Quantitative measures of pivot shift on knee rotatory instability

Dhong Won Lee, Ji Hwan Lee, Du Han Kim, Jung Ho Park, Jin Goo Kim

Department of Orthopedic Surgery, Konkuk University Medical Center, Seoul, Korea

One of the key prerequisites to returning to sports activities after knee injury is restored rotatory instability. The pivot shift test is the standard way to evaluate rotatory instability. However, manual testing methods reliant on the subjective judgment of examiners may fail to discriminate the dynamic stages of rotatory instability, especially because the pivot shift phenomenon occurs as a result of combination of translation and rotation movements of the tibiofemoral joint. To this end, several studies have investigated novel ways to quantitatively measure kinematics of the pivot shift test by developing new measurement devices. Measurement devices, such as navigation, electromagnetic, and inertial sensors, and image analysis systems have been developed. Low-cost, non-invasive, and self-contained devices are gaining popularity for their ease of use. Here, we review the advantages and disadvantages of current measurement systems of pivot shift tests and summarize the relevant scientific knowledge of this field for future research.

Keywords: Anterior cruciate ligament; Anterolateral ligament; Knee kinematics; Rotatory instability; Pivot shift test

INTRODUCTION

Methods commonly used to measure instability of the knee after anterior cruciate ligament (ACL) reconstruction include the Lachman test and the anterior drawer test for anterior instability and the pivot shift test for rotatory instability [1–3]. The sensitivity and specificity have been reported to be 81.8% and 96.8%, respectively, for the Lachman test; 40.9% and 95.2%, respectively, for the anterior drawer test; and 81.8% and 98.4%, respectively, for the pivot shift test [4]. Makhmalbaf et al. [3] however reported a much higher sensitivity for the Lachman test and the anterior drawer test, reporting their sensitivity to be 93.5% and 94.4%, respectively. They also found that the accuracy of the tests can be improved when the measurements are taken under general anesthesia. More objective means of measuring anterior drawer has been developed such as arthrometers. Many arthrometers including the KT-1000 Knee Ligament Arthrometer (Med-Metrics, San Diego, CA, USA), the Genucom Knee Analysis System (FARO Technologies, Lake Mary, FL, USA), and the Rolimeter (Aircast Europe, Neubeuern, Germany) are currently in use. However, limitations of these systems are that they measure anterior instability only in the sagittal view and cannot measure rotatory instability, which has recently been shown to be an important parameter for assessing the knee. Therefore, there is a need to develop new measurement methods that accurately reflect knee function and symptoms [5–7].

Rotatory instability is one of the important determinants of whether a patient can return to sports after an ACL injury. The standard test to measure rotator instability has been the pivot shift test [8–11]. Kocher et al. [7] reported that while the findings of the Lachman test did not correlate with subjective clinical findings those of the pivot shift test did with not only the clinical findings but also the results from functional knee tests, and the actual return of the patients to sports activities postoperatively. Recently, ACL tears have been shown to occur in combination with anterolateral ligament injuries secondary...
to anterior drawer and internal rotation of the knee. In line with this, biomechanical and clinical studies have shown that anterolateral ligament repairs must be appropriately performed especially when the pivot shift test demonstrates a high level of rotatory instability, further highlighting the importance of pivot shift tests [12–14]. However, because the pivot shift phenomenon occurs as a combination of translational and rotational movements of the tibial femoral joint and it is measured on the basis of the subjective judgment of the examiner, the pivot shift tests may not enable differentiation of the dynamic stages of rotatory instability [9,10,15,16]. In addition, because the third clinical grade of pivot shift encompasses a wide range of symptoms from clunking to severe locking, there is a need to expand the grading system to include more clinically relevant sub-classifications and to develop more quantitative approaches to measuring pivot shift.

To this end, numerous studies have investigated ways to quantitatively measure pivot shift and to improve the accuracy of these quantitative pivot shift tests. Novel devices of pivot shift tests have been developed such as navigation systems [17–20], electromagnetic sensors [21,22], inertial sensors [23–25], and image analysis systems [26–28]. But the choice of method of using these devices has largely depended on the preference and the discretion of examiners, and none of these measurement devices have been proven to be accurate or valid enough to be used in the clinic as standard tools. Therefore, there is a need to develop an easy-to-use, accurate, and noninvasive measurement device for improved diagnosis and assessment of treatment outcomes after ACL reconstruction.

The purpose of this review was to analyze the current devices used in pivot shift tests, summarize their advantages and disadvantages, and discuss possible recommendations for future directions of studies on measurement methods of rotatory instability of the knee.

TYPES OF QUANTITATIVE PIVOT SHIFT TESTS

Navigation systems
Navigation systems measure rotatory instability through a computer-assisted system (Fig. 1). Specifically, the anterior drawer and the tibial angle of the pivot shift are measured preoperatively with the patients under general anesthesia. Initially, the computer-assisted navigation device was developed as a complementary device to anatomically place femoral tunnels at the isometric point during ACL reconstruction [29,30]. But because their accuracy and reliability were proved through their application in femoral tunnel placement, the uses of navigation systems expanded to include also the measurement of knee instability and kinematics [10,19,20,31]. For the measurement, a transmitter and a reflective marker are rigidly pinned onto the tibia and femur, and then the pivot shift test is conducted after the standard bony landmarks (the tibial tuberosity, the tibial anterior border, and the mediolateral tibial plateau) and the kinematics at 0°–90° of motion are registered onto the system. The camera detects, tracks the three-dimensional (3D) positions of the devices, and transmits this information to the computer software with < 1° and < 1 mm of accuracy [32,33].

Lane et al. [34] used a navigation system (LaTronche; Praxim Medivision, Grenoble, France) to describe the abnormal movement that occurs during a pivot shift test—anterior translation at the sagittal view and the sudden posterior reduction of the internally rotated tibia—as the “P-angle.” They reported that a significant correlation between the P-angle and the clinical grades of the pivot shift were observed ($R^2 = 0.97, P < 0.001$). Using the same navigation system (LaTronche), Bedi et al. [35] measured postoperative pivot shift in patients who received either single-bundle or double-bundle anatomical ACL reconstruction. They found that the lateral tibial anterior drawer was significantly greater in the former group than the latter, suggesting that double-bundle ACL reconstruc-
tion provides superior biomechanics of the knee. Monaco et al. [20] demonstrated using a navigation system (ver. 2.2 OrthoPilot ACL; B. Braun-Aesculap, Tuttingen, Germany) that performing lateral extra-articular tenodesis during ACL reconstruction decreases the pivot shift phenomenon more than when it is not performed. Imbert et al. [36] reported that lateral extra-articular augmentation during ACL reconstruction did not lead to restored rotatory stability, measured using navigation sensors, of the knee but to increased compression at the lateral compartment of the knee.

As such, computer-assisted devices are useful for the quantitative measurement of dynamic rotatory instability of the knee. However, they require invasive tibial and femoral procedures to be additionally performed and the surgery time to be extended. Moreover, unlike some devices that use navigation devices on the contralateral side raises ethical issues and they are more costly than other measurement methods. Because of the invasiveness of conventional navigation systems, such as the tibial and femoral pin fixation, novel and non-invasive methods of attaching skin markers at bony landmarks have been developed. For instance, Maeda et al. [31] found that the post-reconstruction pivot shift, calculated as the acceleration of the posterior tibial reduction, was similar between the invasive and the non-invasive navigation systems (ver. 3.0 OrthoPilot ACL; B. Braun-Aesculap) and, therefore, demonstrated the validity of the non-invasive method. Specifically, transmitter-attached skin markers were used as the non-invasive devices for assessment.

Electromagnetic sensors

To quantitatively measure the pivot shift with electromagnetic sensor systems, three devices are prepared: 1) a transmitter that generates an electromagnetic spectrum and has a sample rate of either 60 or 240 Hz; 2) an electromagnetic transmitter that is attached to the thigh and calf; 3) and a receiver that is attached to a customized stylus (for digitization) (Fig. 2). Then seven bony markers (greater trochanter of the femur, the medial and lateral epicondyles of the femur, the medial and lateral joint line of the tibia, the fibular head, medial and lateral malleoli of the ankle) are registered onto the system. The bony markers allow spontaneous and real-time measurement of 3D tibial translation and 3D acceleration, enabling the 3D assessment of all six directions of knee exercise [8].

Kuroda et al. [8] used either a non-invasive electromagnetic sensor FASTRAK (Polhemus, Colchester, VT, USA) or LIBERTY (Polhemus) that has an accuracy in terms of root mean square of 0.03 mm and 0.15° to quantify anterior translation of the tibia and posterior acceleration. They suggested that a static parameter in the assessment of rotatory instability is coupled anterior tibial translation, a relative anterior translation of the tibia that occurs during the pivot shift test, which was calculated using hysteresis motion. They found that a dynamic parameter in the assessment of rotatory instability is acceleration of the posterior tibial reduction, which reproduces the dynamics of the pivot shift phenomenon and accurately reflects the subjective measure of instability in patients. The acceleration of the posterior translation is an auxiliary value derived from the anteroposterior position; it can be used to calculate measurements such as maximum acceleration and patterns of movement during posterior tibial reduction. They reported that knees with and without ruptured ACL have an acceleration of 2 to 3 m/s² and 1 m/s², respectively. Using FASTRAK, Araki et al. [37] conducted a quantitative pivot shift test and found that the mean posterior tibial acceleration was −632.7 ± 254.5 mm/s² in normal knees, −1,075.5 ± 398.9 mm/s² in knees with partial ACL tears, and −1,652.2 ± 754.9 mm/s² in knees with complete ACL tears. They found that the values of acceleration in the three groups were significantly different from one another (P < 0.05) and demonstrated that the cut-off value for discriminating a normal knee from that with a partial ACL tear is between −848.8 mm/s² and −1,245.3 mm/s². The suggested that quantita-
Pivot shift tests may be an alternative to conventional methods, which manually discriminate clinical manifestations such as gliding and clunking, to distinguish partial and complete tears. Using LIBERTY, Nagai et al. [38] quantified posterior tibial acceleration in 70 patients who received ACL reconstruction. They found that the preoperative incremental increases in tibial acceleration were closely associated with the pivot shift grades corresponding to a clinically severe condition (P < 0.01). They also found that the tibial acceleration was significantly higher in the affected side (1.9 ± 1.2 m/s²) than the non-affected contralateral side (0.8 ± 0.3 m/s²) (P < 0.01), and that tibial acceleration significantly decreased with ACL reconstruction (0.9 ± 0.3 m/s², P < 0.01). In another study [39] FASTRAK was used to compare the outcomes of single-bundle versus double-bundle anatomical reconstruction. At the 1-year follow-up, they found that patients treated with single-bundle reconstruction had a significantly improved posterior tibial acceleration compared to the contralateral side than those treated with double-bundle reconstruction, allowing the authors to conclude that single-bundle reconstruction was more superior to double-bundle reconstruction.

In sum, although electromagnetic sensor systems enable us to quantitatively measure abnormal tibial acceleration, which contributes towards the pivot shift phenomenon, with a high degree of accuracy and reliability and are completely self-contained, it is interfered by ferromagnetic objects that disturb electromagnetic induction and does not provide spontaneous output of position and velocity through a wireless transmission as of yet.

**Inertial sensors**

Inertial sensors contain a tri-axial accelerometer, which measures linear acceleration, and an gyroscope, which measures angular velocity (Fig. 3). During the pivot shift test, the inertial sensor is securely attached in alignment with the mechanical axis, which is between the lateral aspect of the tibial tuberosity and the Gerdy’s tubercle. The data from the inertial sensor are wirelessly transmitted to a laptop or computer and is used to calculate tibial acceleration. Because previous cadaveric and clinical studies have shown that acceleration (m/s²) and extent of translation (mm) of the tibial lateral compartment are the most prominent phenomena during the pivot shift, these parameters have been given greater importance in quantitative pivot shift tests [35,40].

Ahldén et al. [41] performed pivot shift tests by attaching an inertial sensor (BluIGS; Orthokey LLC, Lewes, DE, USA) onto cadavers. Using this approach, they achieved maximum acceleration that was significantly correlated with grades of pivot shift tests (r = 0.61, P < 0.05) and the calculations derived from electromagnetic sensors (r = 0.67, P < 0.05). Lopomo et al. [24] conducted pivot shift tests with an inertial sensor (KiRA) and a navigation system (BluIGS) on 15 patients with ACL injuries before ACL reconstruction. They found that 3D acceleration measured through the inertial sensor and the anteroposterior acceleration measured through the navigation system showed a high correlation (r = 0.72, P < 0.05). And given the high interobserver reliability (0.86) of measurements of the inertial sensor system also demonstrates the high validity of the inertial sensor system.

Using inertial sensors, Berruto et al. [42] measured maximum and minimum acceleration compared to the contralateral side and calculated the difference in 100 patients before ACL reconstruction. They found that all three measurements were significantly higher in the affected side than the unaffected side. The threshold level of each parameter was defined in terms of the clinical grades of pivot shift (“negative,” “gliding,” or “clunk”). Labbé et al. [25] used an inertial sensor unit that incorporates a microelectromechanical system (MEMS) sensor (nIMU™; Memsense, Rapid City, SD, USA) and consists of an accelerometer, a gyroscope, and a magnetometer. They conducted a pivot shift test based on the MEMS sensor system on 13 patients with ACL tears and found...
that femoral acceleration and tibial acceleration were strongly correlated with the clinical grades of pivot shift \((r = 0.84\) and \(0.69; \ P < 0.0001\) and \(P < 0.001\), respectively). However, the correlation was only significant between grades 1 and 2.

Because excessive internal rotation of the tibia has been shown to play an essential part in the pivot shift phenomenon in patients with ACL tears, inertial sensors that can measure tibial rotation and rotational speed were also developed. Unlike MEMSense\textsuperscript{TM}, which calculates tibial rotation from rotational speed, ITG-3200 (Invensence, Sunnyvale, CA, USA) calculates tibial rotation at a single axis (the ITG-3200 sensor is rigidly taped to the patient’s ankle for the pivot shift test). Of note, it is important to fix the device in a way that the foot and the tibia are seen as a single mechanical body; this would prevent rotation of the ankle acting as a confounding factor. Using ITG-3200 sensors, Petrigliano et al. \([43]\) found that the angles of external tibial rotation strongly correlated with those derived from potentiometers \(R^2 = 0.984\) in cadavers, which demonstrated the validity of ITG-3200 inertial sensors. However, when Borgstrom et al. \([44]\) (using the same quantitative method) measured tibial rotation and rotational speed, they found that the values only weakly correlated with the clinical pivot shift test grades \(R^2 = 0.09\) and \(0.19\), respectively. On the basis of their findings, the authors emphasized that the pivot shift tests should be used in combination with accelerometer findings when assessing rotatory instability.

Inertial sensors are more compact than preexisting navigational systems and electromagnetic sensors and can wirelessly transmit data. They can be used on the contralateral arm for comparison and be easily carried out in the outpatient’s clinic. However, measurements taken under no anesthesia are still inaccurate and the measurements may be inaccurate even when they are taken under general anesthesia because inertial sensors fail to capture actual bone movement [45].

**Image analysis systems**

Studies have used image analysis systems to quantify the pivot shift by analyzing the extent of lateral tibial compartment displacement, with the assumption it is a crucial parameter in the quantification of the pivot shift in image analysis systems, as with the navigation and image sensor systems [26,35,40] (Fig. 4A). To calculate the position of the distal femur, Hoshino et al. [26] attached skin markers on the lateral epicondyle, the Gerdy’s tubercle, and the fibular head and then defined two lines: 1) the “pivot point” as the intersection between the line connecting the Gerdy’s tubercle and the fibular head (line a) and the perpendicular line from the lateral epicondyle and 2) the line joining the Gerdy’s tubercle and the pivot point (line b) (Fig. 4B). They used a digital camera (Cyber-shot W120 Digital; Sony, Tokyo, Japan) to visualize the markers attached on the lateral tibia and monitored two-dimensional (2D) movements (X and Y axes) on the NIH image J software (National Institute of Health, Bethesda, MD, USA). Using the anteroposterior positions of the femur relative to the Gerdy’s tubercle, they derived the sudden shift of the lateral compartment of the tibia at the reduction phase of the pivot shift test in patients with ACL tears to be approximately \(3.7 \pm 2.1\) mm. Their quantitative measurement of the pivot shift test was optimized through the development of specialized skin markers (Color Coding Labels; Avery Dennison, Pasadena, CA, USA) and an application for iPad (Apple, Cupertino, CA, USA) that tracks movement of these markers [28]. Using

![Fig. 4. (A) Schematic diagram of the image analysis system. (B) Skin markers were attached to the lateral epicondyle, Gerdy’s tubercle, and the fibular head. Then a line connecting the Gerdy’s tubercle and the fibular head (line a) was drawn in perpendicular to the lateral femoral condyle. The resulting intersection was defined as the “pivot point,” and the line connecting the Gerdy’s tubercle and the pivot point (line b) was marked. The anteroposterior positions of the femoral bone relative to the Gerdy’s tubercle were calculated using lines a and b.](image-url)
their optimized method, they found that they able to obtain useful knee kinematics data from 59% of 34 patients with ACL tears; specifically, their method revealed significantly differences between the affected and the unaffected contralateral side and significantly discriminate between grades 1 and 2 of the pivot shift test.

Following previously described methods [26,28], Arilla et al. [27] used 2D-image analysis and 3D-electromagnetic sensor systems (Nest of Birds; Ascension Technology, Burlington, VT, USA) to measure rotatory instability in seven knees and reported that these two quantitative methods of assessing axial movement were highly correlated with each other, showing a Pearson's correlation coefficient of > 0.7. They emphasized that the former method was non-invasive and easy to use. In a different study, Musahl et al. [46] used two image sensor systems—KiRA and the image analysis system (iPad application and NIH image J software) for several reasons. First, they argued that the anterior drawer is more common in the lateral compartment than the medial compartment of the tibia because tibial internal rotation induces the pivot shift phenomenon. Second, they also suggested that the posterior acceleration of the tibia, as well as the anterior drawer of the tibia lateral compartment, plays a key role in the pivot shift phenomenon. Their axial movement tests on 103 patients under general anesthesia before ACL reconstruction revealed that tibial posterior acceleration from inertial sensors and lateral tibial translation from image analysis systems were both able to significantly differentiate between grades 1 and 2 of the axial movement test (P < 0.01).

Like inertial sensors, image analysis systems are relatively cost-effective and non-invasive. They also have other advantages such as ease of use and outside the operating room and on both knees. However, drawbacks include that image analysis systems cannot measure the actual movement of bone, possibly leading to errors in measurement, and that the sensitivity of this measurement method can be compromised when the marker escapes the measurement field, the camera is misplaced, or the axial movement test is conducted more quickly than the frame rate of the camera.

CONCLUSION

Parameters contributing to the pivot shift phenomenon in patients with ACL tears include tibial internal rotation, anterior drawer of the lateral tibia, sudden acceleration of the posterior tibia, etc. Traditional pivot shift tests that require examiners to subjectively grade 3D movements of the tibia have limitations. The more recent, low-cost, and non-invasive inertial sensors and image analysis systems are gaining popularity because they can be used in the outpatient clinics easily. Yet future work is needed to improve their reliability and validity to a level comparable to those of high-cost systems such as navigation systems and electromagnetic sensors, which are able to detect real 3D movement, to standardize the force applied during the pivot shift test, and to develop new mechanical applications of the devices.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

REFERENCES


