Knee Surg Sports Traumatol Arthrosc (2012) 20:621–632
DOI 10.1007/s00167-011-1848-7

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Dynamic knee laxity measurement devices

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Received: 28 November 2011 / Accepted: 16 December 2011 / Published online: 31 December 2011

Abstract
Purpose Studies have reported that knee kinematics and rotational laxity are not restored to native levels following traditional anterior cruciate ligament (ACL) reconstruction. This has led to the development of anatomic ACL reconstruction, which aims to restore native knee kinematics and long-term knee health by replicating normal anatomy as much as possible. The purpose of this review is to give an overview of current dynamic knee laxity measurement devices with the purpose of investigating the significance of dynamic laxity measurement of the knee. Gait analysis is not included.
Methods The subject was discussed with experts in the field in order to perform a level V review. MEDLINE was searched according to the discussions for relevant articles using multiple different search terms. All found abstracts were read and scanned for relevance to the subject. The reference lists of the relevant articles were searched for additional articles related to the subject.
Results There are a variety of techniques reported to measure dynamic laxity of the knee. Technical development of methods is one important part toward better understanding of knee kinematics. Validation of devices has shown to be difficult due to the lack of gold standard. Different studies use various methods to examine different components of dynamic laxity, which makes comparisons between studies challenging.
Conclusion Several devices can be used to evaluate dynamic laxity of the knee. At the present time, the devices are continuously under development. Future implementation should include primary basic research, including validation and reliability testing, as well as part of individualized surgery and clinical follow-up.
Level of evidence Diagnostic study, Level V.

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Keywords Knee · Anterior cruciate ligament · Pivot shift · Laxity · Devices · Kinematics

Introduction

The evaluation of knee laxity is of major importance for treatment selection of the anterior cruciate ligament (ACL)-deficient knee [12]. The manual clinical examination is the foundation for diagnosis, treatment and follow-up. However, clinical examination might be deemed as being subjective in terms of conduction and interpretation [54]. The Lachman's test is the most sensitive and common laxity test used in clinical evaluation and is considered an important part of the gold standard in detecting an ACL injury [68]. Instrumented manual systems such as the KT-1000 (MEDmetric Corp, San Diego, CA, USA) [19] are commonly utilized in order to standardize and quantify anterior tibial translation. The displacement and load applied can be quantified, however, with the limitation of only evaluating static antero-posterior (A-P) laxity. Moreover, the reliability of the KT-1000 has been questioned [70, 71]. Sernert et al. [71] reported poor interclass correlation coefficient (ICC) of 0.55–0.60 between two examiners when using KT-1000 to measure knee laxity in ACL-deficient and ACL-intact knees, respectively.

Robotic systems have been developed in order to control the application of force during laxity testing, which improves accuracy and reproducibility [13]. Such systems enable researchers to evaluate rotational laxity in a more consistent, however static, manner. Nonetheless, in the ACL-deficient patient, symptoms such as "giving way" or "buckling" represent dynamic instability. Dynamic anterolateral rotatory knee laxity can be reproduced by the pivot shift test, which is the most specific clinical laxity test to detect an ACL injury [68]. The pivot shift test was first reported as a reduction-test maneuver by Galway et al. [25]. The grade of the pivot shift test has been shown to correlate with subjective patient satisfaction, return to sports and also the development of osteoarthritis after an ACL reconstruction [35, 39]. Yet, in most studies, clinical success is assessed by restoration of static anterior–posterior (A-P) laxity, despite poor correlation to outcome [39, 45]. Recent progress of investigation on dynamic and rotational laxity has demonstrated that tibial rotation is usually not restored after an ACL reconstruction, especially during high-impact activity [14, 27, 78], and the significance of joint laxity in the development of osteoarthritis has been studied in more detail [5, 6].

The main difficulty when performing the pivot shift test is to standardize the force and movement used to elicit the test, especially in terms of examination on patients who are awake, and extraction of measurable data from this complex movement. Knee kinematics measurements of the pivot shift test have shown considerable difference between examiners, because of great variation in their testing procedures [41, 64]. In order to standardize the external force when measuring rotational laxity, a mechanized and standardized procedure has been developed [59]. However, the reproduced pivot shift movement was still greater by the manually performed pivot shift than by the mechanized device [59]. Even though an objective evaluation of the manually elicited pivot shift would probably be an optimal method, it is still unknown what measurement devices and parameters should be used to quantitatively evaluate the pivot shift [30, 53, 59].

With the aim of regaining native knee laxity and kinematics, there is an increased interest in anatomic single-bundle (SB) and double-bundle (DB) ACL reconstruction, as compared with the traditional and commonly performed transtibial non-anatomic ACL reconstruction. Anatomic ACL reconstruction appears to better resist rotatory loads than the non-anatomical ACL reconstructions [50, 69, 81]. However, most studies have been conducted on cadavers, and little is known about dynamic rotational laxity in vivo [84].

The purpose of this review is to give an overview of some current dynamic knee laxity measurement devices with the purpose of investigating the significance of dynamic laxity measurement of the knee. The aim is not to give a complete overview, but rather describe current techniques in use for the in vivo evaluation of the pivot shift or functional movements in ACL-deficient knees. Gait analysis is not included.

Materials and methods

The subject was discussed with experts in the field in order to perform a level V review. MEDLINE was searched according to the discussions for relevant articles using multiple different search terms. All found abstracts were read and scanned for relevance to the subject. The reference lists of the relevant articles were searched for additional articles within the subject.

Dynamic clinical examination

Computer-assisted surgery and kinematics

The clinical use of computer-assisted surgery (CAS) in ACL reconstruction was first reported in 1995 [23]. The initial goal was to improve accuracy of tunnel placement, based on the findings that malpositioned tunnels—especially in the femur—were the main cause leading to revision surgery [73, 80]. With the implementation of new technologies and more user-friendly software, navigation systems are being utilized to assess knee kinematics and knee laxity before and after ACL reconstruction [86]. This allows for feedback with regard to laxity testing, in terms of both A-P translation and rotation, as well as decomposition of the pivot shift. Intra-operatively, surgeons can precisely quantify the 6 degrees of freedom kinematics using CAS, and the test repeatability can be improved by the precise feedback on the examinations [86]. Even though the accuracy of identifying optical marker position is within the sub-millimeter range, it is important to understand that surgeon-specific factors still matter greatly. For example, most studies using CAS are based on manual clinical examination and accordingly provide a lack of consistent stress loading. Moreover, the invasiveness makes CAS impossible to use in the office or on the contralateral knee [86].

Anatomical data for the navigation systems are collected with either image-based system using different imaging modalities, such as computer tomography (CT), or image-free system without preoperative imaging [33]. A navigated pointer is used for anatomical reference acquisition [18, 85]. Tracking systems are usually either optoelectronic or electromagnetic. The optoelectronic systems use sterilizable markers reflecting infrared light emitted by cameras [18, 51]. The electromagnetic systems use receivers in an electromagnetic field to track positions. The markers or receivers are secured rigidly to bone in the intra-operative setting to provide accurate measurement of bone and joint movement (Fig. 1).

Zaffagnini et al. [85] reported accuracy and repeatability in 15 patients after using computer-assisted in vivo evaluation of joint laxity during ACL reconstructions. The intra-examiner repeatability of four repeated tests was high in terms of tibial starting position, with an error <1 mm in all flexion angles. The average standard deviation (SD) with manual tests at maximum forces was 0.78° for varus–valgus test, 1.83° for internal–external rotation and 0.88 mm for A-P translation. The average SD of the tibia orientation was <3° and secondary laxity during all stress tests remained within 3 mm/3°, demonstrating high reproducibility of the manual tests. The test results were consistent with earlier studies on laxity testing done with conventional methods, both before and after ACL reconstruction [85].

Kendoff et al. [38] used cadaver knees and plastic whole-leg models, comparing navigation to KT-1000 and an external goniometer. They found no significant differences in A-P translation or rotation, although there was a tendency toward increased translation in ACL-intact knees measured with the KT-1000 (4.8 mm vs. 3.2 mm, ns). A-P laxity tested by computer navigation was shown to have improved repeatability compared with KT-1000 or Rolimeter [51, 56].

Martelli et al. [56] reported a series of 79 patients undergoing ACL reconstruction using the navigation system KIN-nav (Klee, Orthokey LLC, Lewes, DE, USA). They found high intra-examiner repeatability, with measurement differences of <0.6° for varus–valgus (VV) rotation, <1.6° for internal–external (IE) rotation and <1 mm for A-P translation. The corresponding values in terms of inter-examiner repeatability were <2° (VV), 5° (IE) and <3 mm (AP), respectively, with less differences between the more experienced surgeons. The authors also reported simulated random error of up to 10 mm for anatomical landmarks on the knee and up to 40 mm for the hip center, but showed no amplification of the initial error. Accordingly, the authors concluded that KIN-nav had a short learning curve and displayed high reliability and sensitivity, especially for an experienced surgeon [51, 56].

Pearle et al. [67] in a controlled laboratory study displayed excellent reliability when comparing navigation to a robotic/UFS testing system with an average ICC of 0.99.

The complexity of the pivot shift movement makes quantitative kinematic analysis of this test challenging. Colombet et al. [18, 67] measured the pivot shift test using an optically based CAS system, with an accuracy of within 1° for angular measurements and 1 mm for linear measurements. During the pivot shift test, a reduction of 30–50% of the tibial rotation was measured after an ACL reconstruction compared with the ACL-deficient knee [18]. Lane et al. [43] reported on correlations between clinical grading of pivot shift and navigation data from 12 patients before and after an ACL reconstruction. The authors defined "angle of p," created by the pathological anterior motion path during the pivot shift maneuver in the

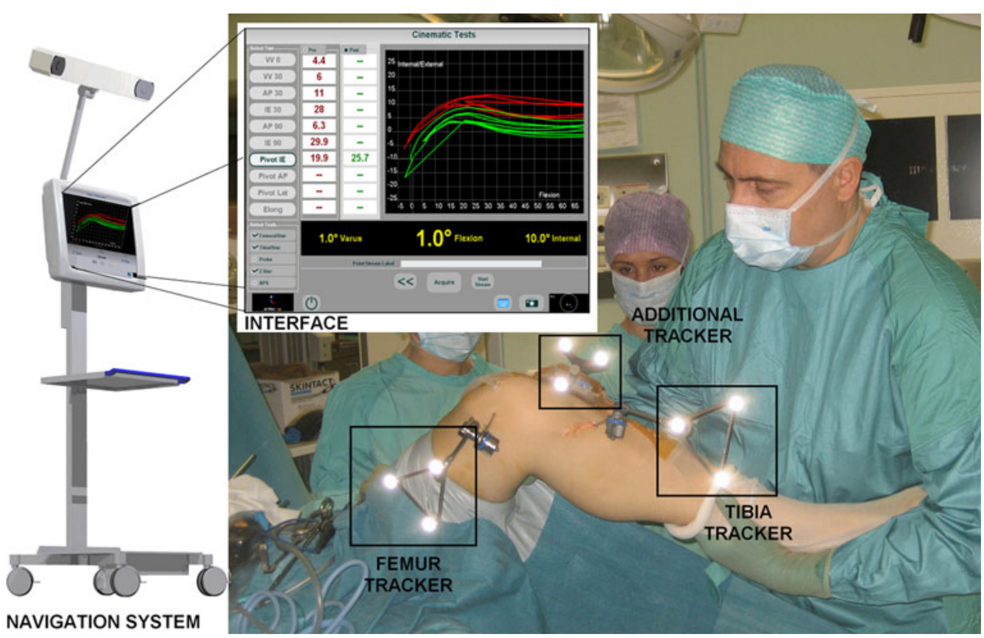

Fig. 1 Computer-assisted surgery (CAS) (Unpublished material, courtesy provided by Lopomo N. and Zaffagnini S., Instituto Ortopedico Rizzoli, Bologna, Italy)

ACL-deficient knee compared with a normal reference motion path. There was an excellent correlation between the “angle of p” and the clinical grade of the pivot shift ($R = 0.97$, $P < 0.001$) [43].

Recently, CAS has been used to evaluate double-bundle ACL reconstructions, highlighting the complexity of evaluating and controlling the pivot shift [18, 29, 33, 52, 87]. The results from these studies further underline that pivot shift is the most reliable test with regard to quantitative assessment of dynamic knee laxity.

In conclusion, CAS provides precise dynamic laxity measurements with the advantage of high repeatability of manual tests such as the pivot shift. However, disadvantages are the invasiveness of the system and evaluation confined to the ipsilateral side.

Accelerometers

An invasive and direct measurement of acceleration during the pivot shift test was reported by Mayema et al. [55] as a potential experimental model for ACL deficiency and reconstruction. The authors presented use of a triaxial accelerometer fixed to the tibial tubercle. They examined the accelerations in ACL-deficient porcine knees and found that an increased acceleration during the pivot shift test was correlated with increased injury of the ACL [55]. Lopomo et al. [53] reported a noninvasive acceleration measurement for the pivot shift where the sensor was placed on the skin between the lateral aspect of anterior tibial tuberosity and Gerdy’s tubercle. The authors utilized a triaxial accelerometer, firmly mounted to the anterolateral leg with a strap, aligned with the mechanical axis of tibia (Fig. 2). This position was chosen because the lateral compartment translation is accentuated during the pivot shift test [11]. A second sensor can be mounted on the femur for reference. The size and noninvasiveness of this accelerometer with wireless connection to a laptop facilitates its office-based use. Also, the system generates various acceleration parameters, that is, maximum, minimum, range and slope of the acceleration, all of which have an acceptable level of the intra-examiner repeatability (intra-class correlation coefficient/ICC, 0.69–0.93). The probability of a correct diagnosis of ACL deficiency was 70% using the slope of acceleration and 80% using the range of acceleration [53].

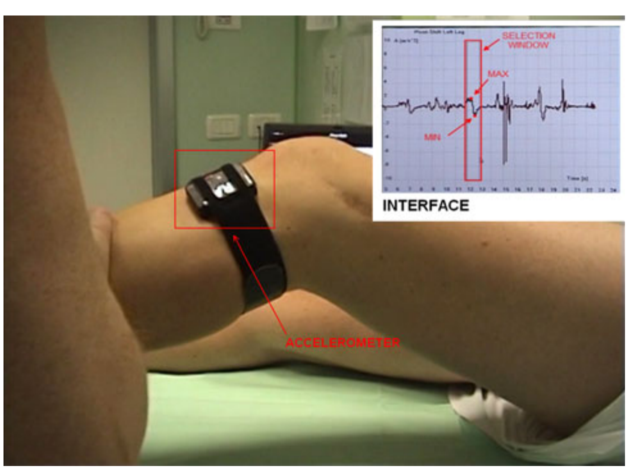

Fig. 2 Accelerometer (Unpublished material, courtesy provided by Lopomo N. and Zaffagnini S., Instituto Ortopedico Rizzoli, Bologna, Italy)

In conclusion, the accelerometer is a feasible and noninvasive device with promising results in terms of quantification of the pivot shift. Further validation and reliability testing is warranted, however.

Electromagnetic tracking devices

Pivot shift measurements in vivo using electromagnetic sensors were first reported by Bull et al. [15]. They conducted direct measurements of knee kinematics on anesthetized patients before and after an ACL reconstruction. The most important finding was that the movements during pivot shift were greatly reduced by an ACL reconstruction. The authors also reported large individual variations in knee kinematics, especially in terms of internal and external rotation, during pivot shift phenomenon. The same research group later reported on the development of skin-mounted sensors using clamps for noninvasive measurement with minimal motion between bone and skin. An accuracy of approximately 1 mm and 1° during a static knee laxity test was achieved. However, when these were used for more dynamic pivot shift tests, the actual motion of the bones could be underestimated, which is a limitation of this method. A sampling rate of 30 Hz was used [3].

Kubo et al. [40] developed a noninvasive measurement system using a similar electromagnetic tracking device (Fastrak®, Pohlemus, Colchester, VT USA). The receivers were attached with plastic braces on the thigh and shank. With the digital information of the anatomical reference point location, knee kinematics could be measured during dynamic movement. The sampling rate was 40 Hz, and their skin-mounted sensors could provide good correlation to the direct bone-fixed measurement with a correlation coefficient of 0.995 and maximum error in translation of 0.85 mm during the pivot shift test. The authors also reported a positive correlation between the clinical assessment and velocity of the pivot shift movement [40].

Hoshino et al. [29, 30] utilized a noninvasive measurement system with higher sampling rate from 60 to 240 Hz. The researchers found positive correlations between anterior tibial translation and posterior tibial acceleration during the pivot shift test and clinical grading of the pivot shift test [30]. Hoshino et al. [29] also reported that abnormal knee movement in the ACL-deficient knee could be detected only by the pivot shift test, and not by a pure rotational stress test or a simple rotation measurement (Fig. 3).

Araki et al. [7] compared anatomical single-bundle versus double-bundle ACL reconstruction using an electromagnetic device. They found that double-bundle ACL reconstruction revealed better restoration of tibial acceleration during the pivot shift test than single-bundle reconstruction.

Labbe et al. [42] used an electromagnetic tracking device to study different components of the pivot shift. They found that the velocity and acceleration of the pivot shift phenomenon accounted for much of the differences and were more closely related to the clinical grade than other features of the pivot shift test, such as simple translation or rotation.

In conclusion, electromagnetic tracking devices can be used in vivo with good accuracy and have helped to further define the kinematics of the pivot shift test. However, the currently used sensors are not wireless, and possible disturbance from ferromagnetic material might limit their clinical utility.

Image-based techniques

Dynamic RSA and image-matching techniques

Radiostereometric analysis (RSA) has been used with a superb accuracy to monitor three-dimensional knee motion not only during A-P laxity testing [24, 34] but also during functional movements ("dynamic RSA") such as active knee extension [14, 32], running [78, 79] and jumping [21]. The procedure involves insertion of multiple (typically 5–10) tantalum markers with the diameter of 0.8–1.6 mm in the femur and tibia. Imaging is done by means of biplane radiographs. The three-dimensional (3-D) anatomic positions of the markers are evaluated using a calibration cage with tantalum markers or using CT imaging of the tibiofemoral joint.

Fig. 3 Electromagnetic tracking device (Unpublished material, courtesy provided by Hoshino Y., Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, USA)

RSA is a highly precise system with reported accuracy of within 0.1 mm when evaluating in vivo joint motion [76, 78]. As highlighted by Tashman et al. [77], the advantages of this technique involve excellent tracking precision, no skin motion artifacts and the possibility to present results in an anatomical reference frame.

The image-matching technique has been developed to capture the knee movement without beads implantation and has often been used for quasi-static movement. Abebe et al. [1, 20] reported the effects of femoral graft placement on in vivo knee kinematics after ACL reconstruction. Each patient performed a single-leg lunge from 0° to 90°, in increments of 15°, within the beams of two orthogonally positioned fluoroscopes. By manually manipulating the 3-D models, made from magnetic resonance imaging (MRI) until the projections matched the edge-detected outlines on the fluoroscopic images, the motion of each subject's knee during the lunge could be reproduced. The researchers found that knees with anatomic femoral placement of the graft more closely restored native knee kinematics. The protocol was validated by DeFrate et al. [20] using a cadaveric knee rigidly fixed to a materials testing machine with an accuracy of 0.001 mm. The average error in measurement of translation was 0.04 ± 0.06 mm, and when rotation was measured, the SD was <0.3°.

Another type of image-matching technique was reported by Nakamura et al. [8, 61] using CT instead of MRI. This study was also performed in a semidynamic fashion. The biplanar radiographs were taken under weight-bearing conditions in the so-called giving way position and under non-weight-bearing conditions when the pivot shift was performed by an examiner. The standard deviations of these measurements were within 0.4 mm of translation and within 0.4° of rotation. Several other researchers have reported image-matching techniques when studying knee kinematics [22, 46, 47, 82].

Dynamic stereo radiograph system (DSX) is a technique that evolved from RSA using the same system but without implantation of tantalum beads. DSX combines data collected from high-speed biplane radiography and CT scans [31] (Fig. 4). A model-based tracking technique is used to align the 3-D CT bone models to the radiographic image pairs, defining the anatomical coordinate system and providing knee kinematics at the same time [4]. DSX measures static joint orientation with a precision of 0.2° and static joint position with a precision of 0.2 mm or better. When measuring joint motion during running, precision for rotation was <1.0°, and for translation, the precision was <1.0 mm [4]. Similar accuracy was reported by Myers

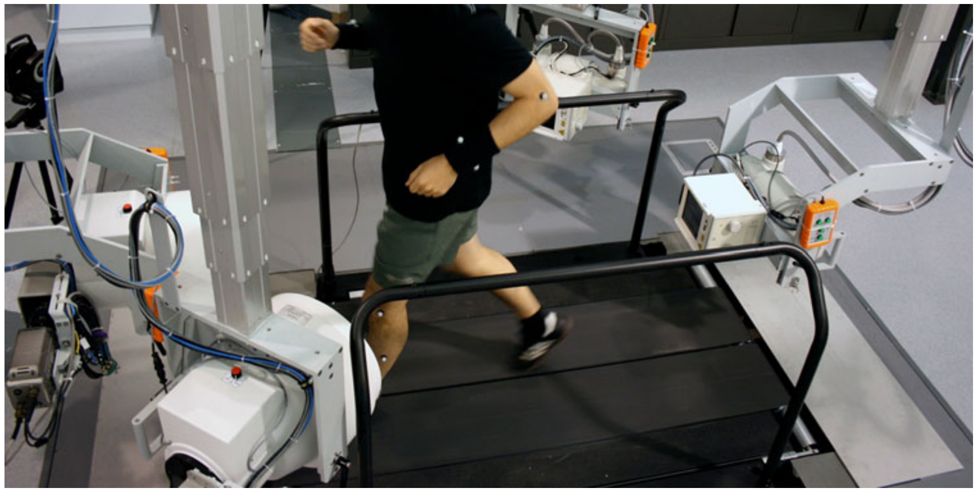

Fig. 4 DSX (Unpublished material, courtesy provided by Tashman S., Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, USA)

et al. [60] using high-speed biplane fluoroscopy when monitoring knee kinematics during landing from a height of 40 cm. The authors validated the system by dropping 3 cadaveric knee specimens with implanted tantalum beads from a height of 40 cm and then comparing the positions of beads and bones, respectively.

Higher sample rates, that is, at least 100–250 Hz, are required for capturing significant events in gait or running/jumping, while very clear images are necessary to properly analyze the knee kinematics using radiographic systems. Thus, the exposure time for each frame is a key to achieve clear images. Longer exposure time and faster movements result in "blurred images"; therefore, many systems often use exposure time of 1 ms or less [75]. Tashman et al. [75] suggested that imaging parameters described in a manuscript should include frame rate, pulse width (exposure time), X-ray protocols (beam current in mA and beam energy in kVp) and X-ray system geometry (source-to-detector distance, inter-beam angle). This information is of major importance in scientific reports.

In conclusion, when studying image-matching techniques, only few studies are performed in a truly dynamic fashion. Different technical aspects are important when evaluating the techniques, such as the frame rate and exposure time. Advantages are the noninvasiveness and the capability of some systems, that is, DSX, to monitor high-speed joint motion, such as running, with high accuracy. However, disadvantages include high costs and the need for manual labor-intensive analysis.

Open MRI

MRI has traditionally been characterized as a static imaging of bone and soft tissues of the unloaded knee. Newer applications have been introduced for in vivo analysis of knee joint kinematics and quantitative imaging of knee joint cartilage deformation, meniscal kinematics and joint contact kinematics. Some researchers have investigated quadriceps extension motions or A-P load in static positions [17, 48, 49, 66, 72], whereas others report the use of dynamic MRI [9, 10].

Logan et al. [48] studied subjects with ACL-deficient knees when squatting to 90° of flexion by using an open MRI. The knees were scanned at 0, 20, 45 and 90° of flexion, and the authors reported that the position of the lateral femoral condyle was subluxed posteriorly at all flexion angles compared with normal. Okazaki et al. and Tashiro et al. [65, 74] simulated the Slocum anterolateral rotatory instability (ALRI) test in an open MRI scanner by applying rotational stress to the tibia and found good correlation between the side-to-side difference of anterolateral tibial translation and pivot shift test grade in both ACL-reconstructed knees and ACL-deficient knees. The same researchers also reported good reproducibility using this method. Differences between two measures of anterolateral translation were 1 ± 0.7 mm, and ICC was 0.91–0.98 for inter- and intra-observer reliability.

In a recent study, Haughom et al. [28] explored relationships between tibio-femoral kinematics following ACL reconstruction and early degeneration of the cartilage matrix. They combined quantitative cartilage assessment scans and kinematic scans. The kinematic scans were acquired in full extension and 30° of flexion with an axial compressive force of 125 N applied to the plantar surface of the patient's foot in the supine position. However, the authors found no significant differences in tibial rotation between the injured and contralateral legs. A major limitation pointed out by the researchers was the small ($n = 11$) and heterogenetic study cohort. The loading configuration can be discussed as other researchers point out the need for weight-bearing or adequate weight-bearing simulation to mimic the in vivo changes in knee kinematics [62, 63]. Nevertheless, earlier studies with simulated weight-bearing in a supine position using MRI have demonstrated kinematic changes with ACL-deficient and ACL-reconstructed knees [17, 72].

In conclusion, technical development has markedly improved image-based techniques in terms of evaluating dynamic laxity even at high-speed activities. Knee kinematics can be correlated to meniscal kinematics and joint contact areas utilizing MRI. As MRI techniques improve, the dynamic assessment of joint function utilizing MRI will most probably improve as well.

Discussion

The main purpose of this study is to report on current techniques for in vivo evaluation of the pivot shift test and functional movements in the ACL-deficient or ACL-reconstructed knee. Clinical studies often report success measured in restoration of A-P laxity and high knee-rating scores [2, 44]. However, many studies have reported that ACL reconstruction does not restore native kinematics [14, 26, 78]. The methods of measuring knee kinematics vary greatly, underlining the lack of a gold standard. In the ACL-reconstructed knee, abnormal knee kinematics has been shown during in vivo functional activity, but it is unclear whether this change in kinematics is correlated with clinical outcome and the development of osteoarthritis in the medium- and long term.

Many devices aim to study the pivot shift phenomenon since the pivot shift test has been shown to correlate to functional outcome, return to sports and osteoarthritis, and is the most specific dynamic instability test in the ACL-deficient knee [36, 39, 68]. Nevertheless, the pivot shift test entails a complicated motion, which is generally described as a two-component rotation about the axis of knee flexion and axis of tibial rotation [16]. These rotational axes are not consistent across subjects [15]. Such variability of the pivot

Table 1 Principal parameters of the pivot shift reported to correlate with clinical grading

Author	Method	Principal parameter
Bedi et al. [11]	CAS	Coupled anterior translation of lateral compartment
Bull et al. [15]	EM-bone fixed	1. Coupled anterior translation
		2. Tibial rotation
Hoshino et al. [30]	EM-skin fixed	1. Acceleration of tibial reduction
		2. Coupled anterior tibial translation
Kubo et al. [41]	EM-skin fixed	Velocity of posterior tibial translation
Labbe et al. [43]	EM-skin	Velocity and acceleration of tibial reduction
Lane et al. [44]	CAS	"Angle of p"
Lopomo et al. [53]	CAS	Coupled anterior translation of lateral compartment
Lopomo et al. [54]	Accelerometer	Acceleration; especially range and "jerk"
Yamamoto et al. [84]	CAS	Coupled anterior translation

CAS computer-assisted surgery, *EM* electromagnetic tracking

Table 2 Advantages and disadvantages of devices for the measurement of dynamic rotational laxity

Device	Advantages	Disadvantages
CAS	Accuracy	Invasive
	Repeatability of manual tests	Ipsilateral side only
Accelerometer	Noninvasive	Skin motion
	Wireless	Only acceleration
	Small	
Electromagnetic tracking	Noninvasive	Skin motion
		Not wireless
		Ferromagnetic influence
Image-matching with beads (RSA)	Accuracy	Invasive
		Cost
		Labor-intensive
Image-matching noninvasive	Highly dependent on system, potentially high accuracy	Highly dependent on system
MRI open	Display of soft tissues	Semidynamic
	No radiation	Restricted space for examination

Table 3 Accuracy and repeatability reported for dynamic knee laxity devices

Author	Device	Validation	Accuracy	Repeatability
DeFrate et al. [20] Abebe et al. [1]	Biplane radiography with image-matching to MRI	Robot	Semidynamic error = 0.04 ± 0.06 mm, <0.3°	
Asano et al. [8]	Biplane radiography with image-matching to CT			SD = 0.4 mm, 0.4°
Li et al. [48]	Biplane radiography with image-matching to MRI	Beads ("RSA")	Semidynamic error = 0.24 ± 0.16 mm, 0.16 ± 0.61°	
Myers et al. [61]	Biplane radiography with image-matching to CT	Beads ("RSA")	Dynamic error = 0.4 ± 0.4 mm, 0.3 ± 0.6°	
Tashman et al. [77]	RSA-dynamic	Implanted beads	Dynamic	
Anderst et al. [4]	DSX		RSA error = 0.2 mm, 0.3°	
Deneweth et al. [21]			DSX error = 0.3–0.7 mm, 0.3–0.9°	
Brandsson et al. [14]	RSA-semidynamic		Semidynamic error = 0.1 mm, 0.1–0.3°	
Shefelbine [73] Carpenter et al. [17] Haughom et al. [28]	MRI-semidynamic		Semidynamic error = 0.6–1.2 mm	ICC (inter-examiner and intra-examiner) = 0.6–0.9 mm, 1.5°
Okazaki et al. [66]	MRI-semidynamic			ICC (intra-examiner) = 0.96–0.98 (inter-examiner) = 0.91–0.93
Barrance et al. [9] Barrance et al. [10]	MRI-dynamic	EM	Variation between systems (rms) = 2.82 mm, 2.63°	ICC (inter-examiner) = 1.44 mm, 2.35°
Bull et al. [15] Amis et al. [3]	EM-skin	EM-bone fixed	Slow dynamic error = 1 mm, 1°	
Kubo et al. [41] Hoshino et al. [30] Hoshino et al. [31] Araki et al. [7]	EM-skin	EM-bone fixed	Variation between systems (rms) = 0.76 mm, 0.15° Pivot shift: correlation coefficient = 0.995, error = 0.85 mm	Coefficient of variation = 0.13–0.50 (mean 0.30) SD = 1.1 mm, −211 mm/s^2
Pearle et al. [68] Bedi et al. [11] Musahl et al. [60]	CAS	Robot	ICC = 0.89–0.99 between systems	ICC (intra-examiner) = 0.92 mm, 0.82°
Colombet et al. [18]	CAS		Error = 1 mm, 1°	
Zaffagnini et al. [85]	CAS		Error (rms) = 0.35 mm	SD = 0.7 mm
Martelli et al. [57] Lopomo et al. [52] Lopomo et al. [53]				ICC (intra-examiner) = 0.85–0.99 (inter-examiner) = 0.68–0.93
Lopomo et al. [54]	Accelerometer			ICC (intra-examiner) = 0.69–0.93
Mayema et al. [56]	Accelerometer			ICC (intra-examiner) = 0.95–0.96

shift movement could possibly be secondary to the degree of ACL injury, bony articular geometry and differences in the state of secondary restraints [16, 25, 31, 57, 58].

Another concern is the subjective nature of the pivot shift examination, in terms of both the force applied and interpretation of the result [41, 64]. Hence, there is a definitive need for reliable methods to quantitate pivot shift and also an understanding of the parameters defining a low-grade versus a high-grade pivot shift. Electromagnetic systems have been used to correlate clinical grading and kinematic measurements, that is, anterior tibial translation, velocity and acceleration of reduction during the pivot shift test [30, 40] (Table 1).

Navigation systems have also found kinematic parameters that have correlations to clinical grade, such as tibial rotation, maximum translation [83], acceleration of posterior translation, "the angle of p" [43] and lateral compartment translation [11] (Table 1). The navigation system can also provide excellent feedback to the examiner, thus resulting in better repeatability when performing the tests. Also, bone-mounted sensors are found to be more accurate than skin sensors. When using computer navigation, examination is usually restricted to the ipsilateral side and only permits assessments at time-zero. Obviously, there is a need for simple in vivo applications, which would allow for follow-up studies in clinical settings. The electromagnetic tracking devices and accelerometers fulfill these criteria, the accelerometer being most feasible in the clinical setting. Improvement of skin sensors is needed to achieve better reliability, whereas exploration of the potential need for standardized loads for the pivot shift test is warranted for a universal standard in terms of rotational dynamic laxity.

When performing functional testing, RSA and DSX are highly accurate methods of measuring kinematics even in high-speed activity such as running or jumping. For monitoring bony kinematics during activity, these methods probably are closest to what can be defined as "the gold standard." However, the complicated setup and costs limit the use in a clinical scenario as a part of routine follow-up or in large study populations. The open MRI devices do not display the same capabilities of monitoring high-speed activities, but valuable information in terms of meniscal kinematics or quantitative cartilage imaging can be correlated to tibio-femoral kinematics (Table 2).

Most systems currently in use to measure dynamic laxity need further validation and reliability testing. Few devices are externally validated. An overview of reported accuracy and repeatability is displayed in Table 3.

There are several implications to quantitate and decompose the pivot shift and other dynamic laxities of the knee joint. In pursue of improved operative techniques, such as anatomic ACL reconstruction, control of rotational laxity is a major argument [37, 84]. In order to perform high-level research, a common language and clear definitions of rotational laxity would be in favor. In addition, valuable in-depth analyses in terms of correlation to clinical outcome and osteoarthritis after ACL reconstruction are also warranted. In order to perform individualized surgery, individual kinematics could be assessed using computer navigation in an intra-operative setting [86]. With an individualized approach to each patient, absence of integrity of secondary restraints of dynamic rotational laxity could warrant addressing other structures than the ACL during reconstructive surgery. In the future, the definition of a "failed ACL reconstruction" will probably have much lower threshold than today, based on newer knowledge regarding dynamic laxity in ACL-deficient and ACL-reconstructed knees.

Conclusion

Several devices can be used to examine dynamic rotational laxity of the knee. The devices are under continuous development. It is important to note that there are advantages and disadvantages to all devices. Studies to validate devices and correlate with clinical outcome are necessary to develop "the gold standard." Since dynamic rotational laxity is not clearly defined, various methods have been used, which make comparisons between studies challenging. Future implementation should include primary basic research, including appropriate validation and reliability testing, individualized surgery and clinical outcome studies. The ideal device for the assessment of dynamic rotational laxity would be cheap, easy to use, noninvasive, provide detailed information on anatomical structures (MRI), have sub-millimeter accuracy, evaluate functional tasks (DSX) and have a powerful correlation to clinical outcome.

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