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Individualized ACL reconstruction

Paulo H. Araujo · Mauricio Kfuri Junior · Bruno Ohashi · Yuichi Hoshino · Stephano Zaffagnini · Kristian Samuelsson · Jon Karlsson · Freddie Fu · Volker Musahl

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Abstract The pivot shift test is the only physical examination test capable of predicting knee function and osteoarthritis development after an ACL injury. However, because interpretation and performance of the pivot shift are subjective in nature, the validity of the pivot shift is criticized for not providing objective information for a complete surgical planning for the treatment of rotatory knee laxity. The aim of ACL reconstruction was eliminating the pivot shift sign. Many structures and anatomical characteristics can influence the grading of the pivot shift test and are involved in the genesis and magnitude of rotatory instability after an ACL injury. The objective quantification of the pivot shift may be able to categorize knee laxity and provide adequate information on which structures are affected besides the ACL. A new algorithm for rotational instability treatment is presented, accounting for patients' unique anatomical characteristics and objective measurement of the pivot shift sign allowing for an individualized surgical treatment.

Level of evidence V.

Keywords Pivot shift · ACL reconstruction · Individualized ACL reconstruction · Anterior cruciate ligament · Treatment · Clinical examination · Physical examination · Rotatory laxity

P. H. Araujo (✉) · M. Kfuri Junior
Department of Biomechanics, Medicine and Rehabilitation of Locomotor System - Ribeirao Preto Medical School, São Paulo University, Av. Bandeirantes, 3900 - Monte Alegre, Ribeirão Prêto CEP 14049-900, SP, Brazil
e-mail: pauloaraujo@hotmail.com

B. Ohashi · F. Fu · V. Musahl
Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, PA, USA

Y. Hoshino
Department of Orthopaedic Surgery, Kobe Kaisei Hospital, Kobe, Japan

S. Zaffagnini
Istituto Ortopedico Rizzoli, University of Bologna, Bologna, Italy

K. Samuelsson · J. Karlsson
Department of Orthopaedics, Sahlgrenska University, Göteborg, Sweden

Introduction

Individualized ACL reconstruction is described as the objective evaluation of knee functional anatomy and patient's individual characteristics to guide surgeons towards the restoration of the ACL and other knee anatomical structures as closely as possible to the native state, which will favourably impact on the joint function [30].

The development of standardized physical examination techniques, as well as quantified methodologies to diagnose ACL deficiency has recently been described [35, 37, 38, 55]. Utilizing these methodologies, it will increasingly be possible to not only diagnose, but also quantify specific laxity patterns revealing partial, complete or combined ACL with associated injuries.

The positive pivot shift test can detect persistent rotatory knee laxity, like no other manual test to detect ACL insufficiency. Additionally, a positive pivot shift following ACL reconstruction correlates with poor subjective and objective outcome, failure to return to play to pre-injury level, and can predict osteoarthritis development in the knee [43, 44]. Therefore, the goal for the treatment of the ACL-deficient knee should be to eliminate the pivot shift sign, whilst maintaining other clinical parameters such as complete range of motion and normal muscle strength in a painless knee allowing for a better outcome [65].

Surgical techniques have evolved as well. Many arthroscopic ACL reconstruction techniques are available and have applicability for individualized ACL reconstruction. These techniques include utilization of different grafts, fixation devices, techniques for tunnel establishment, as well as single-bundle, two–bundle or extra-articular reconstruction.

Additional factors have to be taken into account when performing an individualized surgery, such as patient's preferences, type of sport and activity level, revision ACL surgery or concomitant ligament injuries around the knee.

This article summarizes how anatomical structures affect physical examination and the pivot shift phenomenon. Current research on quantitative pivot shift measuring devices is also presented. The quantification of the pivot shift test would provide valuable information to categorize these knees into groups of injured structures, thereby providing a new treatment algorithm, which is the ultimate goal of individualized ACL reconstruction.

The anatomical ACL reconstruction concept

Anatomical ACL reconstruction has as major goals to functionally restore ACL native dimensions, collagen orientation and insertion sites [83]. To achieve these purposes, single- or double-bundle ACL reconstructive surgery can be performed, as long as the surgeon uses anatomical principles. When performing anatomical ACL reconstruction, insertion site visualization is of paramount importance in order to achieve an anatomical positioning of the graft. The three–portal technique [8] has been shown to improve the visualization of the tibial and femoral insertion sites. Measurements of the tibial insertion site and intercondylar notch are crucial for an individualized approach to the patient's knee instability. Tibial insertion sites of <14 mm are more suitable for a single-bundle reconstruction to avoid overstuffing the joint. Insertion sites >18 mm may be better served with a double-bundle reconstruction since it would cover a larger percentage of the native insertion site. The intercondylar notch is another anatomical reference that can be used when deciding between single- and double-bundle reconstruction. A notch of <12 mm width may be small for placement of two tunnels. Also, a shallow notch (<12 mm) may lead to impingement of the graft [34].

When performing an individualized surgery, all types of grafts should be considered. Tendon thickness can be predicted on MR imaging for the quadriceps tendon and for the patellar tendon [6]. Prediction of graft thickness is difficult for the hamstrings [58], but its use has increased due to ease of harvesting and low morbidity.

Pivot shift test

The pivot shift test determines dynamic rotatory knee laxity. After the first description of the test by Galway and MacIntosh [28], many other variations have been described [20, 40, 56], but despite the technique to produce the pivot shift phenomenon, the interpretation of the pivot shift test has been subjective and examiner dependent [9, 42, 48, 64, 70].

The attempt of quantifying the pivot shift test has been present for a long time. Noyes et al. [70] studied 11 different surgeons in performing the pivot shift test and found large variation in kinematics. They noted that clinical examination should be standardized and instrumented methodologies should be developed.

Hoshino et al. [35] developed a standardized manoeuvre for the pivot shift test. The manoeuvre is broken up into three steps (Fig. 1). Using the standardized technique, a more consistent quantitative evaluation was achieved in their study.

Clinical grading systems are used worldwide to estimate surgeons' sensation during the pivot shift test [33, 35, 42, 48, 70]. However, the grading systems rely on examiners' interpretation and lack of objectiveness, thus raising the need for laxity measurement methods allowing for its use in research, post-operative outcome and comparison of

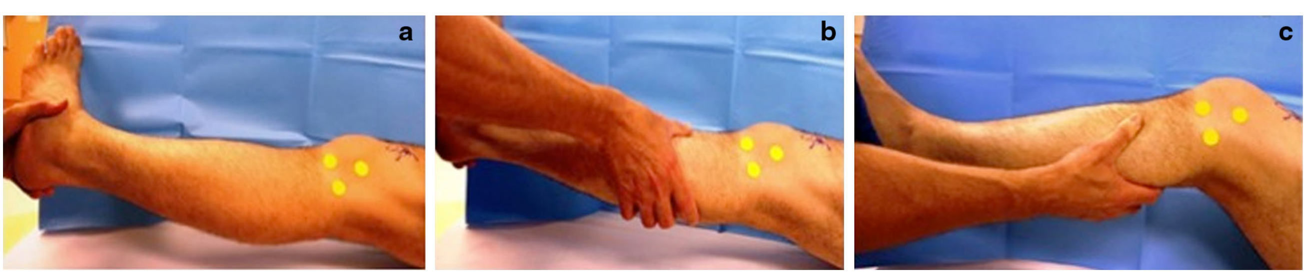

Fig. 1 Standardized pivot shift manoeuvre divided into three steps. **a** Internal rotation in knee extension. **b** Gentle valgus torque is applied. **c** The knee is flexed whilst releasing the internal rotation during knee reduction

surgical procedures. The objective quantification of the kinematics components of the pivot shift could, therefore, deliver the basis for an individualized approach to treatment based on reduction in rotatory knee laxity [50].

Quantitative measuring devices

In order to objectively quantify the pivot shift test, research has been conducted to decompose the pivot shift phenomenon into quantifiable parameters [10, 13, 15, 38, 49, 51, 54, 60, 74]. Of these, tibial translation and acceleration of tibial reduction were shown to provide consistent measures for the shift phenomenon [7, 13, 36, 38, 41, 47, 48, 51, 53–55, 60].

Many devices to quantitatively measure rotatory knee laxity have been developed and proposed [3]. Systems based on robotic technology [22], MR images [24, 32, 73, 81], electromagnetic tracking (EMT) system [38], intra-operative navigation [13] and non-invasive navigation [57] are well described in the literature, however, lacking in clinical applicability due to their complexity, invasiveness or high costs. Other non-invasive devices such as the EMT sensors [38] attached to the skin, the inertial sensors [45, 55] and the image analysis system [37] were developed and are more applicable for the clinical setting. Nevertheless, these systems are not exempt of limitations and still require research efforts to improve clinical applicability.

Evolution of quantitative pivot shift analysis

Jakob et al. [42] compared radiographic measurement of the tibial anterior translation under the anterior drawer stress to the clinical pivot shift test grading, demonstrating the positive relationship between anterior tibial translation and clinical pivot shift test grading. However, this system could not evaluate the knee movement at the time of the pivot shift test nor the rotational angle.

Hysteresis of anteroposterior tibial translation and tibial axial rotation during the pivot shift test has been reported as a potential parameter for assessing rotational laxity using computer navigation [13, 51]. A mechanized pivot shift simulator enables constant application of combined rotational stress and more consistent translation in the evaluation of ACL-deficient knees [68]. Decomposition of the pivot shift test also revealed that the pivot shift movement can be more evidently captured by monitoring lateral compartment translation [11].

Based on the findings of navigation system studies, the lateral translation during the manually performed pivot shift test emerged as a potential parameter to quantifiably assess the pivot shift. Hoshino et al. [37] attempted to evaluate the lateral compartment translation non-invasively using a simple image capturing and analysis. In their method, a video of the pivot shift test was recorded from the lateral aspect of the knee. Shifting movements were successfully detected using skin markers on bony landmarks after a frame-by-frame analysis of the video. The image analysis protocol was then installed into an iPad® (Apple, Cupertino, CA, USA) application. This evolving technology enables for an automated evaluation of the images without the need of a "manual" frame-by-frame analysis of the pivot shift video. The amount of lateral compartment translation and the reduction curve is recorded by the application. This technology is able to discern between injured and contralateral knees as well as between low-grade and high-grade injuries [36].

Electromagnetic tracking systems have also been used to measure the six degree-of-freedom knee kinematics of the knee joint during the pivot shift test. Bull et al. [15] demonstrated the translational and the rotational shifts during the pivot shift test and the wide variation of those measurements between the knees and the examiners. Hoshino et al. [38] utilized a non-invasive EMT system to calculate the acceleration of the tibial posterior reduction movement during the pivot shift. They found that both the tibial translation and the acceleration were correlated with the clinical grading of the pivot shift test. Since then, the relationship between the acceleration of the tibial reduction and clinical grading has been repeatedly reported using other measurement systems, such as accelerometer and navigation [49, 51, 55, 60]. Labbe et al. [49] found that the acceleration is more related to the clinical grading than to the tibial translation.

As increased attention was paid to the acceleration measurement, the potential usability of inertial sensors has been tested. A surge of the acceleration was successfully observed during the pivot shift test not only when the accelerometer was fixed into the tibia [55], but even when simply attached with a strap to the skin over the tibia [60] (Fig. 2).

When considering the clinical application, a quantitative evaluation system should be non-invasive, simple and portable. The image analysis of the lateral translation by iPad® (Apple, Cupertino, CA, USA) (Fig. 3), the acceleration and the electromagnetic system might be possible choices for the quantification of the pivot shift test, although these newly developed systems have yet to be fully validated. Further basic and clinical studies are warranted to verify these new evaluation systems.

Anatomical features and associated lesions that may affect knee laxity

Different factors contribute to rotatory knee laxity. Bull and Amis described primary (ACL) and secondary

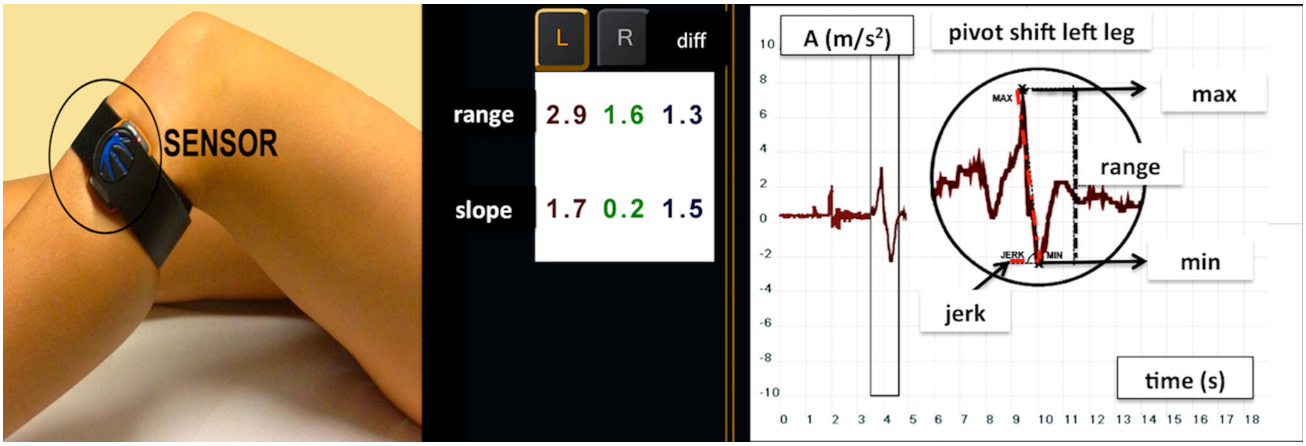

Fig. 2 Use of inertial sensors to measure the acceleration during tibial reduction in the pivot shift phenomenon. **a** Inertial sensors attached to the skin. **b** Acceleration graphic provided by the instrument

Fig. 3 Display of iPad® (Apple, Cupertino, CA, USA) application measuring the anterior translation of the lateral compartment of the knee during the pivot shift test

restraints (collateral ligaments, menisci and joint capsule) for the envelope of laxity [15]. However, it remains unclear what the force distribution is in each of the restraints to maintain the envelope of laxity of the knee [67].

ACL-deficient knees can show different response patterns during the pivot shift test when compared with each other depending on patient's specific anatomy and associated lesions. An adequate treatment for each knee would require an individual approach to the injured ACL, but should also look at the knee envelope of laxity and analyse each knee injury accounting for their anatomical characteristics.

ACL anatomy and partial tears

Over the past decades, the anatomy of the native ACL has been one of the most important fields of study in knee surgery. Nowadays, it is generally accepted that the native ACL has at least two bundles, the anteromedial (AM) and the posterolateral (PL). The AM and PL bundles function in different angles of knee flexion, working to increase knee stability against multidirectional forces applied to the joint. The AM bundle bears maximum load at around 45° of knee flexion whilst the load bearing of the PL bundle increases towards full extension [4, 5, 27]. The AM bundle better restrains anterior translation around 45°–60° of knee flexion whilst the PL bundle is the most important restraint against anterior tibial translation towards full extension [77] and against rotatory loading [86].

In view of this different biomechanical behaviour, partial tears of the ACL are more likely to occur according to the position of the joint and the energy transmitted during trauma [16]. These incomplete tears of the ACL can be defined and classified in different ways regarding to their functionality, overall knee laxity, amount of remaining fibres or bundle integrity. Dejour et al. [19] classified as "functional" a preserved bundle that during arthroscopic probing can resist further stretching. When the remaining bundle shows laxity and the examiner can stretch it significantly further, it is classified as a "non-functional" partial rupture. For Noyes et al. [71], the definition of partial tear was based on the percentage of ACL fibres torn. Partial tears that involve between one-half to three-fourths of the ligament diameter had a great probability to develop a complete ACL deficiency.

The pivot shift test may also detect the pattern of the partial ACL tear, i.e. answer the question if each bundle is torn and if each bundle is still functional. Using acceleration parameters via an electromagnetic system, Araki et al. [18] compared partial and complete tears of the ACL. Decreased knee laxity was found in patients with partial tears during the Lachman test and the pivot shift test. Mean acceleration of tibial reduction was significantly reduced in partial tears when compared with complete tears.

Augmentation surgery with preservation of a functional AM or PL bundle has demonstrated good results. Sonnery-Cottet et al. [79] performed 36 AM bundle reconstructions, achieving a significant difference in side-to-side difference between pre-operative (4.8 mm) and post-operative (0.8 mm) instrumented laxity. Adachi et al. [2] performed augmentation procedures in 40 patients and compared with "traditional" ACL reconstruction, with a minimum follow-up of 2 years. Post-operative anterior translation and the final inaccuracy of joint position sense were significantly less in the augmentation group.

Healing process and proprioception following an ACL reconstruction or augmentation surgery might be improved by the preservation of the ACL remnants. The remnants may provide a proprioceptive function due to the presence of neural mechanoreceptors which can improve joint position sense [1, 30, 72]. Histological studies revealed improved healing potential due to the vascular support provided by the epiligamentous tissue [39]. Also, the remnants may serve as a mechanical restraint in anterior knee stability to some extent [17].

Collateral ligaments and lateral structures

The pivot shift phenomenon is initiated when a valgus torque is applied to the knee and internal tibial rotation torque forces the ACL-deficient knee plateau into subluxation whilst the knee is extended as described by Galway and MacIntosh [29] The pivot shift occurs as the plateau suddenly reduces when the knee is flexed beyond 25 degrees of knee flexion. It has been described that the pivot shift is diminished with complete disruption of the medial collateral ligament (MCL) [61] and accentuated with disruption of the iliotibial band (ITB) [80].

The pivot shift sign is composed of both anterior translation and internal rotation displacement of the tibia in relation to the femur during subluxation. Because of these characteristics, lesions of the lateral structures have been implied to accentuate the pivot shift test [19, 40]. However, it was demonstrated in a cadaveric study that massive lesions of the lateral structures including the ITB, lateral collateral (LCL) ligament and popliteus tendon without injury to the ACL are not capable to produce the pivot shift sign. Yet, isolated ACL injury elicits the pivot shift sign [25]. On the other hand, when both the ACL and lateral structures are injured, the pivot shift sign magnified substantially [25].

Zantop et al. [87] demonstrated in a cadaveric study using a robotic system that the sectioning of the ACL increased the anterolateral rotational instability (ALRI). Also, the additional lesion of the LCL further increased ALRI, whilst the popliteus tendon and popliteofibular ligament injuries did not have a significant impact on ALRI. The authors concluded that the LCL is a secondary knee stabilizer after the ACL against a combined rotatory (valgus and internal rotation) load.

Using a computer-assisted navigation system, Bedi et al. [10] demonstrated that anterior tibial translation is higher in the lateral compartment compared with the medial compartment in knees with a positive pivot shift. They sequentially cut the ACL, medial meniscus and lateral meniscus to produce increasing magnitudes of pivot shift. The study demonstrates the importance of the lateral structures in restraining against the shift phenomenon.

Menisci

The medial and lateral menisci are secondary stabilizers of the knee. In order to specify the functions of each meniscus in knee stability, Musahl et al. [63] studied 16 hip-to-toe cadaveric specimens. Lateral meniscectomy led to a substantial increase in the anterior tibial translation during the pivot shift. On the other hand, the medial meniscectomy had no significant additional effect on the pivot shift. However, medial meniscectomy produced an increased anterior tibial translation under a standardized Lachman's examination compared with the ACL-deficient knees. The same effect was not found after a lateral meniscectomy. The results of this study demonstrate that the lateral meniscus acts as a restraint to anterior tibial translation during the pivoting phenomenon, whilst the medial meniscus is the main secondary restraint to direct anterior tibial translation during Lachman's examination.

Bony morphology

Friden et al. [26] analysed 100 patients with an ACL injury and found that an increased height-to-sagittal depth ratio of the femoral condyles, i.e. a more spherical condyle was associated with a high index of persistent instability.

Kujala et al. [46] studied 20 patients with a chronic ACL injury and found a correlation between instability history and increased slope of the lateral tibial plateau. They also found a link between greater convexity of the lateral plateau and higher grades of the pivot shift test. Musahl et al. [62] examined 49 patients with ACL injury under anaesthesia. It was found that a smaller coronal diameter of the lateral tibial plateau contributed to patient's higher-grade pivot shift.

A decreased tibial slope was found to be protective against anterior tibial translation in ACL-deficient knees [31, 52]. Brandon et al. [14] compared an ACL-deficient group ($n = 100$) with a control group ($n = 100$) and found that an increased tibial slope is associated with ACL rupture and higher grades in the pivot shift test.

Generalized ligamentous laxity

Generalized ligamentous laxity is a risk factor for ACL injury [69, 82] and has been cited as a cause for an anterior laxity of the knee even without an ACL lesion [50]. Moreover, in ACL-deficient knees, patients with hyperlaxity may increase the grade of pivot shift observed in physical examination [50] and also, even after an ACL reconstruction, some authors believe that the risk of instability in patients with generalized ligamentous laxity is greater than in normal patients [78].

Inferior results in patients with generalized ligamentous laxity may be explained by the inherent connective tissue extensibility of secondary knee restraints and autografts used in ACL reconstruction [75, 78].

Algorithm for ACL reconstruction

The quantification of rotatory knee laxity is of paramount importance for an ACL treatment algorithm establishment. Therefore, reliable tools to quantify the pivot shift phenomenon in the clinical setting are necessary. Thus far, the EMT sensors attached to the skin, the triaxial accelerometer and the iPad® (Apple, Cupertino, CA, USA) application for image analysis are available tools for clinical use.

The goal when performing the pivot shift test is to obtain objective, quantifiable and reproducible data enabling the categorization of rotatory knee laxity. The pivot shift must be taken in context along with other physical examination tests, such as varus and valgus stress, Lachman's test and generalized ligamentous laxity tests. Also, radiographic imaging and MRI evaluation should be carefully performed in order to measure ACL insertion site sizes, ACL length and inclination angle [6, 34]. Possible graft sources should have their sizes measured such as the quadriceps and patellar tendons.

According to the results of previous studies [12, 36, 38, 55, 66], we propose the categorization of the pivot shift as high, low or intermediate grade based on the lateral compartment anterior translation or on the acceleration of the tibial reduction during the pivot shift phenomenon (Table 1).

Associated soft tissue lesions and bony characteristics should be carefully analysed for their contribution to rotatory knee laxity. Specific scenarios are as follows.

Low-grade pivot shift

A low-grade pivot shift and absence of other laxity tests would reflect a partial ACL tear. In situations like this, an ACL augmentation or a selective bundle reconstruction would be indicated depending on functionality of the intact bundle during arthroscopic examination.

Table 1 Quantitative definition of high-, intermediate- and low-grade pivot shift based on the anterior translation of the lateral compartment and the acceleration of tibial reduction during the pivot shift phenomenon

	High	Intermediate	Low
Lateral compartment anterior translation	3, 5 mm or more	Between 2 and 3, 5 mm	2 mm or less
Acceleration during tibial reduction	2 m/s^2 or more	Between 1.2 and 2 m/s^2	1.2 m/s^2 or less

Intermediate-grade pivot shift

An intermediate-grade pivot shift determines an isolated complete ACL tear. ACL reconstruction, in this case, should be performed respecting the individual anatomical characteristics obtained prior to the surgery according to MRI measurements and patient's life style. Also, intra-operative measurements help to define the choice for ACL single- or double-bundle reconstruction.

High-grade pivot shift

In a situation of an exaggerated pivot shift, additional procedures, besides ACL reconstruction may be needed.

Collateral ligaments and lateral structures

If a varus stress or PLC tests indicate lateral laxity, the lateral injured structures must be repaired or reconstructed.

The pivot shift is usually decreased with MCL tears because the knee must be forced to remain reduced by the examiner making it difficult to produce adequate valgus stress that would reveal high-grade pivot shift [23]. Although producing a decreasing shift phenomenon, the quantitative analysis of the pivot shift does not seem to be influenced by the MCL injury as manual tests are.

The surgical algorithm for ACL + MCL tears should be based mainly on clinical examination and imaging findings of the MCL/POL (posterior oblique ligament) injury. Ma et al. [59] demonstrated that the MCL injury increases the in situ force in the ACL graft. Therefore, to diminish the high valgus moments, grade III MCL tears must be repaired to protect the ACL graft.

Zaffagnini et al. [84] showed in a 3-year minimum follow-up study that despite greater valgus laxity observed in patients with combined ACL + grade II MCL tears treated with ACL reconstruction alone compared with ACL reconstruction + MCL repair, clinical parameters and AP laxity were not affected by residual valgus laxity. Therefore, they suggested that no additional procedures should be performed besides ACL reconstruction in ACL + grade II MCL tears.

Menisci

Lateral meniscus tears lead to higher grades of pivot shift. Medial meniscus tears influence anteroposterior knee laxity. Therefore, meniscus tears should be repaired whenever possible at the time of ACL reconstruction surgery.

Bony morphology

When varus malalignment is present, and a firm endpoint is observed in varus–valgus stress, usually as a result of a previous medial meniscectomy, a biplane osteotomy should be considered [21, 31] along with ACL reconstruction in a single or staged procedure.

Many other anatomical variations of bony morphology such as spherical condyles, greater convexity of the lateral plateau, a smaller coronal diameter to the lateral tibial plateau and a less round shape of the intercondylar notch can influence knee stability. However, no surgical approach is currently indicated to control these anatomical features.

Generalized ligamentous laxity

In cases of a grade II+ pivot shift, with no additional lesions present, and generalized ligamentous laxity, an extra-articular tenodesis should be considered. A permanent lateral capsule injury might be present when a high-grade pivot shift is observed without additional lesions and no signs of generalized ligamentous laxity. In this situation, some authors advocate extra-articular tenodesis to control lateral plateau subluxation [28, 76, 85].

Conclusion

Successful clinical outcomes following ACL reconstruction depend on complete history and physical examination, detection of abnormal knee laxity and proper surgical planning. Anatomical characteristics of each patient and the correct understanding of associated lesions will dictate an individualized approach for treatment based on the restoration of a patient's individual anatomy, insertion sites, native ACL tension pattern and reduction in rotatory knee laxity. The technological advancement in the laxity measuring devices will provide better precision to detect subtle changes in knee laxity. Inertial sensors and image analysis of the pivot shift test have emerged as available tools to quantify the pivot shift. The information delivered will enable for an individualized approach to restore anatomical structures according to unique characteristics of a patient's knee.

References

1. Adachi N, Ochi M, Uchio Y, Iwasa J, Ryoke K, Kuriwaka M (2002) Mechanoreceptors in the anterior cruciate ligament contribute to the joint position sense. Acta Orthop Scand 73:330–334
2. Adachi N, Ochi M, Uchio Y, Sumen Y (2000) Anterior cruciate ligament augmentation under arthroscopy. A minimum 2-year follow-up in 40 patients. Arch Orthop Trauma Surg 120:128–133
3. Ahldén M, Hoshino Y, Samuelsson K, Araujo P, Musahl V, Karlsson J (2012) Dynamic knee laxity measurement devices. Knee Surg Sports Traumatol Arthrosc 20:621–632

4. Amis AA (2012) The functions of the fibre bundles of the anterior cruciate ligament in anterior drawer, rotational laxity and the pivot shift. Knee Surg Sports Traumatol Arthrosc 20:613–620
5. Amis AA, Dawkins GP (1991) Functional anatomy of the anterior cruciate ligament fibre bundle actions related to ligament replacements and injuries. J Bone Joint Surg Br Vol 73:260–267
6. Araujo P, Eck CF, Torabi M, Fu FH (2012) How to optimize the use of MRI in anatomic ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 21:1495–1501
7. Araujo PH, Ahldén M, Hoshino Y, Muller B, Moloney G, Fu FH, Musahl V (2012) Comparison of three non-invasive quantitative measurement systems for the pivot shift test. Knee Surg Sports Traumatol Arthrosc 20:692–697
8. Araujo PH, van Eck CF, Macalena JA, Fu FH (2011) Advances in the three-portal technique for anatomical single- or double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 19:1239–1242
9. Bach BR, Warren RF, Wickiewicz TL (1988) The pivot shift phenomenon: results and description of a modified clinical test for anterior cruciate ligament insufficiency. Am J Sports Med 16:571–576
10. Bedi A, Musahl V, Lane C, Citak M, Warren RF, Pearle AD (2010) Lateral compartment translation predicts the grade of pivot shift: a cadaveric and clinical analysis. Knee Surg Sports Traumatol Arthrosc 18:1269–1276
11. Bedi A, Musahl V, O'Loughlin P, Maak T, Citak M, Dixon P, Pearle AD (2010) A comparison of the effect of central anatomical single-bundle anterior cruciate ligament reconstruction and double-bundle anterior cruciate ligament reconstruction on pivot-shift kinematics. Am J Sports Med 38:1788–1794
12. Berruto M, Uboldi F, Gala L, Marelli B, Albisetti W (2013) Is triaxial accelerometer reliable in the evaluation and grading of knee pivot-shift phenomenon? Knee Surg Sports Traumatol Arthrosc 21:981–985
13. Bignozzi S, Zaffagnini S, Lopomo N, Fu FH, Irrgang JJ, Marcacci M (2009) Clinical relevance of static and dynamic tests after anatomical double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 18:37–42
14. Brandon ML, Haynes PT, Bonamo JR, Flynn MI, Barrett GR, Sherman MF (2006) The association between posterior-inferior tibial slope and anterior cruciate ligament insufficiency. Arthroscopy 22:894–899
15. Bull AMJ, Earnshaw PH, Smith A, Katchburian MV, Hassan ANA, Amis AA (2002) Intraoperative measurement of knee kinematics in reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br Vol 84:1075–1081
16. Colombet P, Dejour D, Panisset J-C, Siebold R (2010) Current concept of partial anterior cruciate ligament ruptures. Orthop Traumatol Surg Res 96:S109–S118
17. Crain EH, Fithian DC, Paxton EW, Luetzow WF (2005) Variation in anterior cruciate ligament scar pattern: does the scar pattern affect anterior laxity in anterior cruciate ligament-deficient knees? Arthroscopy 21:19–24
18. Araki D, Kuroda R, Matsushita T, Matsumoto T, Kubo S, Nagamune K, Kurosaka M (2013) Biomechanical analysis of the knee with partial anterior cruciate ligament disruption: quantitative evaluation using an electromagnetic measurement system. Arthroscopy 29:1053–1062
19. Dejour D, Ntagiopoulos PG, Saggin PR, Panisset JC (2013) The diagnostic value of clinical tests, magnetic resonance imaging, and instrumented laxity in the differentiation of complete versus partial anterior cruciate ligament tears. Arthroscopy 29:491–499
20. Slocum DB, James SL, Larson RL, Singer KM (1976) Clinical test for anterolateral rotary instability of the knee. Clin Orthop Relat Res 118:63–69
21. Dejour HH, Neyret PP, Boileau PP, Donell STS (1994) Anterior cruciate reconstruction combined with valgus tibial osteotomy. Clin Orthop Relat Res 299:220–228
22. Diermann N, Schumacher T, Schanz S, Raschke MJ, Petersen W, Zantop T (2008) Rotational instability of the knee: internal tibial rotation under a simulated pivot shift test. Arch Orthop Trauma Surg 129:353–358
23. Donaldson WF, Warren RF, Wickiewicz T (1985) A comparison of acute anterior cruciate ligament examinations: initial versus examination under anesthesia. Am J Sports Med 13:5–10
24. Espregueira-Mendes J, Pereira H, Sevivas N, Passos C, Vasconcelos JC, Monteiro A, Oliveira JM, Reis RL (2012) Assessment of rotatory laxity in anterior cruciate ligament-deficient knees using magnetic resonance imaging with Porto-knee testing device. Knee Surg Sports Traumatol Arthrosc 20:671–678
25. Fetto JF, Marshall JL (1979) Injury to the anterior cruciate ligament producing the pivot-shift sign. J Bone Joint Surg Am 61:710–714
26. Fridén T, Jonsson A, Erlandsson T, Jonsson K, Lindstrand A (1993) Effect of femoral condyle configuration on disability after an anterior cruciate ligament rupture: 100 patients followed for 5 years. Acta Orthop Scand 64:571–574
27. Gabriel MT, Wong EK, Woo SL-Y, Yagi M, Debski RE (2006) Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. J Orthop Res 22:85–89
28. Galway R, Beaupre A, MacIntosh D (1972) Pivot shift: a clinical sign of symptomatic anterior cruciate insufficiency. J Bone Joint Surg Br 54:763–764
29. Galway HR, MacIntosh DL (1980) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:45–50
30. Georgoulis A, Pappa L, Moebius U, Malamou-Mitsi V, Pappa S, Papageorgiou C, Agnantis N, Soucacos P (2001) The presence of proprioceptive mechanoreceptors in the remnants of the ruptured ACL as a possible source of re-innervation of the ACL autograft. Knee Surg Sports Traumatol Arthrosc 9:364–368
31. Giffin JR (2004) Effects of increasing tibial slope on the biomechanics of the knee. Am J Sports Med 32:376–382
32. Haughom BD, Souza R, Schairer WW, Li X, Ma CB (2012) Evaluating rotational kinematics of the knee in ACL-ruptured and healthy patients using 3.0 Tesla magnetic resonance imaging. Knee Surg Sports Traumatol Arthrosc 20:663–670
33. Hefti F, Müller W, Jakob RP, Stäubli HU (1993) Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc 1:226–234
34. Hofbauer M, Muller B, Murawski CD, Eck CF, Fu FH (2013) The concept of individualized anatomic anterior cruciate ligament (ACL) reconstruction. Knee Surg Sports Traumatol Arthrosc, June 6 [Epub ahead of print]
35. Hoshino Y, Araujo P, Ahldén M, Moore CG, Kuroda R, Zaffagnini S, Karlsson J, Fu FH, Musahl V (2012) Standardized pivot shift test improves measurement accuracy. Knee Surg Sports Traumatol Arthrosc 20:732–736
36. Hoshino Y, Araujo P, Ahldén M, Samuelsson K, Muller B, Hofbauer M, Wolf MR, Irrgang JJ, Fu FH, Musahl V (2013) Quantitative evaluation of the pivot shift by image analysis using the iPad. Knee Surg Sports Traumatol Arthrosc 21:975–980
37. Hoshino Y, Araujo P, Irrgang JJ, Fu FH, Musahl V (2012) An image analysis method to quantify the lateral pivot shift test. Knee Surg Sports Traumatol Arthrosc 20:703–707
38. Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamaguchi M, Muratsu H, Yoshiya S, Kurosaka M (2007) In vivo measurement of the pivot-shift test in the anterior cruciate ligament-deficient knee using an electromagnetic device. Am J Sports Med 35:1098–1104

39. Howell SM, Knox KE, Farley TE, Taylor MA (1995) Revascularization of a human anterior cruciate ligament graft during the first 2 years of implantation. Am J Sports Med 23:42–49
40. Hughston JC, Andrews JR, Cross MJ, Moschi A (1976) Classification of knee ligament instabilities. Part I. The medial compartment and cruciate ligaments. J Bone Joint Surg Am 58:159–172
41. Ishibashi Y, Tsuda E, Yamamoto Y, Tsukada H, Toh S (2009) Navigation evaluation of the pivot-shift phenomenon during double-bundle anterior cruciate ligament reconstruction: is the posterolateral bundle more important? Arthroscopy 25:488–495
42. Jakob RP, Stäubli HU, Deland JT (1987) Grading the pivot shift. Objective tests with implications for treatment. J Bone Joint Surg Br Vol 69:294–299
43. Jonsson H, Riklund-Åhlström K, Lind J (2004) Positive pivot shift after ACL reconstruction predicts later osteoarthritis 63 patients followed 5–9 years after surgery. Acta Orthop Scand 75:594–599
44. Kocher MS, Steadman JR, Briggs KK, Sterett WI, Hawkins RJ (2004) Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. Am J Sports Med 32:629–634
45. Kopf S, Kauert R, Halfpaap J, Jung T, Becker R (2012) A new quantitative method for pivot shift grading. Knee Surg Sports Traumatol Arthrosc 20:718–723
46. Kujala UM, Nelimarkka O, Koskinen SK (1992) Relationship between the pivot shift and the configuration of the lateral tibial plateau. Arch Orthop Trauma Surg 111:228–229
47. Kuroda R, Hoshino Y, Araki D, Nishizawa Y, Nagamune K, Matsumoto T, Kubo S, Matsushita T, Kurosaka M (2012) Quantitative measurement of the pivot shift, reliability, and clinical applications. Knee Surg Sports Traumatol Arthrosc 20:686–691
48. Kuroda R, Hoshino Y, Kubo S, Araki D, Oka S, Nagamune K, Kurosaka M (2012) Similarities and differences of diagnostic manual tests for anterior cruciate ligament insufficiency: a global survey and kinematics assessment. Am J Sports Med 40:91–99
49. Labbe DR, de Guise JA, Mezghani N, Godbout V, Grimard G, Baillargeon D, Lavigne P, Fernandes J, Ranger P, Hagemeister N (2010) Feature selection using a principal component analysis of the kinematics of the pivot shift phenomenon. J Biomech 43:3080–3084
50. Lane CG, Warren R, Pearle AD (2008) The pivot shift. J Am Acad Orthop Surg 16:679–688
51. Lane CG, Warren RF, Stanford FC, Kendoff D, Pearle AD (2008) In vivo analysis of the pivot shift phenomenon during computer navigated ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 16:487–492
52. Liu W, Maitland ME (2003) Influence of anthropometric and mechanical variations on functional instability in the ACL-deficient knee. Ann Biomed Eng 31:1153–1161
53. Lopomo N, Signorelli C, Bonanzinga T, Muccioli GMM, Visani A, Zaffagnini S (2012) Quantitative assessment of pivot-shift using inertial sensors. Knee Surg Sports Traumatol Arthrosc 20:713–717
54. Lopomo N, Zaffagnini S, Bignozzi S, Visani A, Marcacci M (2009) Pivot-shift test: analysis and quantification of knee laxity parameters using a navigation system. J Orthop Res 28:164–169
55. Lopomo N, Zaffagnini S, Signorelli C, Bignozzi S, Giordano G, Marcheggiani Muccioli GM, Visani A (2012) An original clinical methodology for non-invasive assessment of pivot-shift test. Comput Methods Biomech Biomed Eng 15:1323–1328
56. Losee RE, Johnson TR, Southwick WO (1978) Anterior subluxation of the lateral tibial plateau. A diagnostic test and operative repair. J Bone Joint Surg Am 60:1015–1030
57. Lustig S, Magnussen RA, Cheze L, Neyret P (2012) The KneeKG system: a review of the literature. Knee Surg Sports Traumatol Arthrosc 20:633–638
58. Ma CB, Keifa E, Dunn W, Fu FH, Harner CD (2010) Can pre-operative measures predict quadruple hamstring graft diameter? Knee 17:81–83
59. Ma CB, Papageogiou CD, Debski RE, Woo SL (2000) Interaction between the ACL graft and MCL in a combined ACL + MCL knee injury using a goat model. Acta Orthop Scand 71:387–393
60. Maeyama A, Hoshino Y, Debandi A, Kato Y, Saeki K, Asai S, Goto B, Smolinski P, Fu FH (2011) Evaluation of rotational instability in the anterior cruciate ligament deficient knee using triaxial accelerometer: a biomechanical model in porcine knees. Knee Surg Sports Traumatol Arthrosc 19:1233–1238
61. Matsumoto H (1990) Mechanism of the pivot shift. J Bone Joint Surg Br Vol 72:816–821
62. Musahl V, Ayeni OR, Citak M, Irrgang JJ, Pearle AD, Wickiewicz TL (2010) The influence of bony morphology on the magnitude of the pivot shift. Knee Surg Sports Traumatol Arthrosc 18:1232–1238
63. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD (2010) The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med 38:1591–1597
64. Musahl V, Hoshino Y, Ahldén M, Araujo P, Irrgang JJ, Zaffagnini S, Karlsson J, Fu FH (2012) The pivot shift: a global user guide. Knee Surg Sports Traumatol Arthrosc 20:724–731
65. Musahl V, Hoshino Y, Becker R, Karlsson J (2012) Rotatory knee laxity and the pivot shift. Knee Surg Sports Traumatol Arthrosc 20:601–602
66. Musahl V, Kopf S, Rabuck S, Becker R (2012) Rotatory knee laxity tests and the pivot shift as tools for ACL treatment algorithm. Knee Surg Sports Traumatol Arthrosc 20:793–800
67. Musahl V, Seil R, Zaffagnini S, Tashman S, Karlsson J (2011) The role of static and dynamic rotatory laxity testing in evaluating ACL injury. Knee Surg Sports Traumatol Arthrosc 20:603–612
68. Musahl V, Voos J, O'Loughlin PF, Stueber V, Kendoff D, Pearle AD (2009) Mechanized pivot shift test achieves greater accuracy than manual pivot shift test. Knee Surg Sports Traumatol Arthrosc 18:1208–1213
69. Myer GD, Ford KR, Paterno MV, Nick TG, Hewett TE (2008) The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. Am J Sports Med 36:1073–1080
70. Noyes FR, Grood ES, Cummings JF, Wroble RR (1991) An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. Am J Sports Med 19:148–155
71. Noyes FR, Mooar LA, Moorman CT III, McGinniss GH (1989) Partial tears of the anterior cruciate ligament: progression to complete ligament deficiency. J Bone Joint Surg Br 71:825–833
72. Ochi M, Iwasa J, Uchio Y, Adachi N, Sumen Y (1999) The regeneration of sensory neurones in the reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br 81:902–906
73. Okazaki K, Tashiro Y, Izawa T, Matsuda S (2012) Rotatory laxity evaluation of the knee using modified Slocum's test in open magnetic resonance imaging. Knee Surg Sports Traumatol Arthrosc 20:679–685
74. Pearle AD, Kendoff D, Musahl V, Warren RF (2009) The pivot-shift phenomenon during computer-assisted anterior cruciate ligament reconstruction. J Bone Joint Surg Am 91(Suppl 1):115–118
75. Pearsall AWA, Kovaleski JEJ, Heitman RJR, Gurchiek LRL, Hollis JMJ (2006) The relationships between instrumented measurements of ankle and knee ligamentous laxity and generalized joint laxity. J Sports Med Phys Fit 46:104–110

76. Pernin J, Verdonk P, Selmi TAS, Massin P, Neyret P (2010) Long-term follow-up of 24.5 years after intra-articular anterior cruciate ligament reconstruction with lateral extra-articular augmentation. Am J Sports Med 38:1094–1102
77. Rudy TW, Livesay GA, Woo SL, Fu FH (1996) A combined robotic/universal force sensor approach to determine in situ forces of knee ligaments. J Biomech 29:1357–1360
78. Alford JW, Bach Jr BR (2005) Instrumented ligamentous laxity testing. In: Scott WN, Insall JN (ed) Insall & Scott surgery of the knee, 4th edn. Churchill Livingstone, Elsevier, pp 584–614
79. Sonnery-Cottet B, Lavoie F, Ogassawara R, Scussiato RG, Kidder JF, Chambat P (2010) Selective anteromedial bundle reconstruction in partial ACL tears: a series of 36 patients with mean 24 months follow-up. Knee Surg Sports Traumatol Arthrosc 18:47–51
80. Suero EM, Njoku IU, Voigt MR, Lin J, Koenig D, Pearle AD (2013) The role of the iliotibial band during the pivot shift test. Knee Surg Sports Traumatol Arthrosc 21:2096–2100
81. Tashiro Y, Okazaki K, Miura H, Matsuda S, Yasunaga T, Hashizume M, Nakanishi Y, Iwamoto Y (2009) Quantitative assessment of rotatory instability after anterior cruciate ligament reconstruction. Am J Sports Med 37:909–916
82. Uhorchak JM, Scoville CR, Williams GN, Arciero RA, Pierre PS, Taylor DC (2003) Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective 4-year evaluation of 859 west point cadets. Am J Sports Med 31:831–842
83. van Eck CF, Lesniak BP, Schreiber VM, Fu FH (2010) Anatomic single- and double-bundle anterior cruciate ligament reconstruction flowchart. Arthroscopy 26(2):258–268
84. Zaffagnini S, Bonanzinga T, Muccioli GM, Giordano G, Bruni D, Bignozzi S, Lopomo N, Marcacci M (2011) Does chronic medial collateral ligament laxity influence the outcome of anterior cruciate ligament reconstruction? A prospective evaluation with a minimum 3-year follow up. J Bone Joint Surg Br 93:1060–1064
85. Zaffagnini S, Signorelli C, Lopomo N, Bonanzinga T, Marcheggiani Muccioli GM, Bignozzi S, Visani A, Marcacci M (2011) Anatomic double-bundle and over-the-top single-bundle with additional extra-articular tenodesis: an in vivo quantitative assessment of knee laxity in two different ACL reconstructions. Knee Surg Sports Traumatol Arthrosc 20:153–159
86. Zantop T, Herbort M, Raschke MJ, Fu FH, Petersen W (2006) The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. Am J Sports Med 35:223–227
87. Zantop T, Schumacher T, Diermann N, Schanz S, Raschke MJ, Petersen W (2006) Anterolateral rotational knee instability: role of posterolateral structures. Arch Orthop Trauma Surg 127: 743–752