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Knee instability scores for ACL reconstruction

Ata A. Rahnemai-Azar[1,2] · **Jan-Hendrik Naendrup**[1,2] · **Ashish Soni**[1] · **Adam Olsen**[1] ·
Jason Zlotnicki[1,2] · **Volker Musahl**[1,2]

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Abstract Despite abundant biological, biomechanical, and clinical research, return to sport after anterior cruciate ligament (ACL) injury remains a significant challenge. Residual rotatory knee laxity has been identified as one of the factors responsible for poor functional outcome. To improve and standardize the assessment of knee instability, a variety of instability scoring systems is available. Recently, devices to objectively quantify static and dynamic clinical exams have been developed to complement traditional subjective grading systems. These devices enable an improved evaluation of knee instability and possible associated injuries. This additional information may promote the development of new treatment algorithms and allow for individualized treatment. In this review, the different subjective laxity scores as well as complementary objective measuring systems are discussed, along with an introduction of injury to an individualized treatment algorithm.

Keywords Anterior cruciate ligament · ACL · Quantitative pivot shift test · Laxity scores · Treatment algorithm

This article is part of the Topical Collection on *ACL Update: Objective Measures on Knee Instability*

✉ Volker Musahl
musahlv@upmc.edu

[1] Department of Orthopaedic Surgery, University of Pittsburgh, 3471 Fifth Avenue, Pittsburgh, PA 15213, USA

[2] Orthopaedic Robotics Laboratory, Center for Bioengineering, University of Pittsburgh, 300 Technology Drive, Pittsburgh, PA 15219, USA

Introduction

Anterior cruciate ligament (ACL) reconstruction surgery has evolved significantly over the last few decades. The continued development of novel research experiments across this period has better characterized the biological, biomechanical, and clinical aspects of ACL injury. In turn, this had led to improved understanding of anatomy, introduction of sophisticated imaging modalities, advancements in surgical techniques, and the use of evidence-based return to sport criteria. Despite these efforts, return to play at pre-injury level is reported to be around 50 % [1]. One of the factors, which is held responsible for the poor functional outcome after reconstructive surgery, is residual rotatory knee instability.

A thorough assessment of knee laxity has a paramount role during ACL injury management. During early evaluation of suspected injury, the objective quantification of specific motion (i.e., lateral compartment translation) is critical in order to determine the level of instability and the treatment algorithm. Intraoperatively, it is important to objectively evaluate for restoration of stability achieved during the surgery and to identify the need to perform a secondary restraint procedure. Lastly, it is important to evaluate stability throughout the post-operative period in order to verify the healing process and rehabilitation course.

Assessment of knee laxity in the injured and uninjured states has been a topic of interest lately, as there is significant inter-observer variation in laxity assessment [2]. This interest has led to development of tools, which can provide repeatable and objective quantification. Improvement in the objective assessment of knee laxity provides clinicians with better insight into the injury profile and can help to specifically shape treatment protocols. This review will focus on the role of scoring laxity in management of the patients with ACL injury, and the use of an individualized treatment algorithm based on objective knee data.

Clinical assessment of knee laxity

In the 1960s, ACL injury was diagnosed by the anterior drawer of the tibia at 90° of knee flexion. Introduction of the Lachman test by Torg et al. [3] and pivot shift test by Galway et al. [4] during the 1970s significantly improved the accuracy of the physical exam in diagnosis of the ACL injury. The Lachman test was determined to be the most sensitive physical exam in diagnosis of ACL injury, while the pivot shift test is the most specific examination, especially when performed under general anesthesia [5].

One of the earliest grading systems of the pivot shift test was based on eliciting the abnormal reduction movement on varying positions of rotation of the tibia (e.g., internal rotation, neutral, and external rotation) with higher grades with abnormal motion during external rotation [6]. However, the weakness of the pivot shift test is its variability and subjective grading. In order to reduce the variability of pivot shift test maneuver between examiners, a standardized technique and mechanized devices have been developed [7, 8].

Subjective scoring of physical exam is traditionally the main component of clinical evaluation for knee ligamentous injuries. According to the International Knee Documentation Committee (IKDC) evaluation form, the anterior drawer test, Lachman test, and pivot shift test are subjectively graded as normal, nearly normal, abnormal, and severely abnormal [9]. Although IKDC is generally accepted as standard for reporting the status of the knee, the subjective nature of the grading system and the potential lack of repeatability are significant limitations. Historically due to inability of traditional methods to completely restore joint stability, the "nearly normal" (IKDC "B") was considered acceptable outcome for patients after reconstruction surgery. With recent improvement in the field of ACL reconstruction technique, however, the value of subjective grading system is further called into question in favor of clinically applicable objective measurement devices [10].

Since the 1970s, several devices have been developed to quantify the anterior translation of the tibia during these examinations. The KT1000 (MEDmetric Corp, San Diego, CA, USA) can quantify the amount of load applied and the resultant anterior translation and is the most accepted device for measurement of anterior translation [11]. To date, this device has been applied extensively in management of patient with ACL injury.

Instrumented assessment of rotatory knee instability

To eliminate the aforementioned subjective grading, attempts have been made to develop devices to objectively quantify the pivot shift test [12]. Computer-assisted surgical navigation systems and electromagnetic tracking devices are among the technologies that can provide kinematic data during the pivot shift test [13, 14]. These technologies provide accurate kinematic data, but limitations exist such as invasiveness, bulkiness, and cost. In recent years, non-invasive technologies have been developed that can help clinicians to objectively quantify the pivot shift test. These technologies measure different aspects of bony motion during the pivot shift. Lateral compartment translation can be calculated by image analysis technology [15•, 16].

Image analysis technology

While performing the pivot shift, anterior tibial translation in lateral compartment of the knee is more than that of the medial compartment. This translation correlates with the subjective grading of the pivot shift [13]. Based on this finding, a software has been developed that uses a computer tablet's camera to record the motion of markers attached to the lateral aspect of the knee during the pivot shift maneuver (Fig. 1). The skin markers are attached to three bony landmarks on lateral side of the knee, i.e., lateral epicondyle, Gerdy's tubercle, and the fibular head. The software is able to calculate the relative motion of tibia in relation to femur by recording and analyzing the video of the knee motion during pivot shift test [17]. The lateral compartment translation measured by this technique has shown to be strongly correlated with bony motion measured invasively by electromagnetic tracking system [18]. In distances less than or equal to 175 cm between iPad and marker position, this calculation has less than 6 % error, which provides sufficient accuracy for the clinical set-up. Considering the analysis time of 10–15 s, image analysis constitutes an easily applicable tool for the daily clinical work [15•].

Inertial sensor technology

The acceleration during the tibial reduction of the pivot shift is significantly higher in ACL-deficient knees and correlates with the clinical grading of the pivot shift [14]. Different types of inertial sensors (accelerometers, gyroscopes, microelectromechanical system sensors) have been used to quantify this acceleration, rotation, and velocity of the bony motion [19–21]. Similar to the principle of image analysis, the sensors are attached to the lateral aspect of the proximal tibia, close to Gerdy's tubercle. Transmitting the gathered acceleration via Bluetooth to a tablet software, named Kira (Orthokey LLC, Lewes, DE, USA), the data is subsequently analyzed, plotted, and saved in a patient data base [22, 23•]. The applicability and reliability of this technology were demonstrated in laboratory setting as well as in the clinical use [24, 25]. Together,

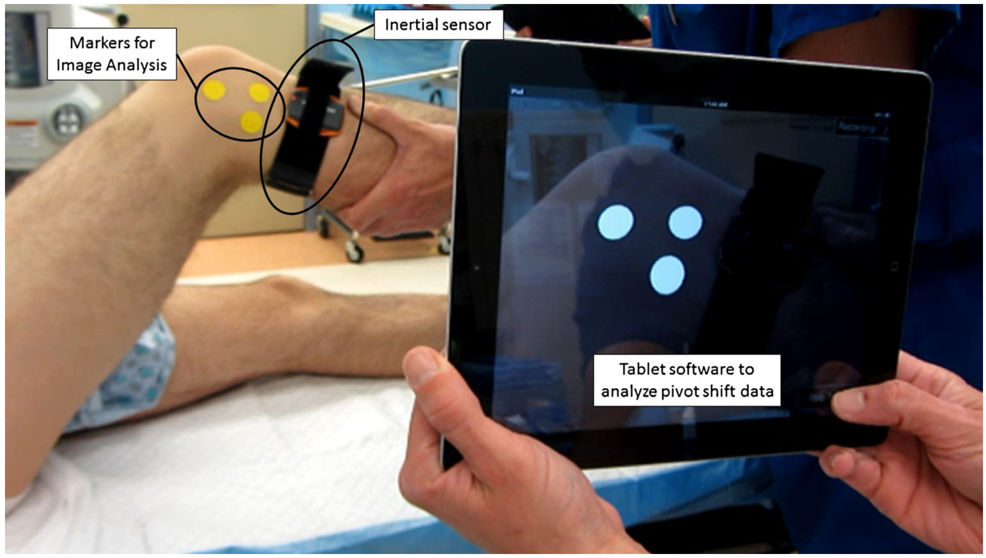

Fig. 1 Testing set-up for the quantitative pivot shift measurement. For image analysis, technology markers are attached to the bony landmarks fibular head, Gerdy's tubercle, and femoral epicondyle to quantify lateral compartment translation. Inertial sensors are attached to the shin using a Velcro strap. Both systems use tablet-software to wirelessly acquire and analysis the data

these devices provide comprehensive insight to joint rotatory laxity (Fig. 1).

Individualized ACL treatment

The concept of "envelope of motion" was described through a series of studies assessing six degrees of freedom of motion by electromagnetic tracking systems. It has been demonstrated that following ACL injury, distinctly different coupled motions occur in response to loads applied during the pivot shift test [26]. Therefore, there is variability in ACL injuries and a single standard treatment approach is unlikely to properly address each individual's injury. Consequently, it is proposed that each patient should be assessed with a series of subjective and quantitative knee laxity assessment tests. This information together with arthroscopic examination helps in providing individualized treatment to the ACL injured patients. Management can range from single-bundle augmentation to isolated anatomic ACL reconstruction along with secondary procedures such as meniscal repair/reconstruction, extra-articular tenodesis, or high tibial osteotomy in revision surgery.

Some ACL injured patients can be treated non-operatively with rehabilitation. These patients are referred to as "copers" and have been demonstrated to have comparable long-term functional outcome scores and radiographic evidence of osteoarthritis to patients undergoing ACL reconstruction surgery [27]. Recent evidence has demonstrated that the pivot shift test might have potential to further complement the criteria currently used to preemptively identify "copers." A recent meta-analysis of studies that reported long-term results demonstrated no statistically difference in positive pivot shift results among patients who underwent reconstruction surgery with those that were managed non-operatively [27]. In a recent randomized clinical trial of young active adults with acute ACL injury, patients undergoing early reconstruction surgery did not demonstrate superior outcomes compared to patients undergoing rehabilitation plus delayed optional reconstruction surgery [28]. However, cost-effective analysis studies failed to show reduced costs for non-operative treatments compared to ACL reconstruction surgery, which highlights the need for careful screening of the potential copers [29].

Anatomic ACL reconstruction surgery

The posterolateral (PL) bundle of the ACL has been shown to have a more prominent role in controlling rotational laxity, especially in lower flexion angles [30–32]. The concept of anatomic ACL reconstruction aims at restoring the native anatomy of the ACL by either single- or double-bundle ACL reconstruction, depending on individual variation of anatomy and injury pattern [33, 34]. Using an electromagnetic tracking device, it was demonstrated that patients with partial ACL injury show lower rotational laxity in both antero-posterior motion and during the pivot shift test [35]. If there are undamaged functional ACL fibers, the knee will show less laxity due to stability provided by remaining fibers during the quantitative evaluation of laxity [36]. Therefore, technologies providing pre-operative laxity information can help clinicians to decide whether the ACL remnants observed during surgery have any contribution to joint stability and can potentially be preserved. Further evidence regarding the long-term benefits of augmentation reconstruction surgeries needs to be generated in future studies [37].

If complete ACL reconstruction surgery is indicated, restoration of the native ACL footprint size is essential for anatomical reconstruction surgery. It has been demonstrated that there is large variation in size of ACL insertion site among patients;

therefore, the same graft size or reconstruction technique cannot restore the native insertion side in all patients [38]. Recent studies highlighted the increased risk of reconstruction failure with smaller grafts [39] and demonstrate that single-bundle reconstruction surgery restores only 70–79 % of the native ACL insertion side [40]. Several biomechanical studies [41–43] as well as randomized clinical trials [44] reported higher antero-posterior and rotational stability in double-bundle reconstructions surgery compared to anatomical single-bundle reconstruction surgery. However, when reconstruction surgery was individualized for patients based on intraoperative measurements, no difference was observed between single-bundle and double-bundle reconstruction surgery emphasizing importance of patient selection for either treatment group [45]. Overall, based on evidence from recent meta-analysis, it appears that double-bundle reconstruction provides superior stability and mid-term outcome scores; however, more research is needed to determine long-term outcomes [46, 47].

Treatment of associated injuries

Though the ACL serves as the primary restraint to both anteroposterior and rotational stability, especially at low flexion angles, other surrounding knee structures contribute to joint stability [48]. Concomitant injury to medial or lateral meniscus is reported to be present in 16 to 82 % in acute ACL injuries and up to 96 % in chronic ACL injuries [49–51]. In addition to load distribution function, menisci also play a role in joint stability. It has been well demonstrated that injuries to either the medial meniscus or lateral meniscus significantly increase the grade of the pivot shift test [52–54]. Not surprisingly, anterolateral capsule injuries also have been shown to increase the rotatory laxity during pivot shift test [53, 54]. In vitro biomechanical studies have supported a mainly secondary role of the anterolateral capsule to rotatory knee laxity [55–57]. However, a recent study reported that the iliotibial band (ITB) might have a more significant role in controlling knee rotatory laxity compared to the so-called anterolateral ligament or ALL [58]. Injury to the medial collateral ligament increases internal and external rotation of the knee; conversely, the pivot shift grade is reduced in this injury pattern due to elimination of the tension on the medial compartment [59].

Understanding the relative contributions of intra- and extra-articular knee stabilizers, it can be theorized that increased rotatory laxity due to untreated or undiagnosed injury to these secondary structures will cause abnormal loads on the menisci and cartilage that may ultimately increase the risk of osteoarthritis. Moreover, due to load sharing of the structures in the knee, neglected injury to secondary restraints can result in increased force on ACL graft tissue and subsequent graft failure [60]. Therefore, injuries to any or all of the secondary restraints should be timely diagnosed and addressed properly to achieve an optimal patient outcome (Table 1). The objective assessment of rotatory laxity before and during reconstruction surgery can provide physicians with subtle, previously

Table 1 Treatment algorithm: ACL and associated injuries management

Primary ACL reconstruction	
Partial ACL	Single-bundle augmentation
ACL small footprint	Single-bundle anatomical ACLR
ACL large footprint	Single- or double-bundle ACLR
ACL + medial and/or lateral meniscal tear	Anatomic ACLR + medial/lateral meniscal repair
ACL + RAMP lesion	Anatomic ACLR + RAMP lesion repair
ACL + MCL injury	Anatomic ACLR + healing response/consider repair
ACL + PLC injury	Anatomic ACLR + PLC repair/reconstruction
ACL + medial or lateral capsule injury	Anatomic ACLR + healing response capsule/consider repair
Revision ACL reconstruction	
ACL + medial meniscus deficiency	Revision ACLR + MM transplant
ACL + lateral meniscus deficiency	Revision ACLR + LM transplant
ACL + chronic MCL laxity	Revision ACLR + MCL reconstruction
ACL + posterolateral corner injury	Revision ACLR + posterolateral corner reconstruction
ACL+ marked increased posterior tibial slope	Revision ACLR + de-flexion proximal tibial osteotomy
ACL + coronal plane malalignment	Revision ACLR + proximal tibial osteotomy—for varus malalignment
	Distal femur osteotomy—for valgus malalignment

ACLR anterior cruciate ligament reconstruction, *MM* medial meniscus, *LM* lateral meniscus, *MCL* medial collateral injury, *PLC* posterolateral corner unavailable information to more carefully identify injuries to secondary structures that may warrant operative intervention.

Extra-articular tenodesis

Recent reports regarding the lateral capsule complex have stimulated increased interest in combining an extra-articular tenodesis (EAT) to ACL reconstruction surgery. Different surgical techniques and graft types have been described in the literature [61–63]. However, biomechanical studies comparing different reconstruction techniques have failed to show improved stability when the so-called anatomic anterolateral ligament reconstruction was performed. Despite these findings, these studies have reinforced a significant role for a previously known tenodesis technique using a strip of iliotibial band [64].

Randomized clinical trials that compared combined EAT and ACL reconstruction with isolated ACL reconstruction have reported conflicting results regarding restraining laxity or improving functional outcome [65•]. Two recent meta-analysis of these studies revealed that patients with ACLR and EAT had superior pivot shift test and Lachman results, but no difference was found in functional outcomes or return to play [65•, 66]. Another multicenter study of revision ACL reconstruction patients with minimum 2-year follow-up revealed that combined EAT was more successful in controlling pivot shift test compared to isolated ACL reconstruction surgery [67]. Addition of EAT to ACL reconstruction has also shown to reduce stress on ACL graft by 43 % at time zero in a cadaveric study [68]. Although, adding an EAT has shown to have a positive effect on controlling knee laxity after ACL reconstruction, some authors have raised concerns about over-constraining the knee joint by restricting internal rotation [55, 69, 70•]. Hence, decision to add an EAT should be made carefully.

Combining an EAT to ACL reconstruction surgery could be considered in primary ACL reconstruction in patients with high-grade rotatory knee instability without associated meniscus or collateral ligament injuries. In revision ACL reconstruction, it should be considered if high-grade rotatory laxity is observed after treatment of all associated injuries (e.g., meniscus). Possible indications are summarized in Table 2.

Table 2 Indications for considering combined extra-articular tenodesis with ACL reconstruction

1. Primary ACL injury + high-grade pivot shift without additional soft tissue injury
2. Primary ACL injury + generalized ligament laxity, i.e., hyperextension >10°
3. Chronic ACL injury + high-grade pivot shift
4. Revision ACL + persistent high-grade pivot shift after managing associated injuries

Future directions

In the era of individualized medicine and restructured bundled reimbursement in health care, the development of clinically applicable devices to objectively score knee instability for each individual patient is of critical importance. The evaluation of knee instability scores along with other screening scores can provide important insight influencing treatment decisions. Using the pivot shift combined with quantitative devices pre-operatively, different injury patterns and instability grades can be characterized based on patient factors.

Objective quantification of the pivot shift test in a routine clinical setting requires methods that can easily, reliably, and inexpensively measure variable knee kinematics. These devices provide objective quantification of rotatory knee instability and avoid second-guessing with subjective grading scales. Furthermore, standardized exam techniques support a universally acceptable scientific exchange [71]. The preliminary results from a cohort of ACL injured patients using two of these technologies show that rotatory knee instability is widely variable between patients. This only further emphasizes the need for individualized treatment of patients with ligamentous knee injuries. Future research is necessary to evaluate clinical outcomes of different reconstruction procedures for patients with outlier scores (Fig. 2) [16, 23•]. Developing registries of ACL injured patients could also help to define optimal thresholds by distinguishing between injury patterns and the associated outcome of different reconstruction procedures. Furthermore, in clinical outcomes research, subjective scoring systems may not be sensitive enough to detect meaningful, significant differences. The future application of widespread quantitative evaluation technologies will

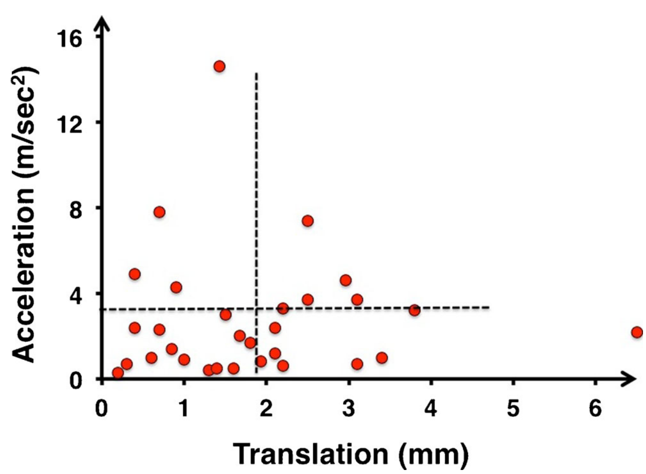

Fig. 2 Quantitative pivot shift data for 30 ACL-injured patients. The *dotted lines* represent the median number for acceleration and translation, respectively. Outliers might require further treatment in addition to anatomic ACL reconstruction

help correlate patient-reported outcome with objective findings of knee instability with the goal of improved patient outcomes.

Conclusions

Quantitative evaluation of knee instability allows clinicians to make strong, informed decisions by presenting knee kinematics in a manner that is accurate, reproducible, and patient specific. In the future, different treatment categories, such as non-operative, isolated ACL reconstruction or additional soft tissue repair/reconstruction can be assigned based on side-to-side comparison of quantitative knee instability. Using pre-operative side-to-side quantitative knee instability scores as a baseline, patient specific rehabilitation can be more focused on individual patient performance with the restoration of knee stability continuously monitored until return to full activity. Thus, the implementation of objective scoring systems by means of technologic advancements has a great potential to contribute to the individualized treatment in all aspects and stages of ACL reconstruction surgery.

Compliance with ethical standards

Conflict of interest Ata A. Rahnemai-Azar, Jan-Hendrik Naendrup, Ashish Soni, Adam Olsen, and Jason Zlotnicki declare that they have no conflict of interest. Volker Musahl has received educational funding as a consultant from Smith and Nephew. He also has a patent for Pivot software Serial (No. 61/566,761) licensed to Impelia.

Human and animal rights and informed consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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