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Assessment of the pivot shift using inertial sensors

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Abstract The pivot shift test is an important clinical tool used to assess the stability of the knee following an injury to the anterior cruciate ligament (ACL). Previous studies have shown that significant variability exists in the performance and interpretation of this manoeuvre. Accordingly, a variety of techniques aimed at standardizing and quantifying the pivot shift test have been developed. In recent years, inertial sensors have been used to measure the kinematics of the pivot shift. The goal of this study is to present a review of the literature and discuss the principles of inertial sensors and their use in quantifying the pivot shift test.

Keywords Pivot shift · ACL · Acceleration · Quantification · Clinical grade

Introduction

Rupture of the anterior cruciate ligament (ACL) is one of the most common injuries encountered in sports medicine. A thorough physical examination is important in order to confirm the diagnosis and determine the appropriate management. The pivot shift is one of the many tests used to assess the degree of instability of the knee. Unlike unidirectional tests like the Lachman and anterior drawer, the pivot shift is able to evaluate rotational stability by applying multi-directional loads through a range of knee motions [1, 2]. In fact, the pivot shift has been shown to be the most specific test for ACL injury [3]. Studies reveal that it correlates best with clinical symptoms [4, 5], subjective instability [6], reduced sport activity [7], and articular and meniscal damage [8]. Despite its popularity, there is a significant variability in the performance and interpretation of the pivot shift manoeuvre [9•]. Consequently, a means to standardize and quantify the test is needed.

In recent years, a number of innovative devices aimed at measuring the kinematics of the pivot shift manoeuvre have been developed [9•]. The majority of these systems rely on advanced technology such as open magnetic resonance imaging [10], special markers [11], robots [12], complex software [13•], and electromagnetic sensors [14–17]. Unfortunately, these techniques are too complex and expensive for application in daily clinical practice. Accordingly, inertial sensors are gaining popularity as a more practical and economical alternative to the more advanced systems. The purpose of this review is to introduce and discuss the use of inertial sensors in quantifying the pivot shift test.

Inertial sensor for pivot shift quantification

Inertial sensors are specialized instruments which typically consist of an accelerometer to measure linear acceleration (inertia to linear motion) and a gyroscope to measure angular velocity (inertial angular motion). They contain an internal mass which is attached to a spring. When the sensor is accelerated by an external force, it begins to move along the direction of force while the internal mass remains in its resting state due to inertia. This results in a lengthening of the spring which

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is directly proportional to the acceleration. Velocity can then be directly calculated by taking the integral of acceleration.

In 2012, Lopomo et al. [18] used inertial sensors during the performance of the pivot shift test on 66 consecutive ACL-injured patients (Fig. 1). A set of specific parameters in the inertial sensor signal were identified and used to quantify the test. The manoeuvre was repeated three times on injured and uninjured limbs and shown to have good intra-rater reliability (mean intra-rater intra-class correlation coefficient was 0.79). Moreover, the ACL-deficient knees were shown to have statistically higher values for the identified parameters than the uninjured knees [18].

Subsequently, the same authors compared their technique using inertial sensors to a commercially available navigation system [19•]. Knee joint kinematics during the pivot shift test was measured simultaneously by an accelerometer fixed to the skin and a navigation system. An optical tracker was connected to the accelerometer to follow the sensor movements using the navigation system camera. In particular, the a-p acceleration measured by the navigation system was compared with the absolute 3D acceleration range as measured by the accelerometer. Moreover, the displacement between the tibia and the tracked accelerometer was also analysed to identify the effect of skin mobility and test-retest positioning. Correlation between the two measurements and repeatability of the acceleration parameters and signal waveforms were calculated. The authors observed good intra-rater reliability in the acceleration range (Cronbach's alpha = 0.86) and mean acceleration waveform (correlation of 0.88 ± 0.14). Furthermore, a positive correlation between the acceleration range of the two techniques was identified ($rs = 0.72$, $p < 0.05$) [19•]. Based on these results, Zaffagnini et al. [20] proposed the use of the KiRA (Orthokey LLC, Lewes, DE, USA) device to quantify the pivot shift test. This instrument employs the acceleration signal acquired using inertial sensors to determine the presence and severity of ACL injury. The authors discuss its use in the clinical setting to provide a standardized pivot shift assessment, enable objective comparison following ACL reconstruction surgery, and serve as a teaching tool in instructing the pivot shift manoeuvre.

Fig. 1 KiRA (Orthokey LLC, Lewes, DE, USA) device for quantitative pivot-shift analysis

In a related study, Berruto et al. [21] used the KiRA device to assess the pivot shift of 100 patients with a unilateral ACL injury. Thirty patients were also evaluated following ACL reconstruction surgery. In the cases evaluated preoperatively, the involved knees displayed significantly higher values of acceleration parameters compared with healthy knees. Postoperatively, the differences between pathological and healthy knee joint concerning these values were significantly inferior to the ones detected preoperatively but still significant. A correlation between the clinical and numerical data was identified, and mean reference values for each pivot shift grade (negative, glide, and clunk) were established. The authors also assessed the effect of operator experience on the reliability of the measurements obtained using the KiRA device. They showed no statistically significant difference between the values obtained by experienced and inexperienced examiners in both injured and uninjured knees.

Nakamura et al. [22] used the KiRA device to assess the pivot shift test in 29 ACL-injured patients under two different conditions: awake and under anaesthesia. All of the assessments were performed by a single surgeon, and the quantitative results were compared with the subjective clinical grades based on modified IKDC criteria. The authors found that the acceleration of ACL-injured knees was greater than that of the uninjured knees during the pivot shift test under anaesthesia (p value <0.001). Labbè et al. [23] used a different device, the MEMSense™ sensor (nIMU™, $5 \times 2 \times 1$ cm^3, Lewes, MEMSense™), to quantify the pivot shift in 13 ACL-injured patients. This instrument employs an embedded microelectromechanical system (MEMS) sensor that integrates a triaxial accelerometer, gyroscope, and magnetometer in order to calculate the acceleration and velocity of the tibiofemoral joint during the pivot shift manoeuvre. All tests were performed by a single experienced surgeon who also attributed a clinical grade to each patient based on the IKDC-2000 scale. The results showed that the femoral and tibial accelerations correlated well to the clinical grade based on the previously established criteria ($r = 0.84$, p value <0.0001 and $r = 0.69$, p value <0.001, respectively). Similarly, the femoral and tibial velocity—characterized by a spike-shaped variation in all subjects with a positive pivot shift—correlated well with the clinical grade ($r = 0.71$, p value <0.001 and $r = 0.70$, p value <0.001, respectively).

The ITG-3200 (ITG-3200, Invensense, CA) represents another device used to quantify the pivot shift test. This is a non-invasive, MEMS gyroscope that is capable of calculating the angle of rotation by integrating the direct measurement of rotational velocity. Unlike the MEMSense™, the ITG-3200 gyroscope is a single-axis device that can be placed directly on the lower extremity to measure (in a transverse plane) the external rotation of the tibia during a pivot shift manoeuvre. It functions by producing a voltage output that is directly proportional to rotational velocity. Petrigliano et al. [24] validated the use of the ITG-3200 gyroscope in quantifying axial rotation of the tibia during the pivot shift test in cadaveric specimens. A single examiner performed ten simulations of the pivot shift manoeuvre in nine cadaveric knees under intact and ACL-deficient conditions. The femur of each specimen was securely clamped, and the tibia was manipulated in the standard manoeuvre. The gyroscope was positioned on the tibia. A rotatory potentiometer was used as a reference, and a linear regression and relative correlation coefficient (R^2) were calculated. The measurements of maximum external tibial rotation during the simulated pivot shift manoeuvre were shown to be highly correlated between the ITG-3200 gyroscope and the potentiometer ($R^2 = 0.984$). The angle of rotation was higher in the ACL-deficient knees compared to the intact specimens; however, tibial rotation and rotational velocity were only partially predictive of the clinical grade of the pivot shift manoeuvre. These findings suggest that it is not possible to grade a pivot shift test based on tibial rotation and rotational velocity alone. This is supported by the results of Borgstrom et al. who used the same device (ITG-3200) to show that gyroscopic measurement of tibial rotation and rotational velocity correlates poorly with the clinical pivot shift grade ($R^2 = 0.09$ and 0.19, respectively) [25]. They proposed that the gyroscope data may need to be combined with accelerometer data in order to provide a more precise assessment of the pivot shift manoeuvre.

Conclusion

Several clinical tests exist to evaluate laxity of the knee joint following ACL injury. Of all those described, the pivot shift test has been shown to be the most specific in assessing dynamic stability. Unfortunately, given its relative complexity, there is a significant variability in the performance and interpretation of this manoeuvre. Navigation systems have been employed in an attempt to standardize the pivot shift test. They have been integral in increasing our understanding of knee kinematics, improving diagnostic capabilities, and stimulating the development of non-invasive devices for quantifying knee laxity in the clinical setting. Despite their efficacy, navigation systems are often invasive, complex, and expensive [26–29]. Moreover, they cannot be employed in the clinical setting and are typically reserved for intra-operative analysis.

In contrast, inertial sensors are a non-invasive, intuitive, and practical means of quantifying the pivot shift manoeuvre. Another important strength of these devices is the ability to use the uninjured limb as a reference. These devices provide an accurate assessment of the acceleration, velocity, and rotation of the tibia relative to the femur during the pivot shift. However, testing by multiple examiners as well as the development of a standardized test methodology is needed in order to further improve the inter-rater reliability.

In conclusion, there is a need for a simple, inexpensive, and reliable way to quantify the pivot shift test. Inertial sensors appear to fulfil all of these criteria in early studies. Further investigation is needed in order to optimize these devices and develop a universal instrument to assess knee laxity following ACL injury in the clinical setting.

Compliance with ethical standards

Conflict of interest Stefano Zaffagnini, Cecilia Signorelli, Alberto Grassi, Han Yue, Federico Raggi, Francisco Urrizola, Tommaso Bonanzinga, and Maurilio Marcacci declare that they have no conflict of interest.

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

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