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ACL UPDATE: OBJECTIVE MEASURES ON KNEE INSTABILITY (V MUSAHL, SECTION EDITOR)

Objective measures on knee instability: dynamic tests: a review of devices for assessment of dynamic knee laxity through utilization of the pivot shift test

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Abstract Current reconstructive methods used after anterior cruciate ligament (ACL) injury do not entirely restore native knee kinematics. Evaluation of dynamic knee laxity is important to accurately diagnose ACL deficiency, to evaluate reconstructive techniques, and to construct treatment algorithms for patients with ACL injury. The purpose of this study is to present recent progress in evaluation of dynamic knee laxity through utilization of the pivot shift test. A thorough electronic search was performed and relevant studies were assessed. Certain dynamic knee laxity measurement methods have been present for over 10 years (Navigation system, Electromagnetic sensor system) while other methods (Inertial sensor, Image analysis system) have been introduced recently. Methods to evaluate dynamic knee laxity through the pivot shift test are already potent. However, further refinement is warranted. In addition, to correctly quantify the pivot shift test, the involved forces need to be controlled through either standardization or mechanization of the pivot shift test.

Keywords Anterior cruciate ligament · ACL · Injury · Pivot shift test · Dynamic laxity · Instrumented laxity

Introduction

The knee joint is a complex structure, where bone, muscle, menisci, and ligamentous tissues cooperate in generating a flexible yet stable joint. One of the most important structures concerning stability is the anterior cruciate ligament (ACL). In a recent study, two diverse types of measurable joint instability were described: static and dynamic laxity [1]. Static laxity is measured through uniplanar examinations as supposed to dynamic laxity, which is more often associated with symptoms and is distinguished by the pivot shift test (PST) [1]. To assess knee instability, the Lachman test, the anterior drawer, and the PST are widely used [2, 3]. The most specific clinical test for ACL rupture is the PST [4], which was first described by Galway et al. in 1972 [5]. The pivot shift is a phenomenon observed in ACL-deficient knees where a primary anterior subluxation of the lateral tibial plateau occurs. As flexion increases, the anterior translation converts into reduction of the tibia upon the femoral condyle and a posterior tibial acceleration commences as the iliotibial band pulls the tibia posteriorly. Bull et al. determined the motion of the tibia during reduction to be a combination of external tibial rotation and posterior tibial translation [6].

Even though the Lachman's test has long been considered the gold standard in terms of establishing diagnosis of ACL rupture, the measured entity, being static anterior tibial translation, poorly correlates with patient satisfaction. Moreover, it has been shown that the PST better correlates with both

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clinical outcome [7–9] and development of osteoarthritis (OA) [10]. However, the PST is not flawless; one obvious limitation is the subjectivity of the test and there is a considerable inter-examiner variability [11]. This can be derived partly from the various techniques used when performing the pivot shift maneuver [12–15], and the lack of standardization is a current issue [16]. A globally accepted standardized technique of performing the PST is an important step; however, the manual loading of involved forces would still vary and render both intra- and inter-examiner variability. To address this problem, a method for performing mechanical pivot shift has been developed. The results are promising; regrettably, the instruments are not yet available in the clinical setting [17, 18]. Moreover, means of objectifying measurements during the PST is desirable and in recent years, various methods have been developed with this objective. Development of innovative technology is accelerating within this particular field, which is why an updated review is necessary. Multiple devices for assessment of static or semi-dynamic rotational laxity have been developed in recent years [19–22]; however, it has been shown that measurement of static rotational laxity is insufficient for detection of rotational instability in ACL-deficient knees when compared with the PST (Table 1). [23, 24] Important measurement devices for detection and quantification of the PST have been described in the literature, the most important being surgical navigation [25–27], electromagnetic sensor systems [6, 24, 28], and inertial sensors [29–32, 33•]. In addition, a new promising image analysis system has recently been presented [34]. There is disagreement related to the optimal reconstructive technique for ACL deficiency [35, 36]. In order to evaluate surgical interventions, the quantification of dynamic knee laxity is essential. Pre- and intraoperative quantification of knee kinematics during the PST can be used to create treatment algorithms for complicated cases of knee instability [37]. Moreover, it is important to improve the diagnostic accuracy of non-invasive, inexpensive measurement devices to facilitate diagnosis in both orthopedic clinics and in primary healthcare.

This review will focus on novel methods of objectively measuring dynamic knee instability through utilization of the PST in vivo. The objective is to provide a concise update about important progress in the field during the last couple of years.

Materials and methods

A systematic electronic search was performed in collaboration with a medical librarian with expertise in electronic search methods. The objective was to present recently published data regarding technical equipment utilized in quantification of the PST. The PubMed (MEDLINE) database was searched and articles published between 1 January 2012 and 1 November 2015 were eligible for assessment and inclusion. Abstracts were read to evaluate relevance to the subject and reference lists of influential publications were scanned for additional publications of interest. Each paragraph will introduce the subject with a succinct review about earlier publications to put new information in a clear context.

Technical equipment for assessment of dynamic knee laxity

Electromagnetic sensor systems

Electromagnetic sensor systems (EMS) have been utilized to assess rotational knee laxity since 2002 [6]. In the first study by Bull et al., measurements were obtained during the PST both prior to and after ACL reconstruction. The device (Ascension Technology, Burlington, VT, USA) had an accuracy of 0.23 and 1.8 % for the step size of translation and rotation, respectively. It was shown that anterior tibial translation (ATT) was greater in ACL-deficient knees, and a reduction movement could be observed at around 30 degrees of knee flexion. After reconstruction, the amount of ATT decreased and no reduction movement could be observed. This first study highlighted the advantages of quantitative evaluation of knee laxity using electromagnetic technology; however, there were also evident limitations in the methodology. Tracking receivers were fixed using Kirschner wires (K-wires) and consequently, an increased time under anesthesia could be observed. Moreover, the invasive method limited use to the operating room only and entailed a potential risk for infection [6].

A recently published study by Kuroda et al. [38•] summarizes data from previous influential publications utilizing an electromagnetic tracking device (FASTRAK or LIBERTY, Polhemus, Colchester, VT, USA) [24, 28, 38•]. The system consists of a transmitter with a sampling rate of 60 or 240 Hz that produces an electromagnetic field and communicates using three electromagnetic receivers (Fig. 1a). In order to digitize the three-dimensional anatomy of the involved structures, one receiver with these abilities was utilized and the six degree-of-freedom kinematics was evaluated. Estimations of the three-dimensional movement of the thigh and shinbones were made with two receivers that were attached to the femur and the tibia using Velcro™ straps. The device had a root mean square (RMS) accuracy of 0.15 and 0.76 mm for orientation and position respectively when within optimal operational zone [28]. A previous study had shown good correlation between described non-invasive method and a method with rigid fixation using K-wires. To determine a relative rate of tibial anteroposterior (AP) translation, the pivot shift was compared to a standardized maneuver. The maneuver is executed by external rotation and passive flexion and a calculated comparison value, named by the authors as the coupled anterior tibial

Table 1 Accuracy and repeatability of assessed measurement devices

Author	Device	Name	Accuracy	Repeatability
Hoshino et al.	EMS	Fastrak	RMS 0.76 mm, 0.15°	*Intra-examiner:* correlation coefficient: c-ATT (0.98–0.99), APT (0.95–0.97)
Nagai et al.	EMS	Liberty	RMS 0.76 mm, 0.15°	Standard deviation of APT (0.2 m/s^2)
Lopomo et al. [30, 44•]	Accelerometer	KiRA	RMS 5.5 ± 2.9 mm [30]	*Intra-examiner:* mean ICC for all parameters (0.79) [44•]
Kopf et al. [47]	Inertial sensor	Razor-IMU	–	–
Borgstrom et al. [33•]	Gyroscope and accelerometer	ITG-3200 and ADXL345	ITG-3200 ± 1.8°	–
Labbe et al. [49•]	MEMS	nIMU™	Stated accuracy: acceleration ±0.03g, RV ±1° Measured error: 2.57 ± 1.08° compared to optical reference	–
Imbert et al. [61, 63, 68]	Navigation	Praxim	Error 1 mm, 1° [63]	*Intra-examiner:* <0.6° for VV rotation, <1 mm for AP translation, <1.6° for IE rotation *Inter-examiner:* <2° for VV rotation, <3 mm for AP translation, <5° for IE rotation [68]
Porter et al. [64•, 68]	Navigation	Stryker Navigation Inc	–	See Imbert et al. above [68].
Zaffagnini et al. [60]	Navigation	BLU-IGS	RMS 0.350 mm [69]	*Intra-examiner:* mean ICC (0.98)
Monaco et al. [62]	Navigation	Orthopilot	Error <1 mm, <1°	–
Hoshino et al. [34, 66•]	Image analysis system	–	3.0 ± 0.8 mm compared to 22, 8 ± 0, 4 (EMS) [34]	–

AP anteroposterior, *APT* acceleration of posterior translation, *c-ATT* coupled anterior tibial translation, *EMS* electromagnetic system, *ICC* intra-class correlation coefficient, *IE* internal-external, *MEMS* micro-electromechanical system sensor, *RMS* root mean square, *RV* rotational velocity, *VV* varus-valgus

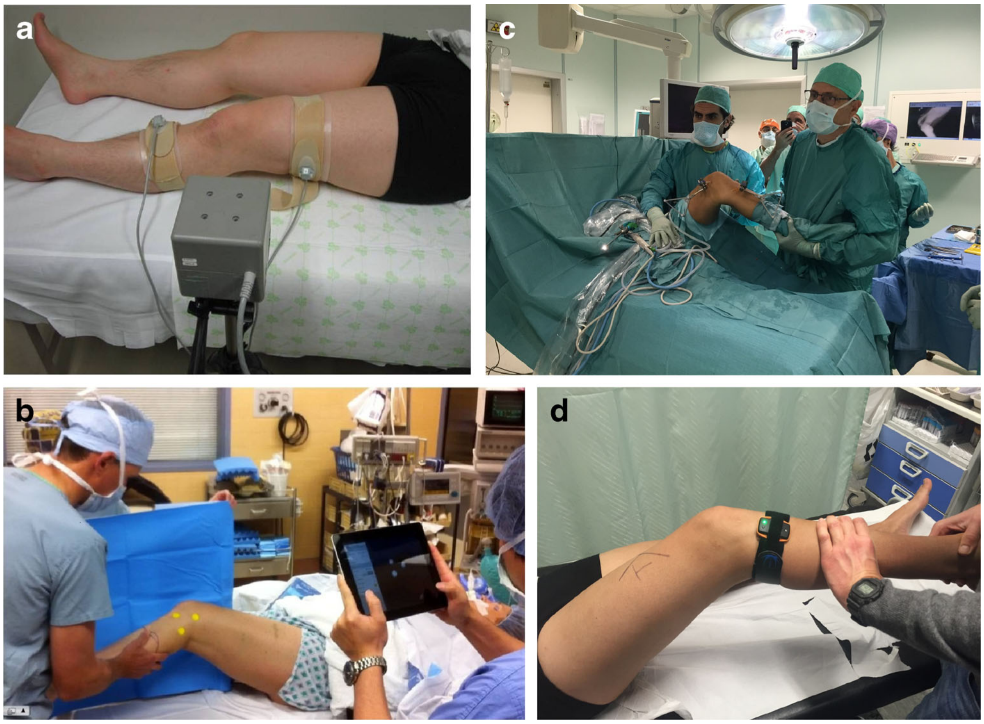

Fig. 1 Pictures demonstrating electromagnetic sensor system (**a**), image analysis system (**b**), surgical navigation (**c**), and inertial sensor (**d**)

translation (c-ATT), is determined. The acceleration of posterior translation (APT) was assessed by secondary derivative to positional data in the anteroposterior direction. Acceleration in knees with ACL injury was approximated to 2–3 m/s^2 compared to 1 m/s^2 in intact knees [24, 28, 38•]. The c-ATT was considered a reliable parameter in assessment of ACL deficiency and the average standard deviation of three consecutive measurements were 1.1 ± 0.6 mm and $-211 + -176$ mm/s^2 for the c-ATT and APT, respectively. No intra-class correlation coefficients were calculated.

Araki et al. designed a study to compare laxity measurements of complete ACL ruptures ($n = 20$), partial ruptures ($n = 20$), and contralateral knees ($n = 40$) [39]. An electromagnetic device (FASTRAK, Polhemus, Colchester, VT, USA) was used to assess both the Lachman test and the PST; examinations were performed under general anesthesia. Values regarding mean tibial acceleration were significantly different between all three groups. Tibial acceleration was not analyzed in relation to clinical grading. Cutoff values for distinction between intact knees (sensitivity 85 %, specificity 80 %) and partial tears (sensitivity 75 %, specificity 75 %) using tibial acceleration during the PST were determined [39].

Matsushita et al. assessed the difference in APT with an EMS (FASTRAK, Polhemus, Colchester, VT, USA) during the PST by comparing examinations in the awake state as supposed to under general anesthesia [40•]. Fifty patients with unilateral ACL injury were examined. Results showed that mean APT in ACL-deficient knees were larger compared with intact knees, both when patients were awake and when they were under anesthesia. However, the APT in ACL-deficient knees was significantly larger when performed under general anesthesia, a pattern that was apparent also concerning clinical grading of the PST. Furthermore, the authors established correlation coefficients for both states of consciousness, both displaying high repeatability. Matsushita et al. recommended utilization of the PST under anesthesia to accurately evaluate rotational laxity based upon the results of this study.

The EMS is considered a reliable technology for detection of ATT and APT. Accordingly, it was recently used by Kitamura et al. to compare different techniques to assess dynamic rotational knee laxity [14]. The FASTRAK (Polhemus, Colchester, VT, USA) device was used and the PST, the N-test [41], and the jerk test [42] were compared. The authors concluded that the three respective tests had different advantages and disadvantages, where the PST had greater peak c-ATT as supposed to the N-test that had greater APT as detected by the EMS.

In 2015, Nagai et al. published a study comprising 70 patients who were subjected to ACL reconstruction [43]. The PST was performed bilaterally with the same electromagnetic device used in the abovementioned studies [14, 28] (LIBERTY, Polhemus, Colchester, VT, USA). Examinations were executed prior to ACL reconstruction and repeated 1 year post-operatively. A significant correlation between stepwise escalations in tibial acceleration and clinical grading of the PST were observed. Furthermore, there was a significant difference between ACL injured and contralateral knees. A decrease in tibial acceleration was observed between pre-operative and post-operative measurements. Additionally, tibial acceleration was consistent when pre- and post-operative data was compared in contralateral knees. The examiners were cautious to perform the PST in a similar manner to minimize inter-examiner variability. A limitation to this particular study was a risk of observer bias at the time of acceleration measurements.

Taken together, electromagnetic devices have been in use for over a decade and have a well-documented precision and reliability. The current devices provide non-invasive data, which can be extracted both in the operating room and in the office setting. However, there are a few complications. Metallic objects can produce signal disturbances leading to preparation of examination/operation rooms in order to eliminate ferromagnetic materials. Moreover, wireless systems are yet to be developed to facilitate examinations and the limited operational zone of the transmitter complicates the setup, primarily when used intra-operatively.

Inertial sensors

To our knowledge, Maeyama et al. was the first to document the use of a triaxial accelerometer in evaluation of ACL deficiency [29]. The study compared porcine ACL-deficient knees to intact knees and could demonstrate a significant difference in acceleration during the PST. An accelerometer (Kistler, Winterthur, Switzerland) was attached invasively to the anterior tibial tuberosity with a screw. In order to facilitate precise measurement in three dimensions, a triaxial sensor was utilized, measuring the X (anteroposterior), Y (mediolateral), and Z (superoinferior) axes. Similar technology has been exerted henceforth [29].

Lopomo et al. have contributed to enhance the knowledge regarding the use of accelerometers in patients with ACL tears [44•]. A non-invasive triaxial accelerometer sensor (KiRA, Orthokey, LLC, Lewes, DE, USA) was embedded in a protective plastic sheath and was connected to a laptop, or tablet as in more recent versions, through a wireless connection (Fig. 1d). The sensor was attached to the proximal tibia using a brace. It was positioned between the lateral aspect of the tibial tuberosity and the tubercle of Gerdy, aligned with the mechanical axis of the tibia. This specific position was elected since previous studies have indicated that the lateral tibial compartment produces the largest acceleration and coupled tibial translation during tibial reduction [45]. The acceleration of the tibia upon the femur is measured and presented in m/s^2. The sudden tibial reduction can be visualized as a graph when the pivot shift occurs and the following parameters are calculated: a_{max} (maximum value), a_{min} (minimum value), a_{range} (a_{max}–a_{min}, variation in acceleration). Examinations were executed under local or general anesthesia to minimize the influence of refractory muscular contractions. Sixty-six patients with unilateral ACL injuries were evaluated by a single examiner. Four distinctive parameters were extracted and reliability was calculated with intra-class correlation coefficients (ICCs). The ICCs showed a mean for all parameters of 0.79, ranging from 0.69 to 0.93 in mean values for individual parameters. All parameters showed statistically significant differences in acceleration between ACL injured and intact knees [44•]. The same authors designed an additional study to validate the aforementioned accelerometer to a navigation system (Klee, BluIGS, Orthokey, LLC, DE, USA) [30]. A positive correlation between the systems was found ($rs = 0.72$, $p < 0.05$). Data of intra-examiner reliability was presented as average RMS error (5.5 ± 2.9 mm). The average RMS displacement caused by soft tissue artifacts was determined to 4.9 ± 2.6 mm.

Berruto et al. utilized the KiRA accelerometer, identical to the device used by Lopomo et al. [30, 44•], when conducting their study of 100 patients with unilateral ACL tear [46•]. Thirty of the patients attended follow-up examinations at a minimum of 6 months post-operatively. The results from this study support previous publications [30, 44•] with regard to pre-operative evaluations where all three parameters for the injured knee displayed significantly higher acceleration than for the healthy knee. Moreover, patients subjected to post-operative assessment normalized their values of acceleration, thereafter consistent to the contralateral intact knees. Berruto et al. studied the precision of the method for three examiners with different levels of experience and could observe a linear learning curve. The initial specificity of the accelerometer was 50 % for all examiners and increased with time and experience up to 90 %. Lastly, it was concluded that clinical grades, specified as negative, glide, or clunk, of the PST significantly differed in a stepwise order divided by increase in acceleration values by one parameter (a_{max}). The authors did not explicitly specify if examinations were performed awake or under anesthesia [46•].

Moreover, the KiRA device was implemented in a study by Nakamura et al. Their objective was to evaluate the PST and the N-test [41] in awake as well as in anesthetized patients with unilateral ACL injury. The N-test was performed as an inverted PST test; the knee is passively flexed to 90° where after the examiner starts to extend the knee while exerting valgus force and internal rotation. Twenty-nine patients were examined and the results showed that both the PST and the N-test generated significantly higher degree of acceleration in ACL-deficient knees when patients were under anesthesia. When patients were awake, no difference could be observed. Spearman's rank correlation was used to determine correlation between clinical grading and magnitude of acceleration. A moderate correlation was observed for both the PST ($r = 0.57$) and the N-test (0.69).

Kopf et al. tested 20 patients with ACL injuries under anesthesia using six degree-of-freedom inertial sensors (Razor-IMU, Sparkfun® Electronics, Boulder, CO, USA) connected to both the femur and the tibia [47]. The femoral sensor was positioned above the patella and the tibial sensor was placed at the medial surface of the tibia to ensure rigid fixation to the bone. The authors conducted preliminary tests that favored the use of two sensors, observing improved accuracy in this scenario. All three of the measured parameters were significantly higher in ACL-deficient knees as supposed to intact knees during the PST. Calculation of the standard deviation of acceleration was used to create a grading scale of four points corresponding to the grading system of the IKDC-2000 (0, 1, 2, 3). However, the authors concluded that there was no correlation between the subjective evaluation by the examiner and grading by the device.

Tibial rotation is an important part of a representative pathologic PST during tibial reduction. This fact was exploited by Borgstrom et al. who utilized a wireless gyroscope (ITG-3200, Invensense) to measure tibial rotation and tibial rotational velocity. The gyroscope was fixed to an aluminum plate that in turn was taped to the foot of the patient, an original fixation-technique that was developed in order to minimize skin motion artifacts. To counteract ankle movement, the foot was firmly taped to form a single moving unit conjoined with the tibia. Ten patients with unilateral ACL injury were examined under anesthesia pre-operatively; however, the results were not convincing. Using tibial rotation, 50 % of the patients were correctly diagnosed compared with 70 % using tibial rotational velocity. Correlations with clinical pivot shift grade were weak for both tibial rotation ($r^2 = 0.09$) and rotational velocity ($r^2 = 0.19$) [32]. The same research group published an article in 2015 comprising 32 patients with unilateral ACL injury and 29 patients with intact ACLs bilaterally [33•]. Inertial sensors consisting of a triaxial gyroscope (ITG-3200, Invensense) and a triaxial accelerometer (ADXL345, Analog Devices Corp.) were fastened to both the femur and the tibia using elastic straps. Examinations were performed under general anesthesia by one physician. Originally, 23 variables were computed though 3 distinctive variables in particular, determined with regression analysis, provided strong correlation with pivot shift grading. Non-linear support vector machine classifiers (SVMs) [48] were utilized to estimate the pivot shift grade. Ninety-four (77 %) of the knees were correctly diagnosed and 120 (98 %) were within the ±1 grade. The average error was 0.24 grades. Additionally, a system fusion method utilizing both SVM and regression methods were used to determine whether the patients had an intact ACL or had sustained a right or left-sided ACL injury. The system fusion method reached an overall diagnostic accuracy of 97 % with 6 % false negatives and no false positives [33•].

Labbe et al. published a study evaluating 13 patients with the use of a micro-electromechanical system sensor (MEMS) that contained a triaxial gyroscope, a triaxial accelerometer, and a triaxial magnetometer [49•]. The device (nIMU™, MEMSense™) has a stated accuracy of ±0.03 g for linear acceleration and ±1° in angular velocity and connects to a laptop through a USB port. Data was compared to optical readings from a camera (Vicon 460, Oxford Metrics™), also connected to the aforementioned laptop. Sensors were attached to both the femur and the tibia. A single surgeon performed all examinations in the clinical setting and was blinded to the MEMS data. The main finding was a strong correlation between the clinical grade of the PST and a decrease in femoral acceleration at the time of tibial reduction ($r = 0.84$); however, this parameter could not differentiate between grades 0 and 1 or between grades 2 and 3 [49•].

Taken together, inertial sensors (accelerometers, gyroscopes, and MEMS) are relatively new devices in the context of ACL injury assessment. The progress during the past 3 years has been impressive and publications have presented possible methods to provide precise information of diagnosis of ACL injury and even accurate indications of clinical grading. Devices are small and maneuverable, connected to laptops or tablet computers, which simplifies implementation in the clinical context. However, it appears that current inertial sensors may be inaccurate in evaluation of awake patients, as discovered by Nakamura et al. In addition, skin artifacts might cause further inaccuracy in relation to actual bone movement.

Computer-assisted surgery and navigation

One of the most important techniques of measuring dynamic rotational laxity was initiated as early as the 1990s when the use of computer-aided surgery (CAS) was first reported in ACL reconstruction [25]. The original idea of CAS was to enhance tunnel placement to create better isometry and avoid graft elongation; however, the technique has been implemented also in the evaluation of knee laxity and kinematics [50–52]. Determination of patient anatomy can be elicited through either pre-operative computed tomography, intra-operative fluoroscopic X-rays, or through an image-free system using predetermined anatomical landmarks [50, 53]. Image-free digitization of involved anatomic structures can be achieved either arthroscopically or percutaneously using navigated pointers [50, 51]. In order to evaluate knee kinematics, either electromagnetic or optoelectronic technology is utilized. Electromagnetic devices communicate with receivers through an electromagnetic field, a technology that is described in better detail in a section above. Optoelectronic systems use optical localizers to evaluate joint positions and movement through emission and reception of infrared light (Fig. 1c) [54, 55]. Trackers and receivers are invasively fastened to bone; hence, no skin-related artifacts are present. With few exceptions, examinations are performed under anesthesia. Navigation systems in multiple studies have been confirmed to have good precision and reliability [26, 56–58]. Evaluation of the PST with use of navigation systems has been reported in the literature [52]. In short, Colombet et al. showed decreased tibial rotation and AP translation after ACL reconstruction using navigation [54]. Lane et al. presented a phenomenon produced by a navigation system called "the angle of P" representing the pathological translation during a PST. The angle is created from the motion of the anterior tibial point in the sagittal plane, creating a slightly bent arc during the reference motion and a rounded arc when subluxation occurs. Addition of the two arcs resembles the letter P, and the vertex of the angle is positioned where the two arcs converge, a point where reduction occurs. The authors showed that the aforementioned angle correlated with clinical grading of the PST. The correlation between clinical grading and the angle of P was excellent ($R = 0.97$), while the correlation with ATT ($R = 0.87$), APT ($R = 0.81$), and tibial rotation was considered good [27]. Recent publications using CAS and navigation to assess the PST will be discussed in the following section; for additional information about earlier articles, we refer to previous publications [52, 59].

Recently, there has been a reborn of interest in extra-articular tenodesis as a complement to intra-articular reconstruction. A study by Zaffagnini et al. examined 35 patients comparing double-bundle (DB) ACL reconstruction to single-bundle (SB) ACL reconstruction with extra-articular tenodesis [60]. Static and dynamic laxity measurements were evaluated by a navigation system (BLU-IGS, Orthokey, Lewes, Delaware, DE, USA) that has a reported good reliability for the pivot shift analysis (ICC 0.98). Single-bundle reconstruction with extra-articular tenodesis produced less knee laxity during varus/valgus stress tests and produced a better control over lateral compartments during the drawer test; however, the DB reconstruction performed better in reducing laxity measured during the PST. On the same subject, Imbert et al. concluded that extra-articular anterolateral reinforcement in addition to intra-articular reconstruction could not fully normalize knee kinematics using navigation (Praxim, Medivision, La Tronche, France) [61]. However, Monaco et al. performed intra-articular and lateral tenodesis reconstructions on 125 patients concluding that the two methods interacted in normalizing dynamic stability of the knee joint as measured by the PST. The Orthopilot navigation system was utilized [62].

Assessment of the contralateral knee using navigation is uncommon due to ethical issues related to invasiveness. Nevertheless, a study by Imbert et al. compared both knees on 35 patients performing 6 different clinical tests. The PST showed a significant 70 % larger anteroposterior laxity in ACL-injured knees when compared to the contralateral healthy knee. Moreover, it was the only test that showed significantly different rotational instability compared to the healthy contralateral knee [63].

In a recent study, Porter et al. used navigation (Stryker Navigation Inc, Kalamazoo, MI, USA) to assess knee kinematics pre- and post-operatively to anatomic ACL reconstruction. The apparatus has an intra-examiner repeatability of less than 1 mm and 1.6° for ATT and rotation, respectively. Significant reduction of ATT (63 %) and internal rotation (IR, 67 %) could be observed post-operatively. Interestingly, two types of tracking devices were used. The standard method of intra-osseous fixated tracking devices was utilized on the operated leg, a method that was compared with skin markers fixed on both ipsilateral and contralateral knees. The reliability of skin fixation was encouraging with an ICC for internal rotation of 0.94 and for ATT of 0.89 [64•].

Lopomo et al. conducted a study to examine whether post-operative knee laxity could be predicted [65]. Anterior tibial translation and APT was analyzed retrospectively in 42 patients both pre- and post-operatively. It was stated that the post-operative magnitude of ATT could, in approximately 40 % of patients, be derived from the pre-operative values [65].

Taken together, navigation systems have been utilized in multiple clinical studies and continue to provide important and precise information about dynamic knee laxity. The ability to measure knee kinematics intra-operatively with high precision without skin-artifacts is a major benefit. Moreover, the fact that patients are under anesthesia prevents muscular guarding. However, disadvantages comprise invasiveness, a high cost, and risks related to prolonged surgical time. It is also, in most cases, not appropriate to examine the contralateral leg. Using skin fixation in combination with navigation as done by Porter et al. is not standard routine, hence the presented disadvantages.

Optical motion capture technique

Presentation of optical motion capture techniques using a camera to evaluate dynamic knee laxity is a new technique and, to our knowledge, the first publication was presented in 2012 [34]. As mentioned above, there is a correlation between the AP translation of the lateral compartment and the clinical grading of the PST. [45] This fact was exploited by Hoshino et al. in order to determine AP translation of the femur by application of rounded stickers to three positions of the lateral aspect of the knee, the tubercle of Gerdy, the fibular head, and the lateral epicondyle. Using a digital camera (Cyber-shot® W120 Digital, Sony, Tokyo, Japan), the movement of the stickers was captured during a PST. Their relative two-dimensional (X, Y) movements were calculated using computer software (NIH image J software, National Institute of Health, Bethesda, MD, USA), and a graph was plotted showing femoral AP position as a function of time. Preliminary validation of the technique was made in reference to an EMS device and the results showed a consistent lateral compartment translation. However, the magnitude observed was considerably smaller for the image analysis system when compared with the EMS system. A single surgeon examined five ACL-injured knees under anesthesia. Anterior translation of the lateral compartment was on average 3.7 ± 2.1 mm. No comparison to the healthy contralateral knee was made [34]. The image analysis system was further developed by Hoshino et al. who recently presented the use of an iPad (Apple Inc, Cupertino, CA, USA) application system to detect and analyze the translation of the lateral compartment (Fig. 1b) [66•]. Thirty-four patients who had sustained ACL injury were recruited. Examinations were performed under general anesthesia and the PST was executed in a recently described standardized manner to minimize intra- and inter-examiner variability [16]. Both injured and contralateral healthy knees were examined and the detected translation of the lateral compartment was related to clinical grading according to the IKDC criteria. Clinical grading was determined before review of calculated translation values to avoid bias. As described above, three stickers (Color Coding Labels, Avery Dennison Corporation, Pasadena, CA, USA) were applied to abovementioned anatomic landmarks. Representable data was acquired for 20 patients (59 %); the remaining 14 patients were excluded due to either zero or excessive translation (more than 10 mm). The exclusion was made due to the difference between acquired translation values and visibly detected translation. For the 20 included patients, significant differences were found comparing ACL-deficient knees to contralateral healthy knees. Moreover, there was a significant difference in mean translation between knees graded as 1 when compared to knees graded as 2. However, the side-to-side difference between patients graded as 1 or 2 was not significant [66•].

Taken together, the image analysis system developed by Hoshino et al. is promising with multiple fields of application could it be established as accurate and reliable. Apparent advantages being its simplicity, non-invasive methodology, and low cost. However, in the present moment, the low sensitivity of 59 % is an issue. The authors explain the large amount of outlying values as caused by three separate reasons: marker movement outside the tracking field, faulty camera angle in relation to the lateral aspect of the knee joint, and performance of the PST that is too fast for the frame rate of the camera. As for previously described non-invasive methods, the image analysis system is at risk of inherent skin artifacts in comparison to underlying bones. Consequently, if the above-stated issues could be solved, the image analysis system has the possibility of being a versatile tool in dynamic knee laxity measurement.

Discussion

The purpose of this study was to review methods of evaluating dynamic knee laxity through the PST. Important findings comprise new focus on the learning curve when using quantifiable instruments, utilization of different PST maneuvers, and the promising capabilities of the novel, non-invasive inertial sensors.

A major issue related to assessment of the PST is the diversity in the execution of the maneuver [12–15]. The manual loading used to elicit the PST will never be exactly identical; both the implemented force and velocity will differ and cause inconsistencies. In order to address this problem, execution of mechanical pivot shift test (MPST) has been developed and results show great repeatability [17, 18]. However, indications that MPST produces less ATT when compared to manual loading might lower the sensitivity [18]. Furthermore, to our knowledge, the current technology has not yet been utilized in vivo. Mechanical pivot shifters will probably be important and reliable tools in assessment of rotational laxity in the future; nevertheless, the cost of the system will probably limit the use to scientific studies for the near future. Consequently, execution of manual PST will henceforth continue to be the cornerstone. On that subject, Kitamura et al. compared three different maneuvers using an EMS. The authors found that the N-test rendered more APT while the PST produced more c-ATT [14]. Nakamura et al showed that both the N-test and the PST produced significantly more acceleration using an accelerometer when under anesthesia [67]. Consequently, there are various feasible tests; however, there might be slight advantages and disadvantages to separate tests. Further studies to determine a “gold standard” maneuver are warranted. In the meantime, we recommend the use of a previously presented standardized maneuver in order to minimize inter-examiner variation and to facilitate comparisons between studies [16]. When the standardized technique was compared with the personally preferred technique of 12 expert surgeons, a decrease in variation of tibial acceleration could be observed [17, 18].

Assessment of the PST using technological equipment has been presented above (Table 2). The utilization of dynamic knee laxity devices is apparent though it is important to comprehend that all devices have strengths and weaknesses. Surgical navigation is reliable and precise (Table 1). Porter et al. recently developed and validated a non-invasive method; however, intra-operative utilization of navigation is still the standard approach [64•]. Navigation was used by Lopomo et al. to investigate whether post-operative rotary knee laxity values could be predicted by pre-operative values [65]. Results showed that there was a connection between pre- and post-operative magnitude of ATT. This information can be used to construct treatment algorithms where larger magnitude of pre-operative rotary knee laxity could warrant combinations of surgical interventions or DB instead of SB ACL reconstruction. Post-reconstruction intra-operative residual dynamic knee laxity can be handled in the same manner [37, 51]. Treatment algorithms for dynamic knee laxity using navigation will likely be more widely utilized in the future. However, one problem is that in order to plan the procedure in advance, an examination under anesthesia has to be performed before reconstruction, with increased costs and risks associated with anesthesia. The development of a novel non-invasive navigation system is exciting; nevertheless, further assessment and validation is necessary [64•].

Table 2 Clinical capabilities of assessed measurement devices during pivot shift test

Author	Device	Injured knee pre-op vs post-op	Injured vs contralateral knee	Parameters correlated to clinical grading
Hoshino et al [28]	EMS	–	c-ATT^{AN} and APT^{AN}: Injured > contralateral ($p < .01$)	c-ATT^{AN} ($p = 0.03$), APT^{AN} ($p < 0.01$)
Araki et al [39]	EMS	–	APT^{AN}: Injured > contralateral ($p < 0.05$)	–
Matsushita et al [40•]	EMS	–	APT$^{AN/AW}$: Injured > contralateral ($p < 0.0001$)	–
Kitamura et al [14]	EMS		pCAT^{AN} and APT^{AN}: Injured > contralateral for PST, N-test and Jerk test ($p < 0.0001$).	–
Nagai et al [43]	EMS	APT^{AN}: Post-op reduction ($p < 0.01$)	APT^{AN}: Injured > contralateral ($p < 0.01$)	Pre-op APT^{AN} ($p \leq 0.01$)
Lopomo et al [44•]	Accelerometer	–	Difference in all parameters^{AN} ($p < 0.0001$)	–
Lopomo et al [30]	Accelerometer	–	–	–
Berruto et al [46•]	Accelerometer	Difference in all parameters ($p < 0.001$)	Difference in all parameters ($p < 0.001$)	$a_{\max}$ reference values for PS-grades 0, 1. and 2.
Nakamura et al [67]	Accelerometer	–	${a_{\text{range}}}^{AN}$ for PST and N-test: Injured > contralateral knees ($p < 0.001$). ${a_{\text{range}}}^{AW}$: n.s.	${a_{\text{range}}}^{AN}$: PST ($r = 0.57$), N-test ($r = 0.69$). ${a_{\text{range}}}^{AW:}$ PST ($r = 0.41$), N-test ($r = 0.31$)
Kopf et al [47]	Inertial sensor	–	All parameters^{AN}: Injured > contralateral ($p < 0.05$).	All parameters^{AN}: N.s.
Borgstrom et al [32]	Gyroscope		TR^{AN}: Injured > contralateral (50 % of patients) RV^{AN}: Injured > contralateral (70 % of patients)	TR^{AN} ($r^2 = 0.0887$), RV^{AN} ($r^2 = 0.1926$)
Borgstrom et al [33•]	Gyroscope and accelerometer	–	MTA^{AN}: Injured > contralateral ($p < 0.0001$). Using system fusion methods 94 % of injured knees were correctly diagnosed.	Using SVM 77 % of patients had a correct PS grade and 98 % ±1 PS grade
Labbe et al [49•]	MEMS	–	–	Femoral acceleration drop^{AW} ($r = 0.84$, $p < 0.0001$), tibial acceleration drop^{AW} ($r = 0.69$, $p < 0.0001$)
Imbert et al [63]	Navigation	–	APL^{AN} and ARR^{AN}: Injured > contralateral ($p < 0.001$)	–
Porter et al [64•]	Navigation	ATT^{AN} and IR^{AN}: Post-op reduction ($p < 0.001$)	–	–
Hoshino et al [66•]	Image analysis system	–	FAPT^{AN}: Injured > contralateral ($p < 0.01$)	FAPT^{AN}: PS grade 2 > PS grade 1 ($p < 0.05$)

Acc acceleration, a_{max} maximum tibial acceleration, a_{range} magnitude of subluxation (a_{range}: $a_{\max}$–$a_{\min}$), *AN* anesthesia, *APL* anteroposterior laxity, *ARR* axial rotation range, *ATT* anterior tibial translation, *AW* awake, *EMS* electromagnetic system, *FAPT* femoral anteroposterior translation, *IR* internal rotation, *MEMS* micro-electromechanical system sensor, *MTA* Mean tibial acceleration, *N.s* not significant, *pCAT* Peak coupled anterior tibial translation, *PS-grade* pivot shift grade, *RV* rotational velocity, *SVM* support vector machine classifiers, *TR* tibial rotation, *TT* tibial translation

Electromagnetic systems are available in the office setting and, as stated above, have acceptable reliability and accuracy (Table 1) [6, 28, 38•, 40]. Araki et al. presented good sensitivity and specificity for establishment of intact knees when compared to partial or complete tears, data that could help the clinician in diagnosis of ACL injury [39]. Nagai et al. found a correlation between the EMS and clinical grading of the PST, an important step toward objective quantification of dynamic knee laxity (Table 2) [43]. However, the issues with EMS remain disturbed from ferromagnetic objects and impracticality using a non-wireless system. Electromagnetic systems will continue to have an important role in ACL research; however, the future of non-invasive clinically practicable dynamic knee laxity measurement might lay elsewhere.

Inertial sensors have seen major development during the last couple of years. Using the KiRA accelerometer, Lopomo et al. showed good reliability and could present a positive correlation with invasive measurement of a navigation system (Table 1) [30]. Zaffagnini et al. have recently recommended the use of the KiRA system in the clinical practice [31]. Berruto et al. elucidated the existence of a learning curve when using objective quantitative measurement tools in general and the KiRA accelerometer in particular [46•]. Contradictory data regarding clinical grading by inertial sensors have been published during the study period (Table 2) [33•, 47, 49•]. Kopf et al. found no correlation [47] and Labbe et al. was partly successful but could not distinguish between grades 0 and 1 or between 2 and 3. Borgstrom et al. used a combination of accelerometer and gyroscope that could accurately diagnose the clinical grade in 77 % of the knees. Further, they were able to present an impressive 97 % accuracy in diagnosis of ACL injury [33•].

The image analysis system presented by Hoshino et al. represents a novel step toward non-invasive evaluation of dynamic knee laxity [34, 66•]. As stated above, the low cost and usability is promising and the capability of determination of ACL insufficiency is essential. However, it remains to be seen how the system performs in awake patients where it will be utilized for the most part.

Future directions

There is a need for a standardized or mechanized PST in order to minimize inter-examiner variability and optimize quantification of dynamic knee laxity using technological devices. Moreover, it is important to elucidate the need for understanding of the learning curve using quantification methods, a question that needs to be addressed in future studies. In addition, it is unclear how sensitivity and specificity alters for different devices depending on the state of consciousness; further research is needed in this area. Finally, future studies should include determination of reliability and validity. Comparisons of kinematic data to clinical grading and subjective outcome are also of importance to continue the progress toward accurate and objective measurement of dynamic knee laxity.

Conclusion

In conclusion, important advances to assess dynamic knee laxity by use of the PST have been made during the last years. Methods presented in this study have different profiles and slightly different fields of application. Currently, the majority of dynamic knee laxity devices are used for research purposes; however, techniques have already been implemented in the clinical practice.

Compliance with ethical standards

Conflict of interest David Sundemo, Eduard Alentorn-Geli, Yuichi Hoshino, Jón Karlsson, and Kristian Samuelsson declare that they have no conflict of interest.

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