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Kinematic predictors of subjective outcome after anterior cruciate ligament reconstruction: an in vivo motion analysis study

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Abstract

Purpose The purpose of this study was to test whether rotational knee kinematics during dynamic pivoting activities are predictive of subjective functional outcome (IKDC, Lysholm), objective laxity scores (KT max), and activity levels (Tegner) in patients after anterior cruciate ligament reconstruction (ACLR).

Methods Thirty-one patients with single-bundle ACLR were evaluated prospectively with 3D-motion analysis during (1) descending a stairway and pivoting and (2) landing from a jump and pivoting. The side-to-side difference of tibial rotation range of motion (SSDTR) between the ACLR and the contralateral intact knee was calculated for the pivoting phase of each task. Linear regression models were applied with SSDTR, for each task predictors of the subjective IKDC score, Lysholm score, anterior tibial translation, and Tegner activity level.

Results SSDTR for descending and landing were predictive of the IKDC subjective score ($R^2 = 0.46, p < 0.001$ and $R^2 = 0.40$, $p < 0.001$, respectively) with "medium" effect sizes and of the Lysholm score ($R^2 = 0.13, p < 0.05$ and $R^2 = 0.09$, n.s.) with "small" to "none" effect sizes. SSDTR was not predictive of anterior translation or Tegner activity level (n.s.).

Conclusions Restoring rotational kinematics during dynamic pivoting activities after ACLR is predictive of functional outcome. The ability of the athlete after ACLR to control tibial rotation during pivoting activities may be predictive of functional outcome.

Level of evidence Case series study. Level IV.

Keywords Anterior cruciate ligament (ACL) reconstruction · Tibial rotation · Motion analysis · Subjective outcome · Knee function

Introduction

Transverse plane biomechanics of the knee joint have been widely assessed in a series of studies mainly in the last decade with consistent findings that abnormally increased tibial rotation range of motion (TR ROM) remains after anterior cruciate ligament (ACL) reconstruction (ACLR) during dynamic joint loading, especially high demanding activities that place increased rotational loads on the knee joint [7, 14, 32–34]. The importance of rotational knee kinematics derived from the screw-home mechanism of the knee joint [22] as well as the demonstrated aspect that the pathologic motion of the pivot shift is coupled tibial rotation and anterior tibial translation [5, 24, 30]. The pivot-shift test and rotational knee kinematics are two different entities, which are both clinically helpful but assess different aspects of the ACL-deficient and reconstructed knee. The pivot-shift test is the most widely used clinical tool for assessing knee joint rotational laxity and when positive demonstrates clinically important rotational instability that

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occurs after ACL rupture. The importance of the ACL in providing rotational stability and subsequent normal knee function cannot be overemphasized [11] as it has been demonstrated that after ACLR a positive pivot-shift test is predictive of poor subjective and objective outcome, patient discomfort, failure to return to previous level of sport, increased scintigraphic activity in the subchondral bone, and development of osteoarthritis of the knee in the long term [21, 23]. On the other hand, rotational knee kinematics describe the subtle changes in normal knee joint movement patterns that have been noticed for ACLR patients even in the presence of a negative pivot-shift test. Rotational knee kinematics may be difficult to accurately assess by visual inspection or clinical examination, and for this reason, studies using high-technology, accurate 3D motion analysis systems have contributed immensely to the understanding of rotational deficits after ACLR.

Prior studies have shown that a negative clinical pivot-shift test after ACLR does not necessarily translate into normal rotational knee kinematics [12, 14, 32–35, 41]. The clinical significance of abnormal knee joint rotational movement patterns after ACLR is that these may lead to abnormal knee joint loading and thus initiate the process for future chondral degeneration [37]. Although this is a very important parameter that underlines the need to restore normal rotatory knee laxity due to its possibly deleterious effect on cartilage health, currently there is a paucity of studies demonstrating the clinical significance of abnormal rotational kinematics of the knee in the short term after ACLR. Therefore, the purpose of this study was to test whether rotational knee kinematics during dynamic pivoting activities are predictive of subjective functional outcome (IKDC, Lysholm), objective laxity scores as measured by maximum anterior translation on the KT-1000 (KT max), and activity levels (Tegner) in patients after ACLR. Our a priori hypothesis was that rotational knee kinematics are predictive of subjective functional outcomes.

Materials and methods

From February 2009 to March 2010, 101 patients underwent arthroscopically assisted ACLR at our institution. All operations were performed by the same surgeon (senior author). Inclusion criteria for the study were as follows: (1) complete, unilateral, isolated ACL rupture, (2) ACLR using single-bundle bone-patellar tendon-bone (BPTB) autograft, (3) no previous injury to either affected or contralateral lower limb, (4) male gender, because outcomes after ACL reconstruction differ between men and women [1] and menstrual cycle-related hormonal factors affect knee joint laxity [42], (5) pre-injury activity level ≥ 7 (Tegner activity score) and desire to return to previous sports activity level after the index operation, and (6) a minimum of 1-year follow-up. Exclusion criteria were as follows: (1) female gender, (2) patients 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), or meniscal injuries that involved more than 25% of meniscus, that required a meniscectomy or a suture repair at the time of ACL reconstruction, (3) prior ligamentous injury to the reconstructed or the contralateral knee, prior surgery on either knee or revision operation of the ACL, and (4) symptomatic anterior knee pain, or objective instability at the latest follow-up examination after ACLR (positive pivot-shift test result, positive Lachman test result, and arthrometer KT-1000 side-to-side differences >3 mm). Finally, due to practical reasons, patients living more than 1 h away from the institution where the present study was conducted were also excluded.

According to these criteria, 31 male patients (median age 27 years and range 18–44 years) with unilateral primary ACLR with BPTB autograft met the inclusion criteria and were enrolled in this study after providing institutional review board–approved informed consent. In all cases, the ACL rupture was diagnosed by MRI, clinical examination, and confirmed arthroscopically during the ACLR. In 9 patients, meniscal damage was also found during the arthroscopic reconstruction, but the level of involved meniscus damage was less than 25%; therefore, these patients were included in the study. The orthopaedic surgeon communicated with the physical therapist to insure that all patients followed a similar criterion-based protocol [29]. Demographic data of the study population are presented in Table 1.

Surgical technique

All surgeries were performed by the same orthopaedic surgeon (the senior author). The BPTB graft was taken from the medial third of the patellar tendon [13, 28]. We did not harvest more than a third of the total tendon width. The ACL remnants were preserved at femoral and tibial attachment sites, and they were debrided only at the tunnel entry points. The drilling of the femoral tunnel was performed arthroscopically through the anteromedial approach, having the knee joint in 120° of flexion. The femoral tunnel was drilled at the center of the anatomic insertion of the ACL [13, 15]. The tunnel position in the tibial plateau 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 is to achieve placing the graft in the center of the anatomical tibial footprint of the native ACL by

Table 1 Patients' demographics and clinical examination results

Number	31
Gender	Male
Injured side	13 left, 18 right
Meniscectomy (yes/no)	9/31
Mean age (years; SD, range)	28.6 (7.7, 18 to 44)
Mean height (m; SD, range)	1.78 (0.067, 1.67 to 1.92)
Mean body mass (kg; SD, range)	83 (11, 68 to 114)
Mean time from injury to operation (months; SD, range)	14.9 (42.4, 1 to 240)
Mean time of data collection (clinical examination and motion analysis; months postoperatively; SD, range)	17.5 (5.8, 12 to 32)
Mean Tegner score (SD, range)	7.5 (0.9, 6 to 9)
Mean Lysholm score (SD, range)	94.8 (5.4, 77 to 100)
Mean IKDC subjective score (SD, range)	90.7 (7.2, 69 to 100)
Mean KT-1000 SSD maximum manual force (mm; SD, range)	1.1 (0.9, −1 to 3)

creating the tibial tunnel more anteriorly and medially. The placement of the graft in the femoral tunnel was with the cortical side of the tibial bone plug close to the over-the-top position [17]. Fixation of the graft was performed with the same bio-absorbable interference screws on both femur and tibia. Interference screws were inserted at the cancellous side of the bone plugs. After the fixation to the femur, the graft was rotated 90° around its long axis, to imitate the natural rotation of the native ACL, and maximal tension was applied manually, by pulling the graft from its patellar bone plug and pushing the tibia posteriorly to correct the anterior tibial translation (ATT). Holding the knee in 30° of flexion [18] and with the graft tensioned as described, we proceeded to the fixation on the tibia with the second interference screw. Finally, the graft was inspected both in full flexion and full extension to exclude graft impingement at the lateral femoral condyle, the intercondylar notch roof, and the posterior cruciate ligament. A notchplasty was not necessary in any of our cases. No posterior wall blowout at femoral tunnels was observed in any of the patients.

Clinical examination

Prior to kinematic data collection a clinical examination was performed on the same day for all subjects and by the same clinician (first author). Negative Lachman test and pivot-shift test results indicated that knee joint stability was clinically restored for all patients. Additionally, Tegner activity level, Lysholm score [39], and International Knee Documentation Committee (IKDC) subjective score [19] were obtained. Anterior tibial translation was measured using the KT-1000 knee arthrometer (MEDmetric Corp, San Diego, CA) for both the ACLR and contralateral intact knee. The measurements were performed using the maximum manual anterior force at the proximal tibia until heel clearance external was achieved. Repeated anterior translations were performed until a constant reading on the dial was registered and the side-to-side difference of anterior tibial translation in mm was recorded for each participant.

Motion analysis

An 8-camera optoelectronic 3-dimensional (3D) motion analysis system (Vicon, Oxford, UK) sampling at 100 Hz was used to capture the movements of 16 reflective markers placed on selected bony landmarks of the lower extremities and pelvis using the model of Davis et al. [10]. Two force platforms (type 4060-10; Bertec, Worthington, OH) that were flush mounted in the center of the calibrated volume were used to detect the touchdown of each leg of the participant during the examined activities. Ground reaction force (GRF) data were collected at a sampling frequency of 1,000 Hz and were synchronized with the Vicon system. We used kinetic data to identify the beginning of pivoting (touchdown of the supporting leg).

The subjects performed two different dynamic pivoting activities: (1) descending from a stair and subsequent pivoting and (2) landing from a platform and subsequent pivoting. The height of the platform used for landing was 40 cm, and it was designed according to James et al. [20]. The stairway was constructed according to Andriacchi et al. [2] All subjects were given enough time (10 min) to warm up and familiarize themselves with the examined tasks. The experimental protocol was the same for every participant and was carried out by the same examiner. During the first activity, the subjects descended the stairway at their own pace. After descending the three steps, the subject contacted the ground with the supporting (ipsilateral) leg. After foot contact, the subject was instructed to perform a 90° pivoting maneuver on the supporting leg. While pivoting, the contralateral leg swung around the body (as it was coming down from the stairway) and at end of pivoting the trunk and foot were oriented perpendicular to the stairway. During the task, the points of touchdown for both legs (the supporting and the swinging leg) were indicated by floor marks to ensure the same 90° pivoting activity for all subjects. After pivoting, the subjects were instructed to walk away from the stairway for at least one stride. During the second activity, the subjects folded their arms across their chest, jumped from the platform and landed with both feet on the force plates. After foot contact, the subjects were instructed to pivot on the supporting leg at 90° and walk away in a similar fashion to the first activity. Each subject performed each activity on both legs (ACLR and contralateral intact leg), which were tested in a randomized order. In order to achieve maximum knee rotational loading during the pivoting period for both tasks, the subjects were instructed to keep the supporting foot in the same position until the contralateral foot contacted the ground (end of pivoting). A careful inspection of foot and trunk kinematics during real-time analysis allowed identifying the trials that fulfilled these requirements and a minimum of 6 successful trials were recorded for each side. In an effort to standardize the procedure as best as possible, we monitored the subjects in real time both visually and with software calculations to insure that the trunk and pelvis were facing forward at the initiation of the pivoting task and at 90° at the end of the pivoting task. When deviations from these instructions were observed the trial was repeated.

The evaluation period was identified from initial foot contact with the ground of the supporting (standing) leg and ended with touchdown of the contralateral leg [33]. To validate our procedures and minimize marker placement errors reported in the literature [26] regarding video capture of skin markers, an additional trial was recorded for each subject in anatomic position (with their feet 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 zero degrees for all segmental movements in all planes [33, 34].

Data analysis

Anthropometric measurements were combined with 3D marker data from the anatomic position trial to provide positions of the joint centers and to define anatomic axis of joint rotations. The position of the markers provided the 3D segmental angles. The convention used for calculating knee rotations was based on Grood et al. [16]. The maximum and minimum tibial rotation (TR) values of the supporting leg during pivoting were identified. These two points were subtracted to acquire the range of motion (ROM) for TR during the pivoting phase. The selection of ROM instead of absolute values of tibial rotation eliminated possible errors reported in the literature [36] when absolute measures (i.e., maximum or minimum) were used. For the purposes of this project, we did not calculate kinematics of the swinging leg. The difference of TR ROM between the two knees was calculated by subtracting the TR ROM of the intact knee from the TR ROM of the ACLR knee. This measure was named the side-to-side difference (SSD) TR ROM. This measure can quantify for each patient the "divergence" of the rotational motion that the ACLR knee exhibits from the normal rotational motion of the contralateral intact knee.

Statistical analysis

Linear regression models were applied with the SSDTR descending and SSDTR landing as predictors of the subjective IKDC score, Lysholm score, KT anterior translation maximum difference with intact knee (mm), and Tegner activity level. R^2 lower than 0.1 was defined as "none," higher than 0.1 and lower than 0.3 as "small," higher than 0.3 and lower than 0.5 as "medium," and higher than 0.5 as "large" [8].

Results

Clinical examination

For the ACL-reconstructed patients, the mean Lysholm score was 94.8 (range, 77–100), the Tegner score was 7.5 (range, 6–9), the subjective IKDC score was 90.7 (range, 69–100). All the ACL-reconstructed patients regained objective stability as indicated by negative Lachman test and pivot-shift test results. The mean group value for side-to-side difference between the anterior tibial translation of the reconstructed and the contralateral intact knee was 1.1 mm (range: (−1) to 3 mm) for the maximum KT-1000 test. Therefore, all patients were considered to have undergone a clinically successful ACLR and were subsequently included in the kinematic analysis of the study (Table 1).

Motion analysis

Linear regression analyses revealed that both SSDTR during descending and SSDTR during landing were predictive of the IKDC subjective score (adjusted $R^2 = 0.46$, $p < 0.001$ and adjusted $R^2 = 0.40$, $p < 0.001$, respectively) with "medium" effect sizes and of the Lysholm score (adjusted $R^2 = 0.13$, $p = 0.027$ and adjusted $R^2 = 0.09$, n.s.) with "small" to "none" effect sizes (Figs. 1,2). SSDTR during descending and landing were not predictive of anterior translation difference between the healthy and intact knee (as measured by the KT-1000) or of Tegner activity level (n.s.) with "none" effect sizes.

Discussion

The most important finding of the present study was that both side-to-side difference tibial rotation range of motion (SSDTR) during descending and SSDTR during landing were predictive of the IKDC subjective score with "medium" effect sizes and of the Lysholm score with "small" to "none" effect sizes. In contrast, SSDTR was not predictive

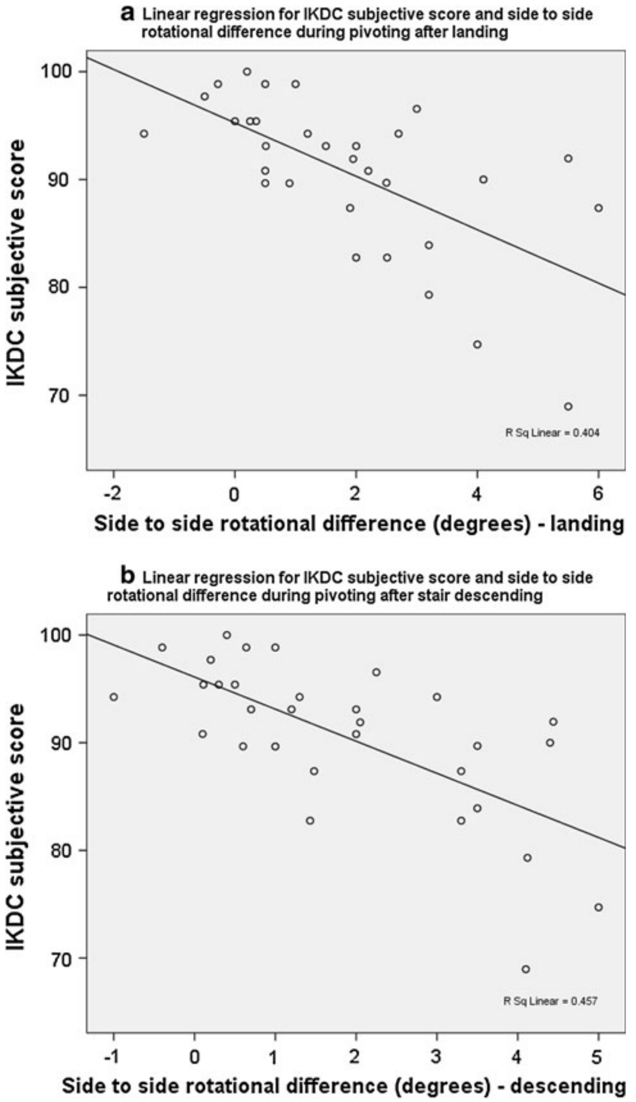

Fig. 1 **a**. Side-to-side difference (SSD) of tibial rotation (TR) (SSDTR) during landing is predictive of the IKDC subjective score (adjusted $R^2 = 0.40$, $p < 0.001$). **b** SSDTR during descending task is predictive of the IKDC subjective score (adjusted $R^2 = 0.46$, $p < 0.001$)

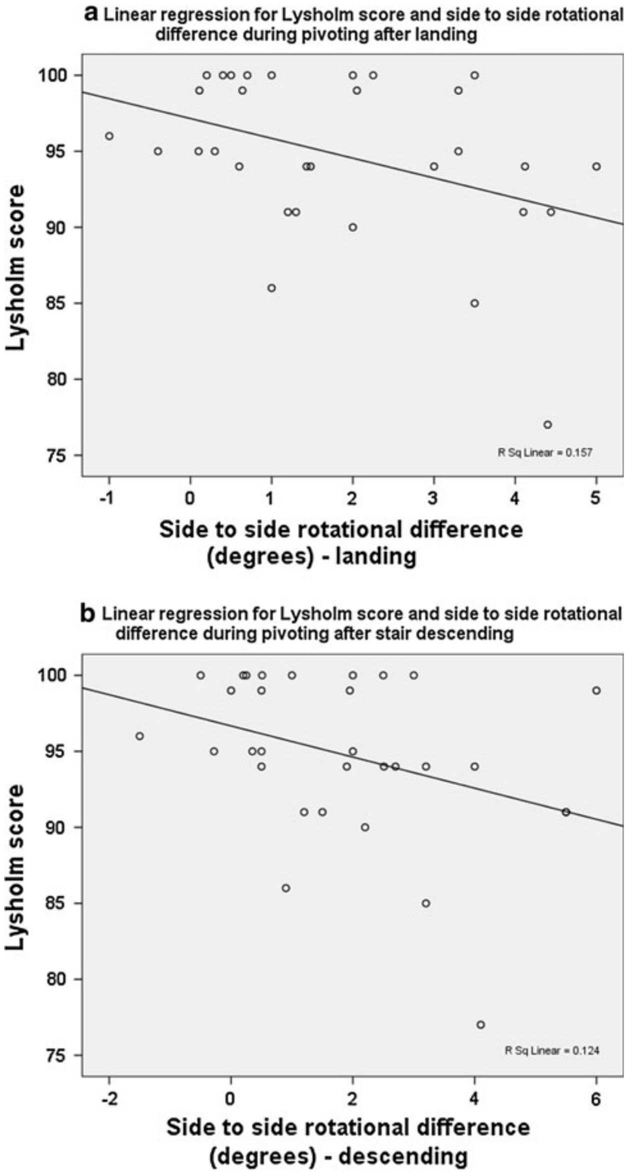

Fig. 2 SSDTR during the **a** descending and pivoting task and **b** the landing task is predictive of the Lysholm score with "small" to "none" effect sizes

of anterior tibial translation SSD nor of Tegner activity level for none of the two examined dynamic tasks.

These findings corroborate what has been previously demonstrated for the pivot-shift test, which correlates significantly with clinical knee symptoms and function after ACLR. More specifically, a positive pivot-shift test is associated with inferior subjective outcome scores, failure to return to previous level of sports participation and increased scintigraphic activity of the subchondral bone [21, 23]. In the present study, rotational knee kinematics during in vivo pivoting activities predict subjective functional outcome of the knee joint after ACLR, underlining the importance of in vivo knee joint biomechanics. Furthermore, this finding is even more clinically relevant as it applies to ACLR patients with a negative pivot-shift test. Therefore, it extends the importance of restoring rotational kinematics in the ACLR patient beyond the clinically detectable levels of the pivot-shift test to more subtle rotational kinematic differences.

In the present study, the difference between the TR of ACLR knee and the contralateral intact knee was the outcome of interest, and our results demonstrate the need to individualize the measurements for each patient. Recently, the SSD of TR that derives from the comparison to contralateral intact knee of ACLR individuals has been considered an imperative outcome variable [27]. As even small changes of the knee rotational motion contribute to cartilage thinning and damage of healthy cartilage [3], the restoration of rotational kinematics to normal levels for each patient is fundamental. In our study, the deviation from the normal kinematic pattern of contralateral intact knee predicts subjective knee joint function. The use of this measure is in accordance with the approach that Pearle et al. suggested [30] in their study where they used surgical navigation aiming to make surgery more precise, minimally invasive, and patient specific. These authors proposed the measurement of knee kinematics preoperatively and postoperatively, including a direct contralateral comparison with the intact knee with relevant information about knee kinematics and stability [30]. In accordance with prior studies, our findings underline the importance of restoring rotational control to the normal levels of each patient during dynamic activities with the aim to maximize quality of life for ACLR patients.

Interestingly, the rotational kinematics were more predictive of the subjective IKDC score than the Lysholm score. This possibly denotes that the IKDC subjective score may be a more sensitive outcome in assessing function after ACLR. One possible explanation for this result may be that the IKDC subjective score allows for a more detailed assessment of sports activities (through items 8 and 9) as compared to the Lysholm score, whereas the latter assigns greater weight to pain and instability than to the other items included in the scale. Additionally, the IKDC has high criterion-related validity for ACLR patients [31]. It should be underlined that the results of the present study apply only to BPTB ACLR patients and that no conclusions can be drawn for patients where a hamstrings autograft or allograft has been used.

On the other hand, rotational knee kinematics was not predictive of activity level as measured by the Tegner activity score. The clinical importance of this finding may be that the patients may have abnormal rotational movement pattern that is not noted, thus potentially leading to unrestricted resumption of athletic activities that involve jump-landing and pivoting and subsequent acceleration of degenerative changes. This is in accordance with prior studies that have shown increased risk of degenerative changes in the presence of abnormal knee movement pattern. The initiation and progression of knee joint osteoarthritis in patients with ACL injury has been related to abnormal knee joint biomechanics during dynamic in vivo activities [4], while similar pathogenetic role of abnormal rotational knee kinematics has been suggested also for ACLR patients [37]. This rotational offset causes the loading of specific regions of the articular cartilage that were not loaded prior to the ACL injury [4, 25], and the altered contact mechanics in the newly loaded regions could produce local degenerative changes to the articular cartilage of the knee joint [3].

It was also found that rotational knee kinematics were not predictive of anterior knee laxity. A possible explanation may be that the rotational kinematics were assessed during dynamic activities using in vivo motion analysis, whereas the anterior laxity was measured through a valid and widely used tool but during static conditions. This drastic difference between the two assessment modalities may be the most important factor that led to this outcome. The knee joint movement under dynamic conditions is a multiplanar motion. The screw-home mechanism of the knee refers to an “automatic” axial rotation that is inevitably and involuntarily linked to flexion and extension. When the knee is flexing the tibia internally rotates. As the knee extends, the femoral condyles roll and glide on the tibial condyles and the tibia externally rotates. At full extension the knee joint “locks” in a position of maximal stability (close-packed position) [22]. Therefore, the different circumstances under which the two motions were assessed (i.e., dynamic versus static joint loading) may be the most important factor that led to a lack of association between the movements in two planes. As previous authors have suggested, the forces placed on the knee joint during a static clinical exam are less than the forces acting on the knee during activity and thus, static, 1-dimensional testing cannot predict the behavior of the reconstructed joint under realistic loading conditions [38]. Many recent studies have used surgical navigation to assess knee joint kinematics intraoperatively with special attention to the multiplanar maneuver of the pivot-shift test [9, 30]. These authors have concluded that this maneuver involves dynamic translational and rotational motions while the knee is brought through a cycle of flexion. However, no test about the association between the motions that occur in the two planes has been carried out and no reference for comparison exists in the literature according to this finding.

There are certain limitations in this study. These are related to the use of skin markers in motion analysis [26]. There are certain circumstances under which, motion analysis is currently widely accepted and is considered as a well-established and reliable method [6, 40]. The interoperator error was minimized 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). A standing calibration procedure was used 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. Finally, our sample consisted of male patients with BPTB graft that does not allow for generalization of our findings to female patients or patients who had hamstrings or allograft reconstructions.

The present study does demonstrate for the first time that knee joint rotational kinematics as assessed by 3D motion analysis during dynamic pivoting activities predict functional outcome after BPTB ACLR. Thus, a clinically relevant message from this study may be that the in vivo rotational kinematics of the knee after ACL reconstruction may be theorized by the surgeons as a parameter closely related to the outcome assessment, as this was found to predict other well-known and established function outcome scores. Without overstating our results, the data of this study allow us to suggest that the in vivo biomechanics are a useful tool for orthopaedic surgeons even in routine clinical practice, whenever possible, and provide additional insight on the importance of knee rotational kinematics on long-term onset and progression of knee joint degenerative disease.

Conclusion

Restoring rotational kinematics during dynamic pivoting activities after ACLR is predictive of function. During realistic loading conditions of daily living and sports performance, SSDTR may be significant parameters that are related to the symptoms and function of the knee joint after ACLR.

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