Journal Articles   Department of Biomechanics

2007

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Effectiveness of Reconstruction of the Anterior Cruciate Ligament With Quadrupled Hamstrings and Bone-Patellar Tendon-Bone Autografts: An In Vivo Study Comparing Tibial Internal-External Rotation

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Background: The 2 most frequently used autografts for anterior cruciate ligament reconstruction are the bone-patellar tendon- bone and the quadrupled hamstrings tendon.

Hypothesis: Hamstring tendon graft is superior to patellar tendon graft in restoring tibial rotation during highly demanding activities because of its superiority in strength and linear stiffness and because it is closer morphologically to the anatomy of the natural anterior cruciate ligament.

Study Design: Case control study; Level of evidence, 3.

Methods: Eleven patients with patellar tendon graft anterior cruciate ligament reconstruction, 11 patients with hamstring tendon graft anterior cruciate ligament reconstruction, and 11 controls were assessed. Kinematic data were collected (50 Hz) with a 6-camera optoelectronic system while the subjects descended stairs and, immediately after, pivoted on their landing leg. The dependent variable examined was the tibial internal-external rotation during pivoting. All patients in both groups were also assessed clinically and with the use of a KT-1000 arthrometer to evaluate anterior tibial translation.

Results: The results demonstrated that reconstructions with either graft successfully restored anterior tibial translation. However, both anterior cruciate ligament reconstruction groups had significantly increased tibial rotation when compared with the controls, whereas no differences were found between the 2 reconstructed groups.

Conclusion: The 2 most frequently used autografts for anterior cruciate ligament reconstruction cannot restore tibial rotation to normal levels.

Clinical Relevance: New surgical techniques are needed that can better approximate the actual anatomy and function of the anterior cruciate ligament.

The 2 most frequently used autografts for ACL reconstruction are the bone-patellar tendon-bone (BPTB) and the quadrupled hamstrings tendon (semitendinosus and gracilis; ST/G). In the past, the BPTB graft had been considered as the gold standard. However, in the early 1990s the use of the ST/G graft increased in popularity and was advocated by many surgeons. One of the reasons for this change was the increased morbidity with the BPTB graft attributable to extension loss and subsequent kneeling problems.[29] In addition, the ST/G graft seems to be stronger and to have a linear stiffness closer to the normal ACL than the BPTB.[12,18,24,41] However, several clinical trials,[1,4,5,13,15,16,26,28,31,37,44] as well as reviews and metaanalyses,[17,45,46,53] showed that neither graft is better than the other. It has been found that both grafts have their advantages and disadvantages. This prohibits a general recommendation for the orthopaedic community regarding the use of one graft or the other.

It is possible that this problem is the result of the absence of carefully designed in vivo experimental work to address this problem in detail. There is only 1 such study, in which Webster et al[49] attempted to compare the 2 grafts in vivo. In this study, reconstructed patients were evaluated while per- forming activities of daily living (ie, walking). It was found that both grafts can affect gait patterns regarding knee flexion and extension moments. Movement patterns in other planes were not evaluated, and, specifically, the effect of graft type on tibial rotation was not assessed. However, evaluating tibial rotation is quite important because it has been found recently, in an in vitro study by Woo et al,[52] that even though the 2 grafts are successful in limiting anterior tibial translation, neither is effective in reducing tibial rotation. It has been found that an ACL reconstruction using the BPTB graft can restore tibial rotation during low-demand activities such as walking.[21] However, other in vivo studies[39,40] that evaluated higher demand activities showed that the BPTB graft could not restore excessive tibial rotation. It is currently unknown if this is also the case with the ST/G graft. Therefore, it would be of great interest to compare in vivo the 2 grafts regarding their effectiveness of restoring tibial rotation, to identify which graft is superior.

The purpose of the present study was to identify in vivo the effectiveness of the 2 grafts in restoring tibial rotation to normal levels. We hypothesized that this study would verify previous findings[39,40] that a BPTB graft does not restore tibial rotation during higher demand activities (eg, pivoting), which are common during daily living. We also hypothesized that the ST/G graft would be able to restore tibial rotation during similar activities because of its superiority in strength and linear stiffness[12,18,24,41] and because it is closer morphologically to the anatomy of the natural ACL.[18]

MATERIALS AND METHODS

Subjects

Three groups were evaluated. Eleven male patients, ACL reconstructed with a quadrupled ST/G graft (mean age 27 ± 9 years, mean mass 78 ± 12 kg, mean height 1.75 ± 0.1 m) and 11 male patients ACL reconstructed with a BPTB graft (mean age 28 ± 4 years, mean mass 75 ± 6 kg, mean height

1.79 ± 0.05 m) formed the 2 experimental groups. It is a significant advantage of our study that the 2 groups were similar in age, mass, and height. Eleven healthy gender-, age-, height-, and mass-matched subjects who had never suffered any kind of orthopaedic or neurological condition (mean age 29 ± 5 years, mean mass 76 ± 7 kg, mean height 1.76 ± 0.09 m) formed the control group. The subjects with the ST/G graft were tested 9 months, on average (range 9-10 months), after the ACL reconstruction, whereas the subjects with the BPTB graft were tested 1 year, on average (range 11-12 months), after the ACL reconstruction.

All our patients were randomly assigned to the 2 groups (BPTB and ST/G) unless there was a reason for specific graft selection. This was the case for only 1 subject; his occupation included kneeling, so we avoided a BPTB reconstruction. All patients with concomitant injuries (eg, chondral lesions, lateral collateral ligament injuries, or meniscal injuries in which a meniscectomy or a suture of the meniscus was performed) were excluded from the study. In addition, all patients with symptomatic anterior knee pain or objective instability at the latest follow-up examination (positive pivot-shift test results, positive Lachman test results, and arthrometer side-to-side differences of more than 3 mm) were also excluded from our study. Thus, by using strict selection criteria in the 2 reconstructed groups (examined via an MRI and arthroscopically by the senior author), we ensured that any observed changes in tibial rotation values were the result of the isolated rupture of the "successfully" reconstructed ACL.

All reconstructed patients underwent the same rehabilitation protocol, starting from the first postoperative day, with the use of continuous passive motion devices until they were discharged from the hospital. Patients were per- mitted to bear weight from the second postoperative day as tolerated and were permitted to fully bear weight by the third postoperative week. Active exercises also were started during the patients' stay in hospital and were followed by a standardized accelerated rehabilitation protocol. Return to sports-related activities was permitted 24 weeks after reconstruction for both groups provided that the patients had regained full functional strength and stability as measured with clinical (Lachman and pivot-shift tests, KT-1000 arthrometer) and isokinetic strength tests. At the time of data collection, no clinical evidence of knee pain and effusion was found in the subjects with ACL reconstruction. All of them had resumed their daily living functions and their sports activities as well. All subjects agreed with the testing protocol and gave their consent in accordance with university policies.

Before any data collection, a clinical evaluation was performed in all subjects by the same clinician. During this evaluation, Tegner and Lysholm scores were also obtained. In

addition, anterior tibial translation was evaluated using the KT-1000 knee arthrometer (MEDmetric Corp, San Diego, Calif) for both ACL-reconstructed groups and the healthy controls.[47] 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 per- formed until a constant reading was registered on the dial.

Surgical Reconstruction With an ST/G Graft

All the subjects were operated by the same orthopaedic surgeon (senior author). The procedure was performed with the aid of an arthroscopic leg holder that permitted full knee flexion-extension. After a 4- to 5-cm longitudinal skin incision over the pes anserinus, a typical harvesting of both the semitendinosus and the gracilis tendons was per- formed in all patients. First, the tibial tunnel was drilled with the knee in 90° of flexion. The entry point was selected close to the anterior border of the medial collateral ligament. The center of the tibial tunnel in the intra-articular region was slightly medial to the center of the intercondylar region on a line joining the inner edge of the anterior horn of the lateral meniscus and the medial tibial spine. With the knee joint hyperextended, we checked whether this point was at a correct position, so that roof impingement of the graft was avoided. Subsequently, the femoral tunnel was placed through the anteromedial portal in a 5-mm offset at the over-the-top position. Then, the femoral guide pin was inserted at the 11-o'clock position (for a right knee) or at the 1-o'clock position (for a left knee). This location was verified by radiographic evidence. Specifically, the patients had an immediate postoperative radiograph with additional radiographs obtained at 3, 6, and 9 months postoperatively.

A 4.5-mm cannulated reamer was used to drill the total femoral cortex, and the femoral tunnel was then measured. Usually, the length of the inserted graft was 2 to 2.5 cm in the femoral tunnel, and the drilling took place 5 to 10 mm deeper than the graft insertion length to allow the "turning radius" of the EndoButton (usual EndoButton length 15-20 mm) (Smith & Nephew Endoscopy, Andover, Mass). The final step was the graft passage through the tunnels and the graft fixation. The graft was secured at the lateral cortex of the distal femur with the EndoButton and fixed at the tibial tunnel with a bioabsorbable screw (usually 1 mm wider than the tunnel diameter), which was secured with the knee flexed at 30°.[25] Then the graft was inspected in both full flexion and full extension to exclude graft impingement both at the notch and at the posterior cruciate ligament. A notch- plasty was not performed in any of our cases.

Surgical Reconstruction With a BPTB Graft

All the subjects in this group were also operated by the same orthopaedic surgeon (senior author). First, the tibial tunnel was drilled. For the tibial tunnel, the anterior horn of the lateral meniscus was used as an arthroscopic reference[27] and, thus, the tunnel was located just behind the center of the ACL footprint. The drilling of the femoral tunnel was performed arthroscopically through the anteromedial approach, having the knee joint in 120° of flexion and about the 11-o'clock position (for a right knee) or the 1-o'clock position (for a left knee). This location was verified by radiographic evidence. Specifically,

the patients had an immediate postoperative radiograph, with additional radiographs obtained at 3, 6, and 9 months postoperatively. 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 anatomical placement in the tibial tunnel. 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 the fixation to the femur, maximal tension was performed manually by pulling the graft from its tibial edge. Holding the knee in 30° of flexion,[25] and holding the graft tensioned as we described, we proceeded to the fixation on the tibia with the second interference screw.

Instrumentation: Procedures

A 6-camera optoelectronic system (Peak Performance Technologies, Inc, Englewood, Colo) 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 using the model described by Davis et al.[14] All subjects were given enough time (10 minutes) to warm up and familiarize themselves with ascending-descending on a stairway that included 3 consecutive steps and subsequent pivoting. The stairway was constructed according to guidelines provided by Andriacchi et al.[2]

The subjects were asked to descend the 3 steps at their own pace. The descending period was concluded on initial foot contact with the ground. After foot contact, the sub- jects were instructed to immediately pivot (externally rotate) on the landing (ipsilateral) leg at 90° and walk away from the stairway. While pivoting, the contralateral leg was swinging around the body (as it was coming down from the stairway) and the trunk was oriented perpendicularly to the stairway. None of the subjects reported pain or discomfort during the experiment. The subjects then continued to walk for at least 5 consecutive strides. The pivoting period was identified from initial foot contact with the ground of the ipsilateral leg until touchdown of the contralateral leg (Figure 1). Each subject performed at least 6 trials for each leg. Data collection was initiated at the top of the stairway and included the descending period, the subsequent pivoting, and the five walking strides.

To ensure that pivoting was always conducted in the same fashion in all trials and for all subjects, we always had the same examiner (SR) next to the subjects advising them how to perform the specific movement correctly and observing if they followed the instructions while carrying out the task. We also had a video camera recording our patients while performing the task and another examiner (CM) simultaneously checking the monitor to observe if the pivoting was performed correctly in all subjects. If the pivot was performed incorrectly, the subjects had to repeat the trial until it was performed correctly. We placed white horizontal and vertical lines on the floor clearly showing to the subjects where to step down from the stairs and pivot away from the stairway. Furthermore, to validate our procedures and minimize errors reported in the literature[10,38] regarding video capture of external skin markers, an additional trial was recorded with the subject in the anatomical position, which was used as the reference to

calculate the anatomical angles. The subjects were instructed to stand in the anatomical position within a purpose-build mold with their feet parallel and 15 cm apart. This calibration procedure allowed for proper definition of the local coordinate system and provided a definition of 0° for all segmental movements in all planes.
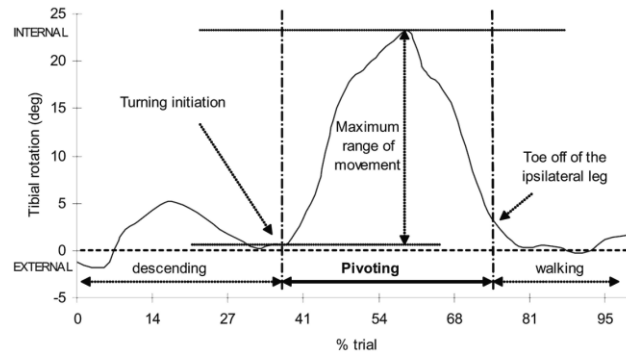

Figure 1. A typical tibial internal/external rotation curve during the period under study for a full "stride" from a representative ACL-reconstructed subject with a semitendinosus and gracilis graft. The difference between the maximum and the minimum tibial rotation during the pivoting period is indicated. This difference was used as the dependent variable in this study.

Data Analysis and Reduction

Marker identification and angular displacement calculations were conducted using Peak Performance software (Motus version 4.3.3; Peak Performance Technologies, Inc, Englewood, Colo). 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.[50] The angles measured were from fixed reference frames embedded in the femur and tibia. The sequence of rotation that we used was flexion-extension, abduction-adduction, and external-internal rotation. Anthropometric measurements were combined with 3-dimensional marker data from the anatomical position trial to provide positions of the joint centers and define anatomical axes of joint rotations.[14] 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. Group means were calculated for both legs of all the groups for this variable.

Statistical Analysis

On the basis of 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 paired *t* test between the left and right sides within the control group revealed no significant differences ($P < .05$) for this variable and, thus, the left side was selected as the representative for the control group. Subsequently, a 1-way analysis of

variance (ANOVA) was performed on the group means to identify if differences exist for the dependent variable between the ACL-reconstructed leg with the ST/G graft, the ACL-reconstructed leg with the BPTB graft, and the control healthy leg. *Post hoc* analysis was performed if significant differences were identified using independent *t* tests. Paired *t* tests were performed within the 2 reconstructed groups to compare the ACL-reconstructed leg with the intact. Last, a 1-way ANOVA was performed on the group means to identify if any differences exist between the intact legs of the 2 reconstructed groups and the control healthy leg. The level of significance was set at α = .05.

RESULTS

All subjects in both ACL-reconstructed groups were satisfied with the outcome of the surgery and resumed their preinjury level of sports participation. Negative Lachman and pivot-shift tests indicated that the knee joint stability was regained clinically for all ACL-reconstructed subjects. For the subjects with ST/G graft ACL reconstruction, the median Lysholm score was 92 (range 87-95) and the Tegner score was 7 (range 6-8) at the time of examination, whereas for the subjects with BPTB ACL reconstruction, the median Lysholm score was 94 (range 90-97) and the Tegner score was 8 (range 7-8). For the healthy controls, the median Lysholm score was 98 (range 96-100) and the Tegner score was 8 (range 7-9).

The KT-1000 arthrometer results revealed that the mean difference between the anterior tibial translation of the reconstructed and intact sides in the ST/G group was 1.1 mm (range 0.5-2 mm) for the 134-N test and 1.3 mm (range 1-2 mm) for the maximum manual test. The KT- 1000 arthrometer results for the BPTB group were 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. No significant differences were found for the KT-1000 arthrometer results between the groups.

The results for the dependent variable examined in the present study are summarized in Figure 2. The 1-way ANOVA that was performed between the 3 groups (ST/ G reconstructed leg, BPTB-reconstructed leg, and healthy control) for the dependent variable showed the existence of significant differences among the groups (F = 8.622; *P* =.001). The *post hoc* comparisons revealed significant differences between the control knee and the ACL-reconstructed knee with an ST/G graft (*P* = .017) as well as between the control knee and the ACL-reconstructed knee with a BPTB graft (*P* = .004). No significant differences were found between the ACL-reconstructed knee with an ST/G graft and the ACL-reconstructed knee with a BPTB graft (*P* =.167). The paired *t* tests also revealed significant differences between the reconstructed and the intact knee in the ACL-reconstructed group with the ST/G graft (*P* = .002) as well as between the reconstructed and the intact knee in the ACL-reconstructed group with the BPTB graft (*P* =.003). No significant differences were found between the uninjured legs of the 2 reconstructed groups (BPTB and ST/G) and the control healthy leg (F = 1.204; *P* = .31).

A paired *t* test between the left and right legs within the control group revealed no significant differences (*P* < .05) for the dependent variable, and thus the left leg was selected as the representative for the control group.
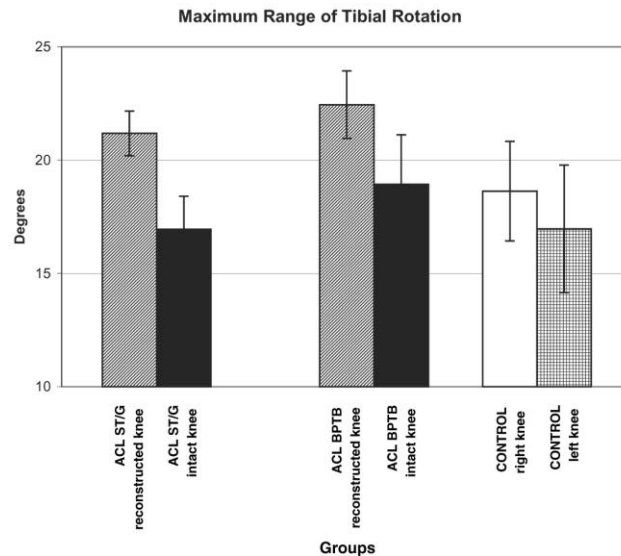

Figure 2. Group mean and SD values for maximum range of motion of the tibial rotation during the pivoting period. It is clearly shown that the bars associated with the ACL- reconstructed legs for both grafts are much higher than all the other bars. The other bars have similar heights. These graphical differences are also shown statistically. BPTB, bone-patellar tendon-bone; ST/G, semitendinous and gracilis.

However, because the right left of the control group revealed slightly larger results (Figure 2), and to be certain regarding the accuracy of the outcome of our statistical analysis, we also conducted our statistical analysis by using the right leg as the control side, and we observed that either leg produced the exact same results.

DISCUSSION

We evaluated in vivo the effectiveness of the BPTB and the ST/G grafts in restoring excessive tibial rotation generated from an ACL injury. We used motion analysis to answer this problem, and our subjects performed an activity (descending and subsequently pivoting) that placed both anteriorly directed and rotational loads at the knee. We hypothesized that this study would verify previous findings[39,40] that tibial rotation using the BPTB graft is not restored during high-demand activities, such as immediate pivoting after descending stairs. However, we also hypothesized that the ST/G graft would be able to restore tibial rotation during similar activities, because of its superiority in strength and linear stiffness[12,18,24,41] and because it is closer morphologically to the anatomy of the natural ACL.[18] Our results supported the first hypothesis but

refuted the second. We found that neither graft is able to restore tibial rotation to normal levels. Thus, tibial rotation remained abnormal and there is no superiority between the 2 grafts regarding restoration of tibial rotation. This conclusion gives further support to the in vitro findings of Woo et al[52] that both grafts can successfully limit anterior tibial translation (as identified from our clinical tests), but they are not effective in reducing tibial rotation.

Our results are also in agreement with recent dynamic radiostereometric analysis technique (dRSA)[7,48] and MRI[32] studies. Brandsson et al,[7] using a dRSA system, found that 1 year after ACL reconstruction with a BPTB graft, tibial rotation was not significantly different compared with the preoperative measurements. In addition, Tashman et al,[48] using a high-speed biplane radiography system, observed in ACL-reconstructed patients that even though anterior tibial translation was similar in both limbs, the reconstructed knees were more externally rotated (2°-4°), during down-sloped treadmill running. Finally, Logan et al[32] showed with an "open-access" MRI system and during a dynamic weightbearing activity that tibiofemoral kinematics are not restored in ACL-reconstructed patients with a 4-strand hamstrings graft, even though sagittal laxity is restored to normative values.

However, there is only 1 more study in the literature where in vivo experimental work on ACL reconstruction comparing a BPTB with an ST/G graft has been reported. In this study by Webster et al,[49] the 2 grafts were compared while ACL- reconstructed patients were evaluated performing activities of daily living (ie, walking). The authors reported that both grafts can affect gait patterns regarding knee flexion and extension moments. However, movement patterns in other planes were not evaluated and, specifically, the effect of graft type on tibial rotation was not assessed.

Most in vivo studies have examined ACL-reconstructed patients with a BPTB graft and have indicated that ACL reconstruction does not fully restore normal ACL function. We expected better results from the ST/G graft because it has been demonstrated in several studies that this graft has mechanical properties similar to those of the ACL. The BPTB graft has been the popular replacement graft for many years because it has high ultimate tensile load (approximately 2300 N) and stiffness (approximately 620 N/mm)[42] and its capacity for rigid fixation at the attached bony ends. The quadrupled ST/G graft seems to be more close to the natural ACL morphologically, and this graft's ultimate tensile load has been reported to be much higher than that of the BPTB (approximately 4108 N).[8] Another advantage of the quadruple ST/G graft is that it provides a 2-bundle replacement graft that may better approximate the function of the 2-bundle ACL.[51] Finally, the tubular shape of the ST/G graft allows for excellent graft-tunnel conformity and fits better to the oval shape of the natural ACL. Nevertheless, excessive tibial rotation was still observed in our study, no matter which graft we used, for the activity examined.

A possible explanation for the results found in the present study may be the positioning of the graft placement.[33,36,43] Scopp et al[43] and Loh et al[33] showed in vitro that a more oblique tunnel placement in the femur is more appropriate than the standard femoral tunnel

placement regarding rotation. In these studies, the more oblique femoral tunnel placement (at 10 o'clock) resulted in less internal tibial rotation compared with the standard femoral tunnel placement. This can be attributed to the fact that the posterolateral (PL) bundle is located more horizontally and toward the 9-o'clock position of the femur. Thus, a more oblique placement can better replicate the PL bundle and result in increased resistive ability to rotational forces. In our study, we placed the femoral tunnel at the 11-o'clock position. However, we are now performing ACL reconstructions with an ST/G or a BPTB graft and place the femoral tunnel in a more oblique position, at about 10 o'clock. Therefore, in future investigations we plan to examine in vivo whether this technique can affect tibial rotation.

Another possible explanation for the inability to restore tibial rotation to normal levels using the ST/G or BPTB graft is the absence of complete reinstatement of the actual 2-bundle morphologic anatomy of the ACL.[3,22] With our current techniques, we imitate mostly the anteromedial bundle. The role of this bundle has been widely demonstrated to be resisting anterior translational loads. However, the PL bundle has received limited attention. A recent study by Gabriel et al[19] revealed that the PL bundle is important for stabilizing the knee against rotational loads. It is then possible that the lack of restoration of tibial rotation after an ACL reconstruction is related to the lack of proper replication of the 2 ACL bundles[23,25] and, specifically, the PL. However, further investigation using in vivo methods, as described in the present study, is war- ranted to clearly establish this conclusion.

One can question how we can have abnormal rotation in patients with normal pivot-shift tests, which is considered to be a rotational test. The fact that all our patients had a negative pivot-shift test demonstrates the absence of rotational instability in them. However, the pivot-shift test is a subjective measure with low sensitivity. Moreover, the rotational load applied to the knee joint during the pivot- shift test is considerably lower than the load applied to the knee joint during the examined dynamic movement. The increased tibial rotation that we found does not mean that the knee was unstable when subjects performed the examined activity. It means that the reconstructed legs had an abnormal movement pattern in the transverse plane when compared with the healthy contralateral and the control while subjects performed the examined activity.

One shortcoming of our study may be that we used different fixation methods for the 2 grafts. However, there is general agreement that interference screws are the most accepted type for fixation of the BPTB; this is the method we used. There is no consensus for fixation of the ST/G. Because of previous studies,[6,41] many surgeons have recommended that the 2 grafts be fixed in different fashion. This is because the BPTB graft follows a bone-to-bone healing process, whereas the ST/G graft follows a tendon-to-bone healing process. Thus, it is logical to use different fixation methods for the 2 grafts, as was the case in our study.

An additional possible limitation of our study deals with the known drawbacks of motion analysis[34] and, especially, the movement of skin markers and their ability to predict bone movements. However, motion analysis is widely accepted and is considered a well-established and reliable method.[11,20] Furthermore, we tried to address these limitations

with careful experimentation procedures. We minimized the interoperator error by having the same clinician placing all the markers and make all the anthropometric measurements. The absolute 3-dimensional marker reconstruction error of the system was very low (maximum SD 1.303 mm, calibration space approximately 8 m³). We incorporated a standing calibration procedure to provide definition of 0° for all segmental movements in all planes. We also incorporated a "double" control group, because we used as controls both the intact legs of the ACL-reconstructed groups and a completely healthy group of subjects. Last, because the same instrumentation was used for all subjects, we can assume that 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

We found that neither of the 2 most frequently used auto- grafts for ACL reconstruction can restore tibial rotation to normal levels in an activity such as pivoting after descending stairs. The improvement of surgical techniques and development of new techniques seem to be a way to address the problem of excessive tibial rotation. However, new techniques should be rigorously evaluated with both in vivo and in vitro studies to identify their advantages and disadvantages.

ACKNOWLEDGMENT

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