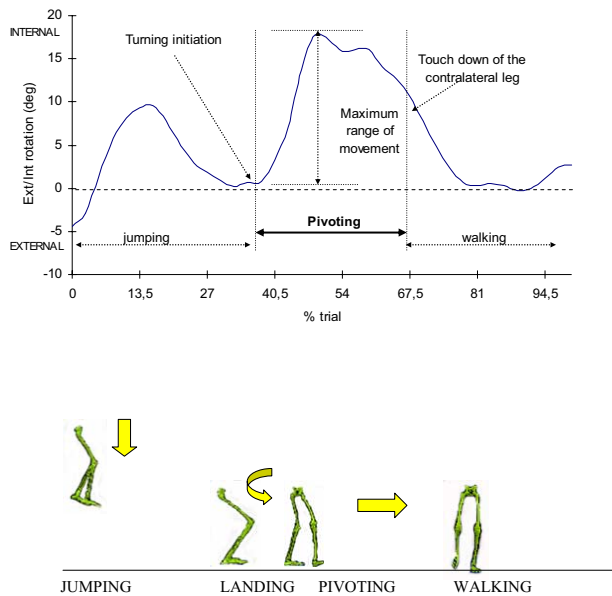


FIGURE 3. This figure is similar to Fig 2; however, it is from a representative healthy subject and is accompanied by a stick figure describing the task. Our study focus was the pivoting period, which is indicated on the curve. Within this pivoting period, we identified the maximum range of motion that is the difference between the maximum and minimum tibial rotation. The maximum range of motion, which is the dependent variable of our study, is also indicated in the graph. When comparing Figs 2 and 3, we can see the larger range of motion which is present in the ACL-deficient subject.

the ACL-reconstructed knee (statistical power, 0.83). Significant differences were found between the control knee and the ACL-reconstructed knee, as well as between the control knee and the ACL-deficient knee. Significant differences were also identified within the ACL-deficient group and between the deficient and intact leg. Lastly, significant differences were identified with the ACL-reconstructed group and between the reconstructed and intact leg (Fig 4).

DISCUSSION

In the present study, we investigated in vivo dynamic knee rotational stability in ACL-reconstructed and ACL-deficient patients during the high-demand activity of immediate pivoting after landing. In this activity, an anterior, followed by a rotational, load was applied at the knee joint. We hypothesized that tibial rotation of an ACL-reconstructed knee will be larger when compared with the contralateral intact knee, in patients with an ACL BPTB reconstruction. In addition, we hypothesized that no significant differences exist in terms of tibial rotation between the

ACL-deficient knee and the ACL-reconstructed knee. The results supported our hypotheses. Therefore, excessive tibial rotation remains 1 year after ACL reconstruction during high-demand activities.

These findings also provide support to previous work^{10-15,29} that found that ACL reconstruction does not fully restore ACL function. In a study from our laboratory,²⁹ we also found that regardless of the fact that anterior tibial translation is restored to the level of normative values, functional dynamic knee stability is not improved in terms of tibial rotation. In that study, our results indicated the existence of increased tibial rotation in the ACL-reconstructed leg when compared with the intact leg of the ACL group. The activity we examined was descending and pivoting, an activity that also places high rotational loads to the knee joint. In that study, the mean value for maximum range of motion of the tibial internal–external rotation was reported to be 22.60° for the reconstructed leg of the ACL group during the pivoting period.²⁹ This result is in close agreement with the tibial rotational values reported in the present study (Fig 4). However, during low-demand activities such as walking, we have found that tibial rotation could be restored to the normative values level after an ACL reconstruction.¹⁴

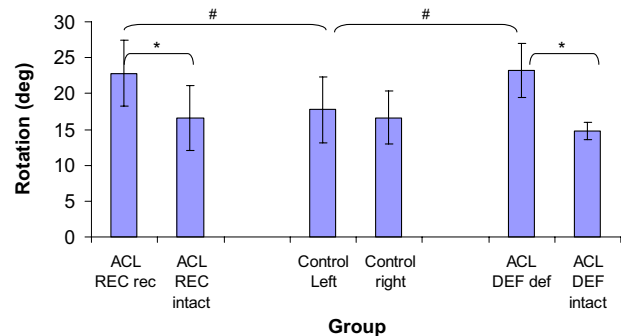


FIGURE 4. Bar graph showing the group mean and SD values for maximum range of motion of the tibial internal-external rotation during the pivoting period. It is clearly shown that the bars associated with the ACL-reconstructed and ACL-deficient legs of the corresponding groups are much higher than all the other bars. The other bars have similar heights. These graphic differences are also shown statistically. Specifically, asterisks (*) indicate a significant difference between the intact and reconstructed sides in the ACL-reconstructed group ($P < .01$) and a significant difference between the intact and deficient sides in the ACL-deficient group, whereas pound signs (#) indicate a significant difference between the control knee and the ACL-reconstructed knee, and a significant difference between the control knee and the ACL-deficient knee. (ACL REC rec, ACL-reconstructed group reconstructed leg; ACL REC intact, ACL-reconstructed group intact leg; Control Left, control group left leg; Control Right, control group right leg; ACL DEF def, ACL-deficient group deficient leg; ACL DEF intact, ACL-deficient group intact leg).

This conclusion is also in agreement with that of the study by Bush-Joseph et al.³⁰ in which the functional outcome of patients who had undergone ACL reconstruction using an autologous patellar tendon technique was assessed dynamically. They noticed that with higher demanding activities like pivoting or jogging, persistent gait adaptations were present, whereas with low-demand activities no abnormality was displayed.

In vitro research¹⁰⁻¹² has also indicated that tibial translation is restored after ACL reconstruction, but tibial rotation is not improved. Woo et al.¹² considered as a possible explanation for these findings the fact that the current practice of ACL reconstruction places the graft in the central part of the tibia and the femur, resulting in inadequate resistive ability to rotational forces. It is known that ACL reconstruction does not re-establish the anatomy of the ACL. The ACL has a 3-dimensional structure consisting of collagen fibrils that can respond differently to various torsional stresses to the knee. Graft tissues consisting of a single band are structurally different from the normal ACL morphology. The graft tissue gradually changes to become an apparently normal ACL through a certain remodeling process over a long period,^{24,31,32} but it seems very unlikely that the graft will regain the normal 3-dimensional structure with normal mechanical properties.

The 2 ACL bundles exhibit different tension patterns during knee motion, and recent studies^{6,10,11,24,32} have shown that there is an uneven distribution of forces between them in response to externally applied loads. It has become popular recently to place the femoral bone tunnel at the so-called 11 o'clock position for the right knee to replicate the origin of the anteromedial bundle.^{11,12} However, when the knee is subjected to an anterior tibial load and the joint is near full extension, two thirds of the total force in the ACL is carried out by the posterolateral bundle. Because ACL anatomic complexity cannot be reproduced with current ACL single-bundle reconstruction procedures, tibial rotation does not seem to become completely restored.

Theoretically, a 2-bundle reconstruction has several advantages over a single-bundle reconstruction with respect to regaining a structure that morphologically and functionally more closely resembles a normal ACL. Muneta et al.³² reported their clinical results after a 2-year follow-up with a 2-bundle procedure in 54 patients and demonstrated good anterior stability with no serious complications. This technique, however, has not been investigated dynamically and future

in vivo and in vitro research using external loading conditions should be performed to determine the advantages of the 2-bundle anatomic reconstruction.

The results of the present study might also explain why the knee is still at risk of future deterioration. It is possible that the excessive tibial rotation of an ACL-reconstructed knee could degenerate the soft tissues, resulting in further pathologies such as osteoarthritis.¹⁰ Theoretically, alterations in the rotational movements of the articulating bones of the knee could result in the applications of loads at areas of the cartilage and are not commonly loaded in a healthy knee.³³ Because of lack of sufficient thickness, these areas may not be able to withstand the newly introduced loading and the end result could be knee osteoarthritis.

A limitation of the present study deals with the known drawbacks of gait analysis,^{26,27} and especially the movement of skin markers and their ability to predict bone movements. However, our results should be viewed in light of the general gait analysis limitations; gait analysis is currently widely accepted and is considered as a well-established and reliable method.^{34,35} Furthermore, it should be mentioned that our primary outcome measure (range of motion of tibial rotation) is not a clinically relevant short-term outcome measure such as the Lysholm score or the KT-1000 score. However, our in vivo model and our measure can be used for the assessment of the success of surgical procedures and rehabilitation protocols with regard to rotational knee stability during dynamic activities.

CONCLUSIONS

We found that the current ACL reconstruction technique using the BPTB graft, although it manages to limit anterior tibial translation, is inadequate to restore excessive tibial rotation during a high-demand activity such as landing and subsequent pivoting. We hypothesized that neuromuscular adaptations in the reconstructed knee could finally restore normal levels of tibial rotation 1 year postoperatively. The results, though, refuted our hypothesis. Longer-term follow-up studies need to be performed that would focus on the effects of ACL reconstruction on the restoration of tibial rotation to preinjury levels.

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