

Individualized ACL reconstruction

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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

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

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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

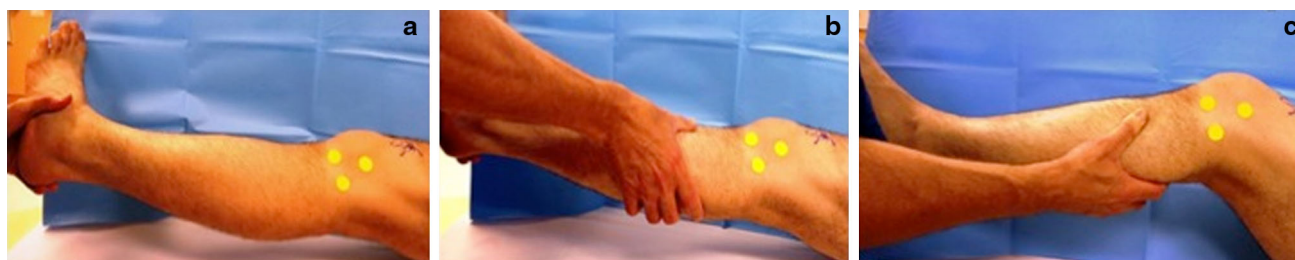


Fig. 1 Standardized pivot shift manoeuvre divided into three steps. **a** Internal rotation in knee extension. **b** Gentle valgus torque is applied. **c** The knee is flexed whilst releasing the internal rotation during knee reduction

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

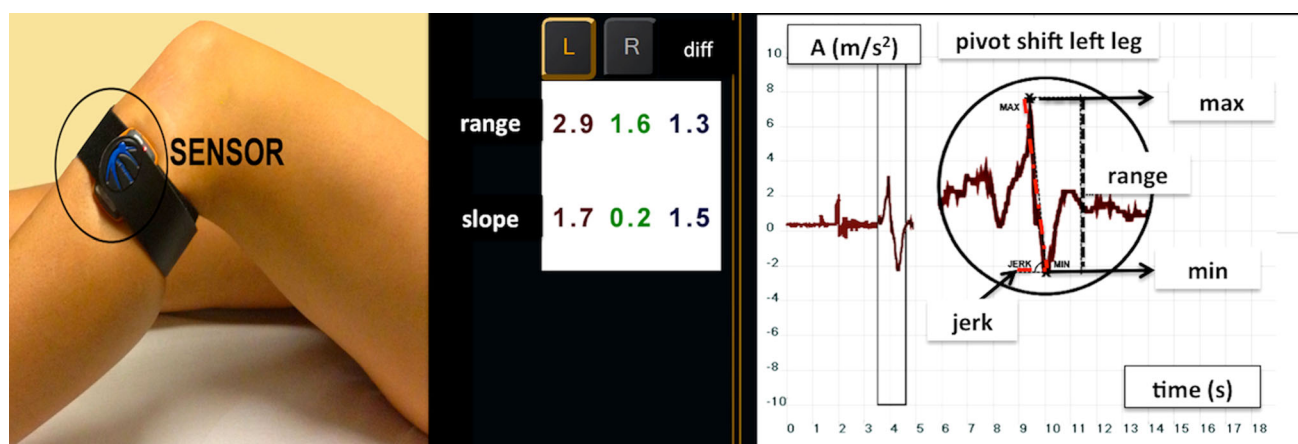


Fig. 2 Use of inertial sensors to measure the acceleration during tibial reduction in the pivot shift phenomenon. **a** Inertial sensors attached to the skin. **b** Acceleration graphic provided by the instrument

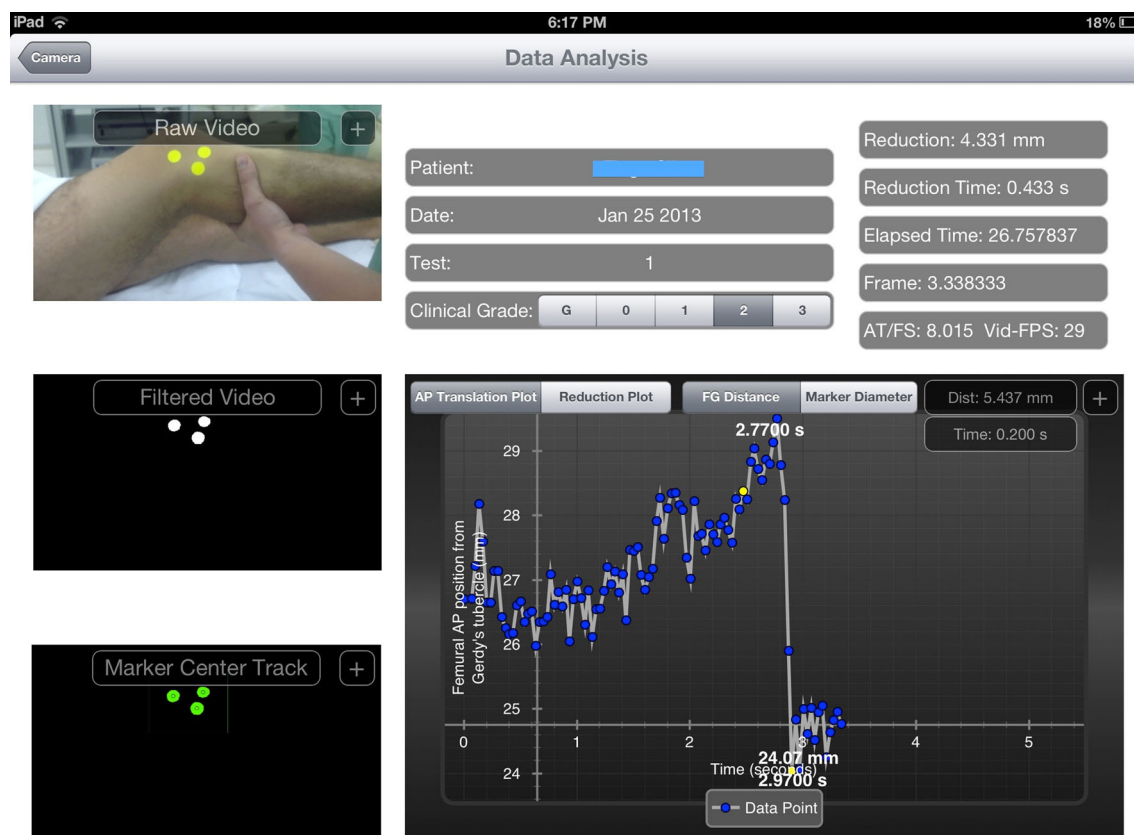


Fig. 3 Display of iPad® (Apple, Cupertino, CA, USA) application measuring the anterior translation of the lateral compartment of the knee during the pivot shift test

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.

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