Original article

Bracing can partially limit tibial rotation during stressful activities after anterior cruciate ligament reconstruction with a hamstring graft

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A B S T R A C T

Background: Hamstring graft has substantial differences with BPTB graft regarding initial mechanical strength, healing sequence, and vascularization, which may imply that a different approach during rehabilitation period is required. The purpose of this study was to investigate the influence of knee bracing on tibial rotation in ACL-reconstructed patients with a hamstring autograft during high loading activities. The hypothesis was that there would be a decrease in tibial rotation in the ACL-reconstructed braced knee as compared to the unbraced knee.

Methods: Twenty male patients having undergone unilateral ACL reconstruction with a semitendinosus/gracilis autograft were assessed. Kinematic data were collected with an eight-camera optoelectronic system during two stressful tasks: (1) descending from a stair and subsequent pivoting; and (2) landing from a platform and subsequent pivoting. In each patient, three different experimental conditions were evaluated: (A) wearing a prophylactic brace (braced condition); (B) wearing a patellofemoral brace (sleeved condition); (C) without brace (unbraced condition). The intact knee without brace served as a control.

Results: Tibial rotation was significantly lower in the intact knee compared to all three conditions of the ACL-reconstructed knee (P ≤ 0.01 for both tasks). Presence of a brace or sleeve resulted in lower tibial rotation than in the unbraced condition (p = 0.005 for descending/pivot and p = 0.0004 for landing/pivot). The braced condition resulted in lower rotation than the sleeved condition for descending/pivoting (P = 0.031) while no differences were found for landing/pivoting (P = 0.230).

Conclusion: Knee bracing limited the excessive tibial rotation during pivoting under high loading activities in ACL-reconstructed knees with a hamstring graft. This partial restoration of normal kinematics may have a potential beneficial effect in patients recovering from ACL reconstruction with a hamstring autograft.

Level of evidence: Level III, case-control therapeutic study.

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1. Introduction

Tibial rotation influences major knee joint function after anterior cruciate ligament (ACL) reconstruction. Restoration of pathological tibial rotation in ACL injured patients after ACL reconstruction is reported in vivo only during low stress activities such as walking [1]. In contrast, tibial rotation is not restored under high demanding tasks regardless of the reconstruction technique with bone-patellar tendon-bone (BPTB) [2,3] or hamstring graft [4].

The role of conservative means, such as bracing, against tibial rotation has been explored in the past [5,6]. It has been demonstrated that functional bracing does not interfere with activity level in athletic activities of healthy athletes, but it may restrict activity level of ACL-reconstructed patients [7,8]. Recently, it was demonstrated in vivo that knee braces could reduce considerably the excessive tibial rotation in ACL-deficient patients during stressful tasks [9]. Similar results showing partial restoration of increased tibial rotation under high loading tasks were found in ACL-reconstructed knees with a BPTB autograft [10].

Hamstring graft has substantial differences with BPTB graft regarding initial mechanical strength, healing sequence, and vascularization [11–14]. In addition, certain aspects of donor morbidity may influence in a different manner knee kinematics when
hamstring graft is used [15,16]. Specifically, it was found that isokinetic quadriceps and hamstring muscle strength per body weight were significantly lower when hamstring tendon was used [16]. Thus, it is reasonable to assume that deteriorating this function by selecting hamstring autograft can be associated with poor functional outcome post ACL reconstruction. Therefore, it is important to investigate the effect of knee braces in ACL-reconstructed patients with a hamstring autograft since these differences may potentially alter the effect of brace on knee kinematics.

The purpose of the present study was to evaluate whether knee braces can restore normal knee rotation in ACL-reconstructed individuals 2 years postoperatively with a semitendinosus/gracilis graft during high loading activities of the knee joint. It was hypothesized that there would be a decrease in tibial rotation in the ACL-reconstructed braced condition as compared to the unbraced condition.

2. Methods

Twenty patients that underwent arthroscopically assisted ACL reconstruction at our institution were included. ACL reconstruction was performed by the same surgeon (senior author) in all patients. Inclusion criteria were:

- a complete, isolated, unilateral ACL rupture reconstructed using semitendinosus-gracilis (ST/G) tendon autograft;
- pre-injury activity level (Tegner activity score) of 7 or greater;
- no history of other orthopedic or neurologic condition that could affect rehabilitation;
- male gender;
- a minimum of 2-year follow-up.

Patients excluded from the study were those with:

- multiligament injuries (posterior cruciate ligament injury and/or collateral ligament injuries along with the ACL rupture);
- serious coexistent chondral lesions (Outerbridge classification III, IV);
- meniscal injuries involving more than 25% of meniscus that required meniscectomy or repair during ACL reconstruction;
- history of ligamentous injury or surgical procedure to the reconstructed or contralateral knee;
- in need of revision operation of the ACL;
- symptomatic anterior knee pain;
- objective laxity at the latest follow-up examination after ACL reconstruction (positive pivot-shift test result, positive Lachman test, and arthrometer KT-1000 side-to-side differences [SSD] > 3 mm).

All participants gave their informed consent for participation according to our university's medical school institutional review board procedures and all rights of subjects were protected.

2.1. Surgical technique

The femoral tunnel was created through the anteromedialportal at the center of the anatomic insertion of the ACL whereas the tibial tunnel was placed approximately 5 mm anterior and medial to the anatomic center of the natural ACL attachment, so that the posterolateral part of the tunnel circumference to be located on the anatomical center of the ACL attachment. This was to achieve placing the graft in the center of the anatomiCal tibial footprint of the native ACL by creating the tibial tunnel more anteriorly and medi-ally. The postoperative physical therapy rehabilitation protocol was a modified accelerated protocol [17]. Return to sports-related activities was allowed 24 weeks after reconstruction provided that the patients had regained full functional strength and stability.

2.2. Clinical examination

All participants were clinically evaluated by the same ortho-pedic surgeon and all data were prospectively collected. Knee joint stability was evaluated with Lachman and pivot-shift tests. Tegner activity level [18], Lysholm score [18] and International Knee Documentation Committee (IKDC) subjective score [19] were obtained, and the IKDC knee examination form was completed. Anterior tibial translation was measured with the use of KT-1000 knee arthrometer (MEDmetric Corp, San Diego, California) at 134-N and maximum manual force.

2.3. Motion analysis

An 8-camera optoelectronic system (Vicon, Oxford, United Kingdom) sampling at 100 Hz was used to capture the movements of 16 reflective markers placed on specific bony landmarks of the lower extremities and pelvis according to the model provided by Davis [20]. The examined protocol included two different pivoting tasks where combined rotational and translational loads were applied on the knee [21,22]:

- descending stairs and subsequent pivoting;
- landing from a platform and subsequent pivoting [2,23] (Supplemental material).

These pivoting tasks have been shown to produce high translational and rotational loads to the knee joint [24,25]. These stressful tasks were executed under three conditions for the reconstructed knee:

- wearing a prophylactic brace (braced condition);
- wearing a patellofemoral brace (sleeved condition);
- without brace (unbraced condition), while for the contralateral intact knee only without brace.

The prophylactic braces due to their metal straps are considered to prevent or reduce the severity of injuries by protecting primarily the medial collateral ligament and secondarily the ACL, whereas the patellofemoral braces are designed to reduce anterior knee pain by mainly obstructing lateral displacement of the patella [26,27]. The stairway was constructed according to guidelines of Andriacchi et al. [28] and the platform, in accordance with the description of James et al. [29]. All subjects were given 10 minutes to warm up and familiarize themselves with the examined tasks. The same examiner carried out and monitored the whole kinematic process for each participant.

During the first task, each subject descended the stairway at his own pace. After descending the steps, the subject contacted the ground with the supporting (ipsilateral) leg. Following foot contact, the subject was instructed to perform a 90° pivoting maneuver on the supporting leg and walk away. While pivoting, the contralateral leg was swinging around the body and at the end of pivoting: the trunk was oriented perpendicular to the stairway [21]. After pivoting, the subject continued to walk away from the stairway for at least three consecutive strides (Video 1). In the second task, having his arms folded across the chest, the subject jumped from the platform and landed with both feet on the ground. After foot contact, the participant pivoted on the ipsilateral leg at 90° and walked away in an analog way to the first task (Video 2). As evaluating period for both tasks was considered the pivoting period from initial foot contact with the ground of the ipsilateral (supporting) leg, until touchdown of the contralateral leg [2,23]. At least six trials
were performed for each one of the examined conditions for both the reconstructed and intact knee, with random order.

To validate the procedures and minimize errors [30, 31] regarding video capture of skin markers, an extra trial was recorded for each condition, with the subject in the anatomic position (with the foot parallel and 15 cm apart). This calibration allowed correction of subtle misalignment of the markers that define the local coordinate system and provided a definition of 0° for all segmental movements in all planes [3, 23] and was repeated at the beginning of data collection for each condition.

An important issue in this study was the proper placement of the knee marker in the reconstructed knee. Regarding the prophylactic brace, the knee marker was placed on the lateral femoral epicondyle through a small cutout (0.8 × 0.8 cm), avoiding the metal strap of the brace [9, 10, 32]. Concerning the patellofemoral brace, another small cutout (1 × 1 cm) on the lateral side of the brace allowed the lateral femoral epicondyle marker to be placed directly on the skin during the sleeved trials [9, 10, 32]. However, the marker had to be removed in order to put/remove the braces for the subsequent conditions. Thus, special care was taken to place the marker exactly on the same location by ensuring that it would be placed within the limits of a circle marked on the reconstructed knee, before repeating the calibration trials.

### 2.4. Data processing

Anthropometric measurements were combined with 3-D (dimensional) marker data from the anatomic position trial to provide positions of the joint centers and to define anatomic axis of joint rotations [20]. The position of the markers provided the 3-D segmental angles. The convention used for calculating knee rotations was based on the system of Grood and Suntay [33]. The maximum and minimum tibial rotation values of the supporting leg during pivoting were calculated. These two points were subtracted to acquire the range of motion (ROM) for tibial rotation during the pivoting phase, which was used as the dependent variable. The selection of ROM as the dependent variable eliminated possible errors reported in the literature where absolute measures were used [34].

### 2.5. Statistical analysis

Two separate repeated measures analysis of variance (ANOVAs) (one for each task) were used to assess significant differences for tibial rotation among the three different conditions of the reconstructed leg and the intact leg. Post-hoc pairwise comparisons with Bonferroni adjustment were performed in the presence of statistically significant ANOVAs. Statistical significance was set a priori at 0.05. All statistical analyses were conducted with the use of SPSS version 19.0, statistical software (SPSS Inc IBM, Chicago, Illinois). A power analysis, based on data from a pilot study, used G-power 3.1.9 software (university of Düsseldorf) to determine sample size using the parameters of a error probability 0.05, α = 0.95, effect size 1.8. A sample size of 10 per group was determined. Our study used the double number (20) of patients.

### 3. Results

Twenty male subjects with a mean age 25.8 ± 2.9 years, mean body mass 79.2 ± 2.6 kg, mean height 1.78m ± 0.07 and mean BMI 25.0 ± 1.6, were evaluated. The mean time from injury to surgery and to data collection was 4 months (range: 2–13 months) and 27 months (range: 25–30 months) respectively. In 8 cases, a meniscal tear (7 medial and 1 lateral) was observed arthroscopically, but the damage was less than 25% and no repair was performed. In these cases, minimal shaving meniscectomy of the torn area was performed.

### Table 1

<table>
<thead>
<tr>
<th>Task</th>
<th>Mean ± SD</th>
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<tbody>
<tr>
<td>Descending and pivoting task</td>
<td></td>
</tr>
<tr>
<td>Unbraced reconstructed knee</td>
<td>20.66 ± 3.02&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Unbraced intact knee</td>
<td>16.54 ± 2.41&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sleeved reconstructed knee (with patellofemoral brace)</td>
<td>19.45 ± 2.78&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Braced reconstructed knee (with prophylactic brace)</td>
<td>18.64 ± 2.74&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Landing and pivoting task</td>
<td></td>
</tr>
<tr>
<td>Unbraced reconstructed knee</td>
<td>20.23 ± 2.77&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Unbraced intact knee</td>
<td>15.56 ± 2.25&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sleeved reconstructed knee (with patellofemoral brace)</td>
<td>18.69 ± 2.85&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Braced reconstructed knee (with prophylactic brace)</td>
<td>17.97 ± 2.56&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
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<sup>a</sup> Statistical significance at P < 0.05 with all other three conditions.

Negative Lachman and pivot shift tests were recorded in all patients showing that objective stability had been regained postoperatively. The mean Lysholm and Tegner scores were 96 (85–100 points) and 7.4 (7–9 points) respectively. The mean subjective IKDC score was 93.4 (83.8–100 points). The IKDC grade was A in 17 patients and B in 3 patients. KT-1000 arthrometer testing showed side-to-side (SSD) differences of less than 3 mm for all the participants with a mean value of 1.12 mm (range: 0–3 mm) for the 134-N test and 1.35 mm (range: 0–3 mm) for the maximum manual test. Therefore, ACL reconstruction was regarded clinically successful for all patients.

Means and standard deviations for both tasks are presented for each condition in Table 1 and graphically in Figs. 1 and 2. The ANOVAs revealed significant main effects for both tasks (P < 0.001). Figs. 3 and 4 show typical curves of tibial rotation from a representative ACL-reconstructed subject, for the two examined tasks.

For the descending and pivoting task, mean range of tibial rotation was significantly lower in the intact knee compared to all three conditions of the ACL-reconstructed knee (P < 0.001, P = 0.001 and P > 0.01 for the unbraced, sleeved and braced condition, respectively). Placing a brace or a sleeve on the ACL-reconstructed knee resulted in lower rotation than the unbraced condition (P < 0.003). The braced condition resulted in lower motion than the sleeved condition (P = 0.031).

![Figure 1](image-url)  
**Fig. 1.** Bars demonstrating means and standard deviations for the maximum range of motion (ROM) of the tibial rotation during descending stairs and subsequent pivoting. All the differences among the four examined conditions (unbraced reconstructed, unbraced intact, sleeved reconstructed and braced reconstructed) are statistically significant (P < 0.05).
Fig. 2. Similarly to Fig. 1, the bar graphs show mean values and standard deviations for maximum ROM of tibial rotation during landing and subsequent pivoting. The asterisks indicate statistically significant differences (P < 0.05) while the pound sign (#) indicates that there are no statistical differences.

For the landing and pivoting task, the post-hoc analysis revealed that the mean range of tibial rotation was significantly lower in the intact knee compared to all three conditions of the ACL-reconstructed knee (P ≤ 0.001). Placing a brace or a sleeve on the ACL-reconstructed knee resulted in lower rotation than the unbraced condition (P < 0.001) while there were no differences between the braced and sleeved conditions (P = 0.230).

Regarding the prophylactic brace, it was found that tibial rotation was decreased in the ACL-reconstructed knee by almost 2.5° as compared to the non-braced condition, representing 50% of the excessive tibial rotation as compared to the intact contralateral unbraced knee. Concerning the patellofemoral brace, it was observed that tibial rotation was restricted by 1–2° in the ACL-reconstructed knee comparatively to the non-braced case, representing 30–40% of the excessive tibial rotation as compared to the intact contralateral unbraced knee.

Fig. 3. Typical tibial rotation curves for a full “stride” from one representative ACL-reconstructed subject during descending stairs and subsequent pivoting. Dashed, little dotted and solid line curves demonstrate the braced, sleeved and unbraced ACL-reconstructed leg respectively. The big dotted line curve displays the unbraced intact knee. The maximum range of motion of tibial rotation regarding the four examined conditions is also recorded.

Fig. 4. Tibial rotation curves representing the landing and subsequent pivoting task. Similarly to Fig. 3, regarding the ACL-reconstructed knee, dashed, little dotted and solid line curves represent braced, sleeved and unbraced conditions. The big dotted line curve demonstrates the unbraced intact knee.
4. Discussion

According to the findings of this in vivo study, knee braces in ACL-reconstructed individuals with a hamstring autograft, can restrict the excessive tibial rotation during pivoting in high-stress activities that still persists, even 2 years postoperatively. Despite this decrease, bracing did not fully restore normal tibial rotation values. Knee bracing after ACL reconstruction has shown to restrict tibial rotation under low to moderate activities [26,27,35–39]. Despite the difference between BPTP and hamstring allograft knees bracing after hamstring ACL-reconstructed patients had analogous findings with bracing in patients reconstructed with a BPTB allograft [10].

One important aspect of the present study is the presented difference when comparing prophylactic brace and sleeve during the descending and pivoting task. Our results confirmed our hypothesis that both forms of bracing have a preventative effect on excessive tibial rotation without a full restoration of tibial rotation to normative values. However, prophylactic brace resulted in almost 50% lower tibial rotation in comparison to sleeve. This higher effectiveness of the prophylactic brace can be attributed to the metal component and the additional stabilization provided by the straps. Interestingly, this effect has been shown in ACL reconstruction with BPTB graft [10], but no difference was detected between the two braces. Noteworthy, this difference was obvious only during descending, while no differences between the braced and sleeved conditions were seen during landing and pivoting task. Further research is needed in order to further clarify whether the superiority of the prophylactic brace in reducing tibial rotation in ACL-reconstructed patients is associated with certain characteristics of hamstring ACL graft.

Both BPTP and hamstring grafts result in non-restoration of tibial rotation during stressful activities [14,20,21,28]. Recently, it was demonstrated that bracing partially restored the increased tibial rotation reported in ACL-reconstructed knees with a BPTB graft during high demand tasks [10], which raised the question whether the same would be true for hamstring graft as well. Hamstrings graft has substantial differences in healing with BPTB graft in ACL reconstruction that make restoration of tibial rotation at the immediate postoperative period critical clinical outcome. Remodeling and “ligamentization” of hamstring graft appears to be slower compared to the BPTP graft [40–42]. Vascularization process of the hamstring graft is reported poor, and it is suggested that the graft is dependent more on synovial diffusion at the early postoperative period [12]. These differences at the early postoperative period may be associated with the increased rate of revision of hamstring graft ACL reconstructions at 1 year postoperatively [43]. For this reason, a less aggressive rehabilitation protocol is proposed for hamstring ACL-reconstructed knees [40]. This may be crucial for the healing process of the hamstring graft as it may protect the graft from excessive load at the early period. It is among our future research goals to demonstrate whether this partial restoration in reconstructed knees with hamstring graft has the potential to provide clinical benefits with improvement in revision and failure rates.

Additionally, the findings of the present study demonstrate that the documented abnormal tibial rotation still remains 2-year after surgery. This is in accordance with previous reports showing abnormal tibial rotation in patients less than a year after surgery [4,44]. Thus, it is likely that the tibial rotation deficits remain permanently in patients after ACL reconstruction and do not improve over time. This increased tibial rotation in ACL injured patients (deficient or reconstructed) could theoretically initiate further biomechanical alterations in the knee joint, subsequent abnormal loading of cartilage, cartilage degeneration or meniscal lesions and subsequent osteoarthritis [45–47].

The present study has certain limitations. Despite motion analysis being considered a well-established and reliable method [48], the results of the study should be viewed in light of general gait analysis limitations, in particular those regarding skin markers movement [30]. Moreover, the placement of the markers and the record of the anthropometric measurements by the same clinician minimized the inter-operator error. In parallel, the absolute 3D marker reconstruction error of the system was very low (maximum SD. 0.303 mm; calibration space, approximately 8 m³). Furthermore, in this study, only two types of braces were evaluated. The American Academy of Orthopaedic Surgeons Committee on Sports Medicine lists four different types of braces (patellofemoral, prophylactic, functional, rehabilitative) [26,27]. In the current study, we did not include functional and rehabilitative braces, the former because of their increased weight and stiff structure and the latter because they are usually used in the early post-surgical phase to limit knee motion, thus are not appropriate for athletic activities. To have a homogeneous study group and eliminate possible bias that would affect the results, strict selection criteria concerning gender, age, and type of graft were used. However, this study design does not allow generalization of findings to female, older patients, patients who underwent BPTB, or allograft reconstruction, and careful interpretation of the findings should be made. Finally, the intact contralateral knee was regarded as control knee. This compromise is a common practice in similar settings and it was done to avoid complicated statistical analysis and to facilitate data processing as structurally and anatomically, no alterations could be found between the intact knee of ACL-reconstructed patients and healthy control knees.

5. Conclusions

In conclusion, knee braces can partially restore tibial rotation during stressful athletic activities in ACL-reconstructed knees with hamstring autograft where reconstruction has proven to be insufficient. This partial restoration of both physiologic and kinematic function in such patients could have a beneficial effect both short-term, by protecting the graft from failure in the early postoperative period, but also long-term, by mitigating degenerative osteoarthritic changes.

Disclosure of interest

The authors declare that they have no competing interest. Institutional review board and ethical committee approval was obtained.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.otsr.2016.04.005.

References


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