

# Electromagnetic tracking of the pivot-shift

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**Abstract** The pivot-shift test is an important examination to assess the rotational laxity in the anterior cruciate ligament (ACL) injured and reconstructed knees. Because this examination is related to subjective knee function, we may still see cases that have residual rotational laxity after ACL reconstruction. Quantitative evaluation of the pivot-shift test is preferable to the clinical pivot-shift test but is difficult to attain mainly due to complicated movements of the pivot-shift. The electromagnetic tracking system was developed to evaluate knee kinematics during the pivot-shift, providing information related to 6-degree-of-freedom knee kinematics with a high sampling rate. Through this device, the abnormal movement of the pivot-shift is characterized in two phases: an increased anterior tibial translation and a boosted acceleration of tibial posterior reduction. Since its invention, this system has been utilized to assess rotational laxity for clinical follow-up and research after the ACL reconstruction.

**Keywords** Anterior cruciate ligament · Pivot-shift test · Rotational laxity · Electromagnetic tracking device · Knee kinematics

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## Introduction

The pivot-shift phenomenon has been identified as the primary anomaly in knee motion after the anterior cruciate ligament (ACL) injury, especially when the patient performs certain sudden movements such as cutting or quick turns [1, 2], and induces the feeling of knee instability which is described as “buckling” or “giving way” in his/her knee joint. This abnormal knee joint movement consists of two phases: anterior subluxation of the tibia and its spontaneous reduction in the lateral compartment of the knee joint [1]. This knee joint instability can be reproduced by a manually performed clinical examination, called the pivot-shift test, which is routinely used for diagnosing ACL insufficiency and for assessing knee stability after ACL reconstruction [2–4].

The pivot-shift test evaluates rotational laxity in the knee joint and is regarded as one of the most important clinical examinations related to ACL injury and treatment. This is due to the fact that the presence of a pivot-shift phenomenon after ACL reconstruction is associated with functional impairment and consequently poor patient satisfaction [5, 6]. In addition, according to the report from Jonsson et al. [7], patients with positive pivot-shift findings demonstrated increased scintigraphic activity in the subchondral bone of the knee joint [7]. Furthermore, negative pivot shift test demonstrated fewer signs of radiographic osteoarthritis [8]. Ayeni et al. demonstrated by a systematic review that the result of the pivot-shift test was correlated to the functional outcomes, such as the IKDC, Lysholm score, and tegner activity level, in most of clinical randomized control studies [3].

One of the most important limitations of current ACL treatment is that residual abnormal rotational laxity, or the pivot-shift, can still be found in the cases whose anterior laxity was fully restored after ACL reconstruction [9–11]. The anterior laxity of the knee is another pathological

finding after ACL injury and can be objectively evaluated by the instrumented measurement, such as KT-1000 [12]. Although the instrumented evaluation of anterior laxity is fairly reliable to diagnose the ACL insufficiency, the result is not necessarily related to subjective knee function [5]. Furthermore, the anterior laxity has been already resolved by the conventional ACL reconstruction [9–11]. In the meantime, the pivot-shift remains a clinical problem but has been often overlooked due to inability to provide a means for quantitative evaluation.

Meticulous clinical follow-up after ACL reconstruction and close comparison of different ACL treatments are necessary to achieve further improvement of ACL treatment, and demand critical evaluation of rotational laxity. While a clinical exam for the pivot shift exists, there are some shortcomings in the clinically performed pivot-shift test. The pivot-shift test provides a rough four-grade evaluation, such as none (–), glide (+), clunk (++), and gross (+++), according to the magnitude of the pivot-shift phenomenon, and the clinical grading is determined in a highly subjective way based on the examiner's feeling [13–16]. In order to achieve more objective evaluation of the pivot-shift test, various measurement systems have been developed, such as an electromagnetic tracking system, a navigation system, an image analysis, and an accelerometer [17–24].

The electromagnetic tracking system was the first instrumented measurement system for the pivot-shift test that was applied to actual patients in a non-invasive manner [17] and, since then, has long been used for clinical follow-up and biomechanical research related to ACL treatment [18, 25, 26, 27]. The aim of this review article is to introduce the original development and the latest improvement of the electromagnetic tracking system for the quantitative evaluation of the pivot-shift and to show new findings derived from quantitative pivot-shift evaluation.

### Electromagnetic tracking for knee kinematics measurement

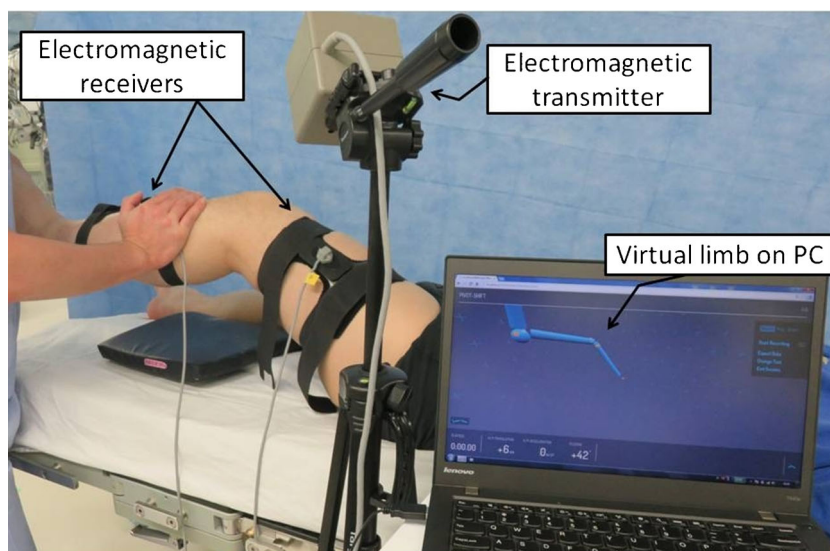
Initially, when experimental effort was made to characterize knee movement during the pivot-shift, full 6-degree-of-freedom (DOF) knee kinematics had to be evaluated to extract the abnormal knee kinematics during the pivot-shift test. Although the instrumented spatial linkage [28–30] or robotic system [31, 32] can accurately measure the 6 DOF of the knee joint, they are exclusively applicable in cadaveric studies. In vivo evaluation of the 6-DOF knee movements during the pivot-shift test was first performed by Bull et al. using the electromagnetic system [33]. They utilized the electromagnetic tracking system intra-operatively by planting sensors into the femur and the tibia with bone pins. Such a direct measurement of bony movement is fairly accurate, but the invasive

nature of the operation limits its clinical usability. Similarly, navigation systems demonstrated capacity to evaluate the in vivo 6 DOF of knee kinematics during the pivot-shift test [20], but its application was also restricted in the intra-operative evaluation.

Non-invasive usage of the electromagnetic tracking system was then attempted to broaden its application in our clinical practice [17, 18]. An electromagnetic tracking device with a high sampling rate, i.e., 60 or 240 Hz (FASTRAK or LIBERTY, respectively, Polhemus, Colchester, VT, USA), was utilized [17, 18, 25, 26, 27]. The root-mean-square (RMS) accuracy of this system is 0.03 mm for translation and 0.15° for rotation. The electromagnetic tracking system was composed of three electromagnetic receivers and a transmitter that produces an electromagnetic field. The electromagnetic receivers were attached onto the thigh and the shank by use of circumferential plastic braces instead of cortical fixation with bone pins, while the 6-DOF measurement of the knee kinematics was similarly executed as previously reported in the setting of intra-operative invasive application. Two electromagnetic receivers were firmly affixed 10 cm above the patella on the thigh and 7 cm below the tibial tubercle on the lower leg using plastic braces. The other third receiver with a pointer stylus was utilized to record three-dimensional (3D) positional data of the seven anatomic landmarks in relation to the two receivers on the skin. Three landmarks were registered to set the femoral coordinate system, the greater trochanter, and medial and lateral epicondyles, whereas four landmarks were used for the tibial coordinate system, the intersection of the medial collateral ligament (MCL) and the knee joint line, the fibular head, and the medial and lateral malleoli of the ankle. Digital reconstruction of these seven anatomical bony landmarks is then accomplished to form a 3D coordinate system of the knee joint. This 3D coordinate system of the knee joint is virtually built on the basis of 3D positional relationship between the femur and the tibia, each of which is reflected by the two electromagnetic receivers. The 6 DOF of knee kinematics is then calculated according to a modified three-cylinder open-chain mechanism proposed by Grood and Suntay [34] (Fig. 1).

The accuracy of this non-invasive application of the electromagnetic tracking system was assessed by comparing findings to those obtained by invasive methods in which the receivers were fixed on the bones with bone pins. The maximum differences between invasive and non-invasive results were 0.85 mm in anterior translation, 1.92° in rotation, and 0.62° in abduction [18]. Considering that the increase of the tibial translation and rotation due to ACL resection is more than 5 mm and 2° according to a report using the robotic system [32], the non-invasive application of the electromagnetic tracking system had an acceptable measurement accuracy to communicate the abnormal knee kinematics in ACL-deficient knees.

**Fig. 1** Pivot-shift test with a simultaneous quantitative measurement using the electromagnetic tracking system. The virtual limb of the patient is displayed on the PC screen



### Detection of abnormal knee kinematics during the pivot-shift phenomenon

The pivot-shift was originally described as anterior subluxation of the lateral tibial plateau and its spontaneous reduction [1]. This simple tibial subluxation–reduction movement in the lateral compartment of the knee becomes more complicated when it is interpreted by the 6 DOF of knee kinematics. The subluxation movement is a combination of anterior tibial translation and internal rotation, whereas the reduction is comprised of posterior tibial translation and external rotation [35].

Bull et al. [36] focused on the measurement of axial rotation to detect the abnormal knee kinematics due to ACL insufficiency in their cadaveric study using the electromagnetic tracking system, but consistent tendency of axial tibial rotation could not be identified during the pivot-shift. Instead, a wide variability of tibial axial rotation between specimens was recognized [36]. Their subsequent study of *in vivo* knee kinematic measurement during the pivot-shift revealed that the abnormal anteroposterior tibial translation was consistently detected, while a large variability was again demonstrated in tibial axial rotation [33].

Kanamori et al. [32] reported using a robotic system that tibial anterior translation occurs when the combined rotational stress of valgus and internal rotational torque, or “simulated pivot-shift test,” is applied to the knee joint [32]. Such anterior tibial translation could be similarly captured by *in vivo* knee kinematics evaluation using the electromagnetic tracking system by comparing knee kinematics between the pivot-shift test and a referral movement [18]. Passive flexion with the tibia held externally rotated was utilized as the referral movement [18], since the external rotational torque could sit the tibia relatively posterior and stabilize the tibial axial rotation [32]. The 6 DOF of knee kinematics during the pivot-shift test was then recorded, and the peak value of the relative tibial

anterior translation was calculated as the coupled anterior tibial translation [18]. Increased peak coupled anterior tibial translation was consistently observed in ACL-deficient knees, validating the fact that this could be used for quantitative evaluation of the pivot-shift test [26, 27, 28].

“Rotational laxity” was often used to describe knee laxity against rotational stress, and ACL-insufficient knees show abnormal rotational laxity in the form of a positive pivot-shift. Although some might pay more attention to the axial rotational angle change than the anteroposterior translation of the tibia due to the name of the rotational laxity, abnormality of the axial rotation was hard to be detected during the pivot shift test in the ACL-deficient knee because of its inconsistency [18, 31, 33, 37]. The rotational laxity is sometimes misunderstood as rotational angle change against a simple axial rotational stress, but a simple axial rotational stress test is unable to demonstrate abnormal knee kinematics in the ACL-deficient knees [38].

The pivot-shift can be captured not only by simple abnormal increase of the tibial anterior translation but also by a more dynamic parameter, such as velocity and/or acceleration, since there is a sudden change in the rate of acceleration during the pivot shift maneuver [39]. High sampling rate of the electromagnetic tracking system made it possible to calculate the velocity and the acceleration of the knee movement during the pivot-shift. Consequently, increases in velocity and acceleration were successfully detected in ACL-deficient knees [17, 18]. Since then, other measurement systems, such as an accelerometer and navigation devices, were applied to detect a similar correlation between acceleration of tibial reduction movement and clinical grading of the pivot shift [19, 23, 24, 40]. Dynamic parameters such as velocity and acceleration could provide another aspect of the abnormal knee movement in the pivot-shift. Furthermore, it has been established that acceleration is more closely related to clinical grading than

tibial translation [19]. The increased acceleration could be reflected in the change of the force in the knee joint and induce the feeling of pivot-shift.

### **Clinical application of the pivot-shift evaluation using the electromagnetic tracking system**

The quantitative evaluation of the pivot-shift using the electromagnetic tracking system can detect small differences of rotational laxity that is not perceived by the manual test. Partial ACL tear is sometimes encountered in our clinical practice, and a small amount of instability due to the partial tear of the ACL can be appreciated but not always recognized in our hands. The electromagnetic evaluation of the pivot-shift can be used to evaluate rotational laxity due to the partial ACL rupture and successfully detect a small but significant difference in the rotational laxity compared to the intact knee and the complete ACL ruptured knee [41]. Subsequently, the criteria to diagnose the partial tear of the ACL based on the quantitative measurement of the pivot-shift can be applied to select one of a variety of ACL reconstruction techniques, i.e., partial ACL augmentation or complete ACL reconstruction. As a result of this methodology, the partial ACL rupture treated by the ACL augmentation provided a comparable clinical result to standard ACL reconstruction [26].

The non-invasive nature of the electromagnetic tracking system enables wide clinical application of pivot-shift evaluation for follow-up examinations after ACL reconstruction and comparison between different types of ACL reconstruction. The first clinical report using the electromagnetic pivot-shift measurement was to compare three different ACL reconstruction techniques: double-bundle, anteromedial single-bundle, and posterolateral single-bundle. The anatomical double-bundle ACL reconstruction provided the best result in terms of the rotational laxity measured by the electromagnetic tracking system [42]. Neither the single bundle anteromedial nor the posterolateral reconstructions could not control the pivot-shift to a comparable level as the anatomically reconstructed double-bundle ACL. A subsequent prospective randomized study of anatomical single-bundle versus double-bundle ACL reconstruction demonstrated further evidence of the usefulness of the electromagnetic system [27]. Twenty patients were randomly allocated to each of the two ACL reconstruction techniques: anatomic double-bundle or single-bundle. Anatomic single-bundle was performed by creating a single tunnel in the middle between the original insertions of the anteromedial and the posterolateral bundle attachments. The pivot-shift measurement using the electromagnetic tracking system was performed before the ACL reconstruction and 1 year after surgery. The results demonstrated that the pivot-shift was better controlled by the anatomical double-bundle ACL reconstruction than the anatomic single-bundle

reconstruction [27]. These studies clearly demonstrated that the pivot-shift evaluation by the electromagnetic tracking system can expose a small but significant difference of rotational laxity between different types of the ACL treatments.

The pivot-shift measurement can also be utilized for clinical follow-up after the ACL reconstruction. In a recently published paper, Nagai et al. [27] reported that an increase of the tibial acceleration during the pivot-shift test was detected in the pre-operative assessment. The tibial acceleration in the ACL-deficient knee was successfully reduced after ACL reconstruction to the same level as the contra-lateral intact knee. At the same time, repeated evaluation of the pivot-shift in the contra-lateral knee before and after surgery demonstrated consistent results [27]. Acceptable repeatability of the pivot-shift acceleration measurement has been previously reported [18], but the consistency of these repeated measurements during a considerably long follow-up period of more than a year was first shown by this experiment [27].

### **Limitations**

There are some limitations to the quantitative measurement of the pivot-shift by use of the electromagnetic tracking system. First, the electromagnetic system should be used in a metal-free environment. The accuracy of the electromagnetic system is guaranteed without any magnetic interference [43]. Large electronics, such as air conditioner, a personal computer, or high-voltage wiring, could generate electromagnetic waves and interfere with measurements. Based on our experience, normal clinical examination rooms and operation rooms can accommodate the measurement space without such interference.

Second, there may be a considerable amount of soft tissue between the electromagnetic sensors and the actual bones which could buffer the actual joint motion. Although the volume of the soft tissue and its effect are different between subjects, the soft tissue movement between bones and the sensors can underestimate the actual bony movement. Preliminary experiments comparing the direct measurement of the bony movement and the non-invasive application of the electromagnetic tracking system demonstrated acceptable difference of knee kinematic measurement [18], but there is still a possibility to miss the small abnormality of knee kinematics during the pivot-shift test. Further technical improvement is still desired to eliminate inaccuracies caused by soft tissues.

Third, muscle guarding against the pivot-shift could affect the measurement. A recent report from Matsushita et al. demonstrated that the acceleration of the pivot-shift was significantly suppressed when the patients were awake [44•]. Possible underestimation of the pivot-shift measurement should be considered when the measurement is performed



without an anesthesia, and every effort should be made to relieve the patient's pain and apprehension during the pivot-shift test.

Finally, the manual execution of the pivot-shift test has a wide variation among examiners [15, 16, 28]. The manually applied force, the testing speed, and the position of the hip joint are potential factors affecting the knee kinematics and the quantitative measurement of the pivot-shift. These factors are difficult to standardize between examiners. Valgus stress is always applied during the pivot-shift test, but axial rotational stress is not necessarily the same between surgeons [16]. Internal rotational stress is more important than external rotational stress, but some do not intentionally apply rotational torque [15]. Such a wide variation of the pivot-shift testing technique leads to great variability of the measurement results [15, 28]. However, similar pivot-shift testing techniques can reduce the variability of the measurement results to an acceptable level [18]. Furthermore, it has been proven that the consistency of the acceleration measurement during the pivot-shift test was improved by standardizing the testing technique [45]. Therefore, it is highly expected that consistency and accuracy of the quantitative pivot-shift evaluation would be improved by teaching standardized testing procedures [45]. At the moment, it is possible to achieve acceptable consistency and accuracy of the pivot-shift measurement by limiting the examiners and/or standardizing the testing procedure.

## Conclusion

The electromagnetic tracking system is able to evaluate the 6 DOF of knee kinematics during the pivot-shift test and to provide quantitative values, such as tibial anterior translation and tibial acceleration during posterior reduction, which can be used to assess the rotational laxity in the knee, especially after ACL injury and treatment.

The advantage of the electromagnetic tracking system is its non-invasive application and enables broad application to our clinical cases. Thus, the quantitative evaluation of the pivot-shift has been employed not only for comparisons between different types of ACL treatments but also for clinical follow-up after the ACL reconstructions. Meticulous evaluation of the pivot-shift by the electromagnetic tracking system has enhanced the diagnosis of the ACL deficiency and the treatment of ACL injuries.

## Compliance with Ethical Standards

**Conflict of interest** Ryosuke Kuroda and Yuichi Hoshino 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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