Current Reviews in Musculoskeletal Medicine (2019) 12:41–49
https://doi.org/10.1007/s12178-019-09529-7

OUTCOMES RESEARCH IN ORTHOPEDICS (O AYENI, SECTION EDITOR)

The Pivot Shift: Current Experimental Methodology and Clinical Utility for Anterior Cruciate Ligament Rupture and Associated Injury

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Published online: 31 January 2019

Abstract

Purpose of Review The purpose of this manuscript is to (1) examine the history, techniques, and methodology behind quantitative pivot shift investigations to date and (2) review the current status of pivot shift research for its clinical utility for management of anterior cruciate ligament (ACL) rupture with associated injuries including the anterolateral complex (ALC).

Recent Findings The pivot shift is a useful physical exam maneuver for diagnosis of rotatory instability related to ACL tear. Recent evidence suggests that the pivot shift is multifactorial and can be seen in the presence of ACL tear with concomitant injury to secondary stabilizers or with predisposing anatomical factors.

Summary The presence of a pivot shift post-operatively is associated with poorer outcomes after ACL reconstruction. Recent clinical and biomechanical investigations can help guide clinicians in utilizing pivot shift in diagnosis and surgical planning. Further research is needed to clarify optimal management of ALC in addition to ACL injury.

Keywords Pivot shift · Anterior cruciate ligament tear · Anterior cruciate ligament reconstruction · Rotatory knee laxity · Anterolateral complex · Physical exam

Introduction

The optimal method of diagnosis and management of anterior cruciate ligament (ACL) ruptures continues to evolve with improved understanding of rotatory knee instability. Decision-making for treatment of ACL injuries depends on many factors, including level of activity or sport participation for the patient. Non-operative management of ACL tears can manifest as residual laxity or instability, especially during cutting, twisting, or pivoting motions. Consequently, it is crucial for clinicians to have an armamentarium of clinical tools, including accurate history taking, focused physical exam, and reliable diagnostic tests at their disposal.

This article is part of the Topical Collection on *Outcomes Research in Orthopedics*

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Understanding of the unique anatomy of the ACL is critical for accurately assessing laxity on physical exam. The ACL originates medially to the anterior intercondylar area of the tibia behind the anterior horn of the lateral meniscus. It travels posterolaterally through the knee joint to attach on the posteromedial aspect of the lateral femoral condyle [1]. Two separate bundles comprise the ACL with each performing a different biomechanical function (Fig. 1) [2]. The bundles function at different stages of knee motion with the anteromedial (AM) bundle taut at 90° of flexion and the posterolateral (PL) bundle tightening as the knee nears full extension. The AM bundle functions to restrain anterior tibial translation while the PL bundle is primarily responsible for controlling rotational stability.

Various diagnostic tests have been developed to evaluate for knee laxity secondary to ACL insufficiency [3]. Tests such as the anterior drawer and Lachman test for anterior tibial translation [4]. The Lachman test is a commonly performed technique as it has a high sensitivity for diagnosing ACL tear, as high as 94% to 98% in one study [5]. However, the Lachman test serves to only assess the AM bundle and fails to evaluate the ACL for objective rotational instability. Previous biomechanical evaluation of single-bundle ACL reconstruction using clinical maneuvers such as the anterior

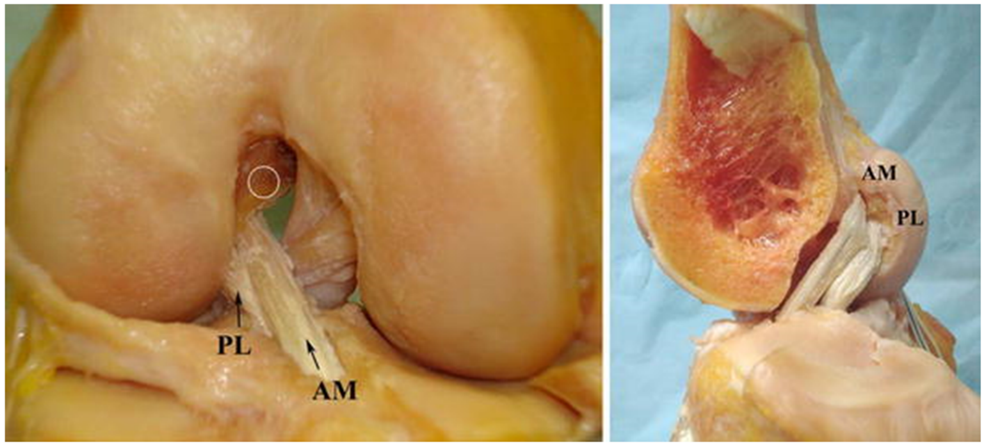

Fig. 1 Cadaveric representation of an anatomic double-bundle ACL reconstruction. The native relationship of the ACL to the PCL and intercondylar notch is reestablished. The circle marks the high AM position. (Reprinted with permission) [2]

drawer and Lachman test demonstrated adequate function resisting anterior tibial loads, but they failed to restore the native kinematics of the ACL under rotatory testing [6–8]. The diagnosis of rotatory instability related to ACL tear is crucial as pivot shift correlated more closely than Lachman test with positive patient-reported outcomes post-operatively [9]. Additionally, the presence of a pivot shift post-operatively after ACL reconstruction is associated with persistent complaints of subjective instability from patients and can predict the development of early arthritis [10, 11]. Initially described by Galway et al., the pivot shift test was developed to test for lateral compartment rotatory laxity related to ACL insufficiency [12]. Current descriptions of the pivot shift test for dynamic ACL insufficiency by evaluating axial and sagittal stability of the knee as it is taken from extension to flexion with an external rotation and valgus stress on the proximal tibia.

The pivot shift is theoretically the ideal test to dynamically evaluate the ligamentous status of the knee, which is especially crucial in diagnosing ACL deficiency, evaluating reconstructive techniques, and constructing treatment algorithms for patients with ACL injury [13, 14]. Currently, the pivot shift test is the most specific clinical test to detect ACL injury [15]. The methodology for standardizing the pivot shift has been described and shown to have improved accuracy [16]. However, many studies utilize alternative methods for testing and quantifying the pivot shift. Accordingly, the pivot shift has been the subject of considerable research interest over the past few years. Investigations have shown that pivot shift phenomenon is multifactorial and that high-grade pivot shift is generally associated with a secondary injury in addition to the ACL. Incomplete understanding of the causes of pivot shift can cloud treatment approaches and may predispose surgeons towards supplementary reconstructive techniques, such as addressing the anterolateral complex (ALC), without identifying the true nature of the pathology. The purpose of this review is to discuss the current status of pivot shift methodology and clinical utility as it relates to ACL rupture and associated injuries.

Pivot Shift Methodology

The historical criticism of the pivot shift mainly stems from the wide array of methods utilized for performing the maneuver [17]. The pivot shift can be inherently difficult to perform, and significant variability can exist between different examiners [18, 19]. The most commonly cited method of performing the pivot shift is: flexing the knee from 0° (full extension) to 90° of knee flexion while applying an external rotation stress to the tibia and a valgus stress to the knee [20]. A positive test is seen with a rapid anterior subluxation of the tibia at 20–30° of flexion as it reduces under the femoral condyles. Functionally, this is reproducing the event that occurs when the knee gives way due to ACL rupture. A slightly different technique in performing the procedure can affect the results; one recent study demonstrated significantly different pivot shift values with the tibia in internal versus external rotation when evaluating ACL-deficient knees [21]. Kuroda et al. described a most common variability in performing the maneuver with regard to flexion version extension type pivot shift and tibial rotation for the test, but they reported no significant differences between examiners for pivot shift acceleration or tibial translation [22]. Two major methods of teaching the pivot shift maneuver exist; either through real-time teaching from an instructor or passive learning through the use of instructional textbooks or videos. Comparing the two methods, the real-time teaching method demonstrated a higher success rate as this group was more effective at recreating the appropriate valgus and external rotation position [23]. The subject of a standardized pivot shift maneuver was discussed at the Panther Global Summit (Pittsburgh, PA, USA, August 2012) [24]. A subsequent study [25] testing 12 expert knee surgeons using their preferred method of pivot shift along with a standardized method (observed via video) was performed; the standardized test demonstrated good correlation between non-invasive (electromagnetic skin sensors, triaxial accelerometer, and image analysis) and direct (electromagnetic bone sensors) measurement parameters (Fig. 2).

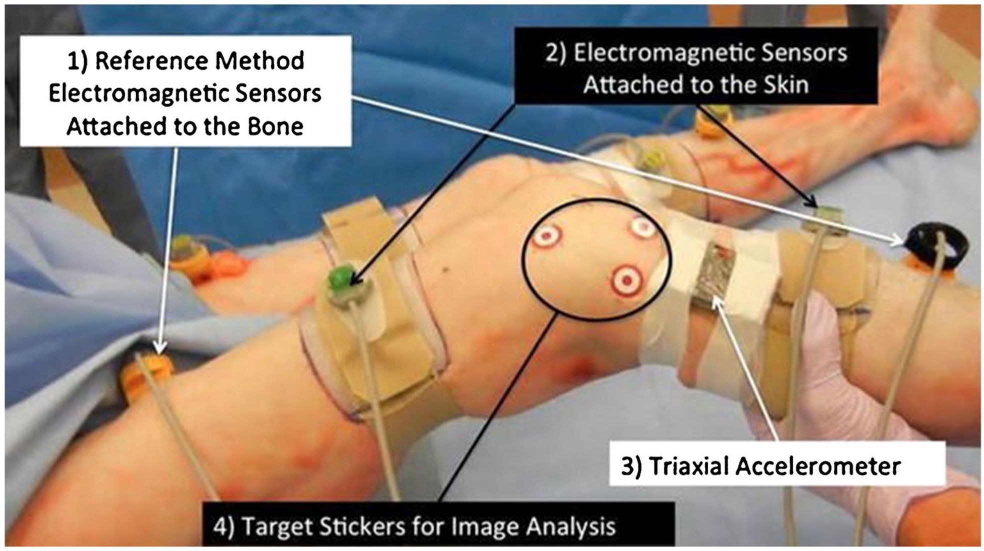

Fig. 2 Pivot shift quantification methods. (1) The electromagnetic tracking system attached to the bone (direct measurement), (2) electromagnetic tracking system attached to the skin (non-invasive measurement), (3) triaxial accelerometer (non-invasive measurement), and (4) image analysis system (non-invasive measurement). (Reprinted with permission) [25]

Subjectivity also exists in the grading systems described for quantifying the pivot shift. Various scoring systems have been proposed but none of these systems has been widely accepted due to the difficulty of assigning numerical values to factors that are not quantifiable [17]. In an ACL-deficient knee, the knee pivots from the medial tibial spine centrally to produce an anterior and medial subluxation. The lateral compartment then has exaggerated anterior tibial translation. The International Knee Documentation Committee (IKDC) classification defined a grading system for pathologic motion observed in a pivot shift test: grade 0 (normal), grade 1 (glide), grade 2 (clunk), or grade 3 (locked subluxation) [12]. A grade 3 pivot shift has been associated with poorer outcomes in clinical studies, including a possible earlier progression to knee osteoarthritis [11, 26].

Quantitative Assessment of the Pivot Shift

The methods for measuring pivot shift have shifted over the last decade. Previously, testing was performed predominately with computer navigation systems and electromagnetic sensor systems [13, 27, 28]. Other methods included biomechanical testing using cadaveric sectioning, serial radiographs, cable linear displacement transducers, and electro-goniometers with load cells [3]. More recent advancements have introduced inertial sensors and image analysis systems. One study found that 2D simple image analysis method and the 3D bony motion of the knee during the pivot shift test had similar outcomes [15]. This study concluded that the 2D simple image analysis is a non-invasive and repeatable tool to quantify the motion of the lateral knee compartment during the pivot shift test. The primary outcomes of interest for inertial sensors are lateral compartment translation and acceleration. It has been suggested that measurement of acceleration of the tibial reduction during the pivot shift can be performed in the office setting using just a single accelerometer [29]. Inertial sensors have also been used to quantify differences in lateral compartment motion between "high-grade" and "low-grade" laxity knees as tested by the IKDC machine [30]. Computer programs such as the KiRA acquisition system (KiRA, Orthokey LLC, Lewes, DE, USA) have been evaluated for as a potential method of standardized objective recording [31]. An iPad (iPad, Apple Inc., Cupertino, CA, USA) application has also been developed with encouraging initial results [24] (Fig. 3) [32]. Despite several studies on navigation systems, electromagnetic sensors, and other devices, issues with inconsistent methodology and technique have limited objective measurements to the research realm [29].

Permutations of Technique

No standardized validated system or technique is widely used. Study methodology varies frequently in outcome measure, manual versus mechanized testing, awake versus anesthetized testing, gravity-assisted pivot shift testing, or other subtle nuances in leg positioning while achieving the pivot shift. A number of in vitro cadaveric studies have been performed to simulate the pivot shift using a variety of different outcome measures including internal rotation torque, valgus torque, and iliotibial tract tension [20]. The outcomes most frequently reported are lateral compartment translation and tibial internal rotation. Musahl et al. examined the differences between manual and mechanized pivot shift testing. They found that in the ACL-deficient knee, manual pivot shift testing was associated with significantly higher tibial translation and rotation, suggesting that mechanized pivot shift measurement may be a more reliable and consistent grading method [33]. One of the main

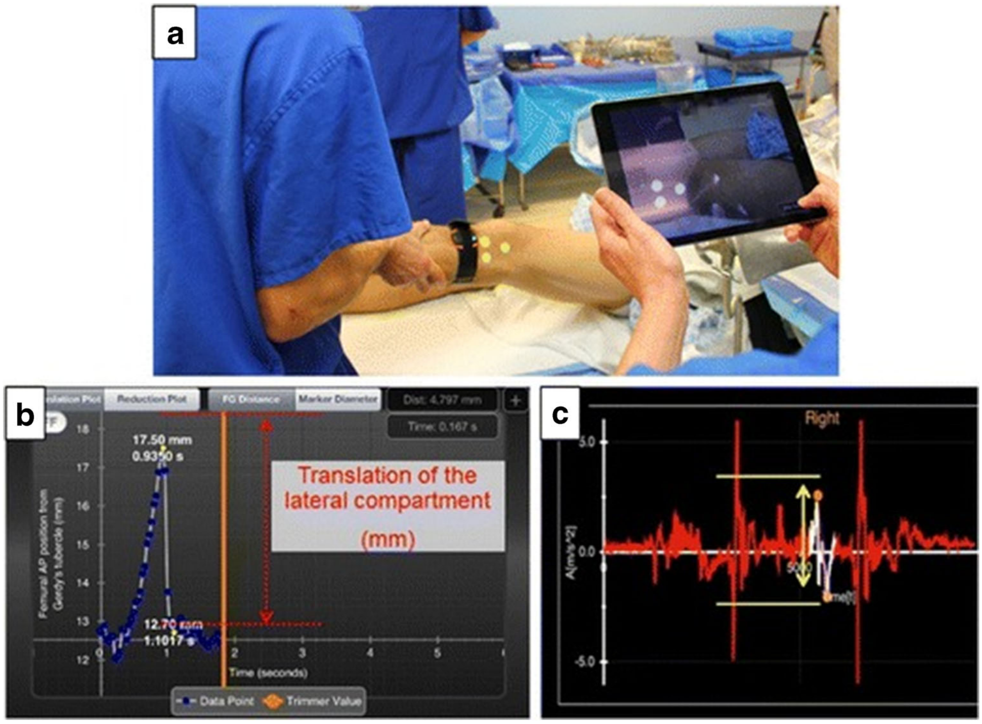

Fig. 3 **a** The PIVOT iPad application software and KiRA accelerometer in clinical use. **b** The anterior translation of the lateral knee compartment in the PIVOT software interface. **c** The measured acceleration curve per unit time is plotted by the KiRA software. (Reprinted with permission) [32]

difficulties is that muscular resistance can suppress the pivot shift phenomenon and therefore many studies have performed the testing under anesthesia rather than with patients awake [34, 35]. The pivot shift has been reported to have higher sensitivity when performed under anesthesia than with awake patients [5]. The gravity-assisted pivot shift has been described and utilized in previous studies [36, 37]. Gravity-assisted pivot shift is performed with awake patients and is regarded as positive with lower leg internal rotation suddenly with the knee subluxating at an angle of approximately 20° of flexion, followed by the reduction with knee flexion. Testing with gravity assistance has been suggested as a more reliable test for predicting patients who may have worse post-operative function after ACL reconstruction [36].

Recent Pivot Shift Investigations

The pivot shift is a complex maneuver combining both translation and rotation of the tibia relative to the femur. The cause of the pivot shift is theorized to involve ACL injury as well as secondary stabilizers of the knee such as the menisci, meniscal roots, meniscotibial ligaments, collateral ligaments, capsule, ALC, and bony morphology of the femoral condyles and tibial plateau [10, 26, 38–41]. Accordingly, investigations into the individual and combined contributions of various anatomic structures towards rotatory knee instability have been performed in the last few years. The pivot shift has been utilized extensively in these recent investigations.

Meniscal Injury

Concomitant meniscal injury occurs commonly with ACL tear. Failure to recognize these injuries may lead to poorer outcomes after ACL reconstruction [42]. Disruption of the circumferential meniscal fibers seen in the meniscal body and root tears leads to compromised biomechanical function and functional loss of secondary restraint. MRI evidence of a concomitant injury to both the medial and lateral menisci is associated with increased knee rotatory instability in patients with an ACL injury [43]. A recent study evaluated the correlation between the pivot shift and lateral compartment acceleration in patients undergoing primary single-bundle ACL reconstruction [40]. It was shown that knees with combined ACL and lateral meniscus injury demonstrated increased lateral compartment acceleration and translation compared to ACL injury alone. Song et al. also reported pivoting sport involvement at time of injury and combined lateral meniscal injuries as additional risk factors associated with a high-grade pivot shift after ACL injury [44•]. Shybut et al. examined lateral meniscal root injuries in ACL-deficient knees in human cadaveric robotic testing [45]. It was shown that combined injury with lateral meniscal root demonstrated significantly higher anterior tibial translation but no significant difference with Lachman testing.

Meniscotibial Ligaments

"Ramp lesions" or tears at the peripheral attachment of the posterior horn of the medial meniscus at the meniscocapsular junction have been suspected to play a role in rotatory instability. DePhillipo et al. examined the biomechanical contributions of the meniscocapsular and meniscotibial attachments of the posterior medial meniscus by performing robotic human cadaveric testing. It was reported that injury to meniscocapsular and meniscotibial lesions of the posterior horn of the medial meniscus increased pivot shift in ACL-deficient knees, and the pivot shift was not restored after isolated ACL reconstruction [46]. A recent study by Pfeiffer et al. looking at the biomechanical profile of ramp lesions before and after repair with simulated ACL reconstruction found that ramp lesion repair with all-inside technique at 10° of knee flexion resulted in decreased anterior translation, increased valgus rotation, and increased bony contact forces in the lateral compartment suggesting potential over-constraint with repair [47].

Bony Morphology

Previous investigations have described the association between a smaller medial-to-lateral tibial plateau diameter and a high-grade pivot shift [39]. One recent study [48] examined the correlation between lateral femoral notch depth and rotatory knee instability. No correlation between rotatory instability using quantitative pivot shift of ACL-injured patients and lateral femoral notch depth was shown; however, they did note a significantly higher rate of associated lateral meniscus injury. Lateral tibial plateau slope has also been shown to have greater correlation with high-grade rotatory laxity with pivot shift testing; compared with the low-grade rotatory laxity group, high grade had a larger slope (9.3 ± 3.4° versus 6.1 ± 3.7°) [49]. Interestingly, another study reported that having a slope less than 5.5% had an association with high anteroposterior laxity at 30° and 90° of flexion [50]. Branch et al. examined a group of patients who had undergone ACL reconstruction and evaluated their bony morphology radiographically. A significantly higher rate of post-operative pivot shift was observed when patients had a higher femur-tibia size ratio (FRSR), when the femur was larger relative to the tibia, or a smaller tibia to posterior femoral condyle ratio (TPFCR), and when there was smaller tibial depth relative to the depth of the lateral posterior condyle [51].

Hypermobility

Joint hypermobility and ligamentous laxity are important factors to assess when evaluating a patient with ACL injury. Ligamentous laxity can be tested using the Beighton criteria, which is a measure of five joint movements and is interpreted based on a maximum score of 9, with scores greater than or equal to 4 being classified as hypermobile [52]. For patients with generalized hypermobility, a recent study showed greater laxity with pivot shift testing in the contralateral uninjured knee in patients with high Beighton hypermobility scores compared to those without hypermobility [53]. Interestingly, a high Beighton score did not correlate with any difference in pivot shift testing for the ACL-injured side. Pfeiffer et al. also examined generalized ligamentous laxity and knee hyperextension as measured in collegiate athletes without a history of knee injury [54]. Significantly higher anterior translation of the lateral compartment was observed during pivot shift in females, but no correlation with knee hyperextension or Beighton criteria was found.

High-grade Laxity

Several studies have investigated what factors play a role in a high-grade pivot shift. Magnussen et al. [55] reported chronic ACL injury, age greater than 20, and female gender to be factors associated with high-grade pivot shift. High-grade pre-operative pivot shift testing and knee hyperextension were found to be associated with higher risk of post-operative pivot shift after ACL reconstruction [56]. Song et al. reported on a comparison between low-grade and high-grade pivot shift patients with acute ACL injuries [41]. It was shown that the high-grade pivot shift group had a significantly higher prevalence of concomitant ALC injury on MRI. In knees designated as "high-grade laxity" with IKDC testing, both lateral compartment motion measured with image analysis and tibial acceleration measured with the inertial sensor were significantly higher compared to the "low-grade" group [30].

Remnant ACL

Kitamura et al. examined the effects of remnant ACL tissue preservation in improving long-term rotational laxity as measured by pivot shift [57]. They reported significantly improved anterior tibial translation and acceleration of posterior translation with pivot shift at 12 months compared to immediately post-operatively. It was suggested that the remnant tissue aided with healing and reported a significant association with the amount of tissue available to cover the graft at index surgery.

Contributions of the ALC

A recent consensus article discussed the anatomy, function, and current body of literature for the ALC [58•]. While some biomechanical studies have demonstrated that the ALC contributes to stability at the time of ACL reconstruction, some concerns remain about the possibility for over-constraining the lateral compartment. Optimal strategies for lateral extra-articular augmentation procedures are not clear as clinical evidence is currently lacking for specific indications. Debate exists as to the importance of the ALC when compared with the ACL and the iliotibial band (ITB) [58•].

The ALC has been investigated extensively over the last several years in relation to ACL injuries and its contributions to rotatory instability. Cadaveric testing has been performed to evaluate the effect of the ALC; one study reported that ACL- and ALC-injured knees had significantly increased internal tibial rotation compared to the intact knee, but isolated ACL injury did not [59]. Noyes et al. performed cadaveric robotic testing and found that sectioning of the ALC after ACL reconstruction resulted in a small increase in internal rotation torque at high flexion and modestly reduced the forces seen by the ACL graft but did not change lateral compartment translation [60]. It was observed that pivot shift was increased at 20–30° of knee flexion. Bell et al. found that the ALC played a significant role as a secondary stabilizer at flexion angles greater than 60°. In this study, the dissected anterolateral ligament had a negligible contribution to rotatory knee instability (Fig. 4) [61•].

Lateral Extra-articular Tenodesis

Cadaver testing of lateral extra-articular tenodesis (LET) in ACL-deficient and reconstructed knees was performed by Herbst et al. [62]. It was shown that ACL reconstruction in combination with LET reduced anterior tibial translation and internal tibial rotation with pivot shift testing in the setting of a knee with pre-existing ACL and ALC injury; for those patients with isolated ACL injury treated with reconstruction and LET, the end result was over-constraining of the knee. Monaco et al. reported that the addition of LET to ACL reconstruction resulted in little change to measured anterior displacement of the tibia at 30° of flexion, but it was more effective than isolated ACL reconstruction at reducing tibial rotation [63].

A clinical study examining chronic ACL injuries and resultant treatment with ACL with or without LET found that the addition of the LET was associated with significantly improved IKDC, Lysholm scores, and KT-1000 scores [64]. A lower rate of post-operative pivot shift with ALC capsular procedure was observed; however, they did not quantify this result.

ITB and Association with ALC

A number of studies have investigated the role of the ITB in its role relating to the ALC. Kittl et al. performed a biomechanical sectioning study; it was reported that the ITB made a greater contribution than the ALC to internal rotation control at larger flexion angles, with the ACL having its greatest contribution closer to extension [65]. Huser et al. also performed cadaveric robotic testing in cadaveric specimens with intact ACL to determine the contributions of the ALC and ITB to potential for pivot shift [66]. It was found that sectioning the ALC alone had no effect on lateral compartment translation or internal rotation under any loading condition, while ITB sectioning resulted in small increases in IR at 60 and 90° of flexion. A combined injury to ALC and ITB (with intact ACL) resulted in clinically undetectable but small increases in pivot shift internal rotation and lateral compartment translation. Similarly, Geeslin et al. examined the roles of the ALC with the Kaplan fibers of the distal ITB in ACL-deficient knees using robotic testing of human cadaveric specimens [67]. Sectioning the Kaplan fibers was found to lead to greater tibial internal rotation at high flexion angles (60–90°) as compared with sectioning of the ALC. Another biomechanical study examining ACL with combined simulated ALC injury compared LET using a Lemaire procedure with an ALC reconstruction; it was concluded that the LET restored normal laxities at all angles of flexion for graft fixation (0°, 30°, or 60°), with the ALC reconstruction only restored intact knee kinematics when tensioned in full extension [68]. In a clinical study, Porter et al. examined a group of patients who had residual pivot shift intraoperatively after revision ACL reconstruction who then underwent ITB tenodesis as a supplementary procedure [69]. ITB tenodesis resulted in a significant

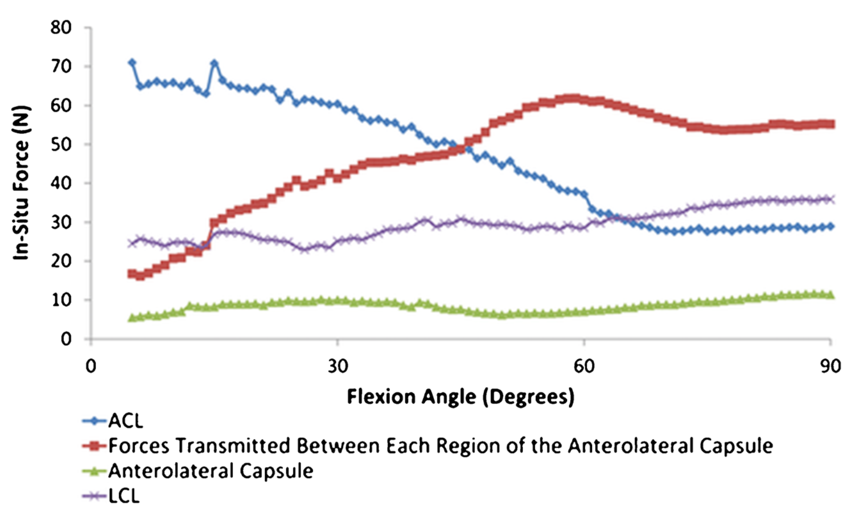

Fig. 4 The in situ force in the ACL and the anterolateral structures throughout the range of flexion for the intact knee (newtons, mean). (Reprinted with permission) [61•]

decrease in anterior tibial translation and in internal tibial rotation. No significant differences were noted in Tegner activity scores post-operatively.

Conclusions

The pivot shift phenomenon is multifactorial. With growing evidence that meniscal, meniscocapsular, and ALC injury may play a role in rotatory knee instability, it is important for the clinician to be aware of concomitant soft tissue injuries with planned ACL reconstruction procedures. Additional patient anatomic factors such as bony morphology or ligamentous laxity should also be considered. While lateral extra-articular tenodesis procedures are regaining popularity, further research is needed to clarify individual contributions of ligamentous structures and to solidify a standardized testing and grading methodology of the pivot shift.

Compliance with Ethical Standards

Conflict of Interest Nicholas J. Vaudreuil, Benjamin B. Rothrauff, and Darren de Sa declare no conflict of interest.

Volker Musahl has done consulting work for Smith & Nephew.

Human and Animal Rights and Informed Consent All reported studies/experiments with human or animal subjects performed by the authors have been previously published and complied with all applicable ethical standards (including the Helsinki declaration and its amendments, institutional/national research committee standards, and international/national/institutional guidelines).

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