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Quantitative evaluation of the pivot shift by image analysis using the iPad

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Abstract
Purpose To enable comparison of test results, a widely available measurement system for the pivot shift test is needed. Simple image analysis of lateral knee joint translation is one such system that can be installed on a prevalent computer tablet (e.g. iPad). The purpose of this study was to test a novel iPad application to detect the pivot shift. It was hypothesized that the abnormal lateral translation in ACL deficient knees would be detected by the iPad application.
Methods Thirty-four consecutive ACL deficient patients were tested. Three skin markers were attached on the following bony landmarks: (1) Gerdy's tubercle, (2) fibular head and (3) lateral epicondyle. A standardized pivot shift test was performed under anaesthesia, while the lateral side of the knee joint was monitored. The recorded movie was processed by the iPad application to measure the lateral translation of the knee joint. Lateral translation was compared between knees with different pivot shift grades.
Results Valid data sets were obtained in 20 (59 %) ACL deficient knees. The remaining 14 data sets were invalid because of failure to detect translation or detection of excessive translation. ACL deficient knees had larger lateral translation than the contra-lateral knees ($p < 0.01$). In the 20 valid data sets, which were graded as either grade 1 ($n = 10$) or grade 2 ($n = 10$), lateral translation was significantly larger in the grade 2 pivot shift (3.6 ± 1.2 mm) than the grade 1 pivot shift (2.7 ± 0.6 mm, $p < 0.05$).
Conclusion Although some technical corrections, such as testing manoeuvre and recording procedure, are needed to improve the image data sampling using the iPad application, the potential of the iPad application to classify the pivot shift was demonstrated.
Level of evidence Diagnostic study, Level III.

Keywords Pivot shift test · iPad · Image analysis · ACL

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Introduction

The pivot shift test is the most specific diagnostic clinical test for ACL injury [5] and relates to patient-reported assessment of knee function after ACL injury and treatment [3, 19, 33]. However, this test can only be assessed subjectively because there is still a lack of prevailing quantitative measurement systems. A widely available and convenient measurement is needed for achieving an objective and comparable evaluation of the pivot shift test.

Recent research efforts to achieve an objective evaluation of the pivot shift test revealed that either tibial translation or acceleration of the tibial reduction could provide a quantitative measure for the pivot shift test [2, 6, 12, 16, 20–28, 31, 32]. While the pivot shift consists of two phases, that is, anterior subluxation of the lateral tibial plateau and its spontaneous reduction [10], the anterior tibial translation during the subluxation phase has been widely used as a parameter, which dictates the magnitude of the pivot shift movement [7, 12, 17, 18, 31]. Bedi et al. [4] demonstrated, using cadaveric experimentation, that the lateral compartment translation, that is, tibial anterior translation on the lateral compartment, could provide a convenient evaluation of the pivot shift test that relates to the clinical grading of the pivot shift test. Although the possibility of establishing a quantitative evaluation of the pivot shift test has been suggested, these measurement systems are not practical in the clinical setting secondary to invasiveness, limited availability and/or high cost. Simple image analysis has been introduced to evaluate lateral translation of the knee joint in a non-invasive way using affordable devices [13].

Image analysis to assess tibial translation during the pivot shift requires intensive labour to process the images on the computer. The time required to analyse the video is not suitable for a typical orthopaedic practice. Therefore, an application to automate the analysis process that can be installed onto an iPad was developed. This application can process video images in almost real time in order to provide data about the translation of the lateral compartment, according to the previously published methodology [13]. In addition to the high quality and frame rate of the video camera (resolution 1,080 p and frame rate 30 fps) in the iPad, the application can complete the image analysis of the pivot shift test with minimal effort.

The purpose of this study was to test a novel iPad application for the detection of the pivot shift. It was hypothesized that the abnormal lateral translation in ACL deficient knees could be detected by using the iPad with a novel image analysis application.

Materials and methods

From May to August 2012, 34 consecutive unilateral ACL deficient patients who underwent ACL reconstruction surgery were tested. Three round yellow stickers, 3/4 inch in diameter (Color Coding Labels, Avery Dennison Corporation, Pasadena, CA, USA), were attached to the skin over specific bony landmarks including the lateral epicondyle, Gerdy's tubercle and fibular head (Fig. 1). The pivot shift test was performed under general anaesthesia in both knees using the standardized pivot shift test manoeuvre [14, 29]. As the examiners assessed the pivot shift test according to the clinical grading scale based on the IKDC criteria [15], movement of the lateral aspect of the knee was videotaped and analysed using the iPad application as described below. The examiner graded the pivot shift test prior to reviewing the output from the iPad application.

Image analysis using the iPad application

Image capture was completed with the video function of the iPad application. An assistant held the iPad in a fixed position perpendicular to the lateral side of the knee joint about one metre away from the knee joint. The assistant assured that the skin markers did not move out of the field of view throughout the testing procedure (Fig. 2). A monotone sheet to reduce chrome interference during the processing stage was used as a background behind the knee. After setting the iPad in the acceptable position and starting video capture, the examiner performed the pivot shift test using a standardized technique [14, 29].

After video capture, each frame of the video image was automatically processed according to the previously reported methodology [13]. The marker area was identified and extracted as the region of interest in the image, and the location of the centroid point in each region of interest was recognized as a landmark point within each video frame. The femoral anteroposterior (AP) position was then determined at the intersection point between the tibial horizontal line (the line connecting the Gerdy's tubercle and the fibula head) and the perpendicular line from the lateral epicondyle to the tibial horizontal line. As the distance from the Gerdy's tubercle to the intersection point was plotted in each frame, femoral AP position over time

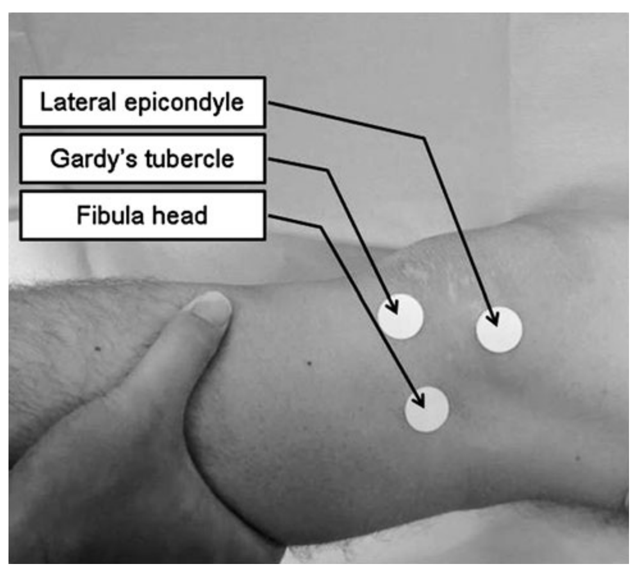

Fig. 1 Lateral aspect of the knee joint during the pivot shift test. The examiner's hand is placed on the lateral shank. Three markers were attached to bony landmarks on the lateral side of the knee joint

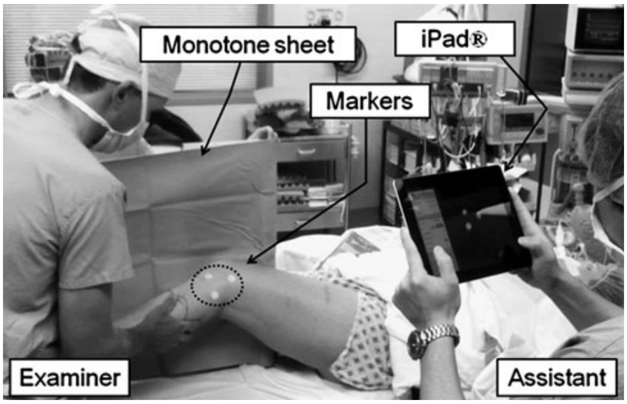

Fig. 2 Video acquisition during the pivot shift test. An assistant holds the iPad in a fixed position so that the skin markers do not move out of the frame throughout the testing procedure, while the examiner performs the pivot shift test

was traced as femoral AP translation by tracking the consecutive frames of the video imaging.

A typical result of the femoral AP translation is shown in Fig. 3. At the time of the pivot shift reduction, the lateral tibial plateau moved posteriorly relative to the lateral condyle of the femur [10], which was reversely observed as an anterior movement of the lateral femoral condyle relative to the lateral tibial plateau. Therefore, the length between the most posterior femoral AP position before pivot shift and the most anterior femoral AP position after the pivot shift was calculated as the lateral translation.

The greatest lateral translation value among two consecutive pivot shift tests was used for further analysis. The average lateral translation was compared between the ACL injured and contra-lateral knees and between the ACL deficient knees of different clinical grading. Based on the preliminary data of the image analysis [13], tests were excluded if there was zero lateral translation (although the pivot shift test was positive clinically) or if there was excessive lateral translation (more than 10 mm), because these data had obvious discrepancy between the resultant value and the visibly confirmed translation.

Statistical analysis

Paired t test was used to test a difference of the lateral translation between the ACL injured and contra-lateral knees, and independent t test was used to test differences of the lateral translation between the ACL injured knees of different clinical grading of the pivot shift test. The statistical significance was set at a p value less than 0.05. All statistical calculations were performed using PASW® Statistics 18 (IBM Corp, Armonk, NY, USA).

Results

Valid data sets were recorded in the ACL injured knees for 20 (59 %) patients. Of those, 18 patients had valid data in the contra-lateral knees. For the remaining 14 patients, no reduction, that is, femoral anterior movement relative to the tibia, could be quantified ($n = 10$) or excessive lateral translation was detected as a reduction ($n = 4$). Intraoperative findings confirmed a complete ACL rupture in all 34 patients.

There was significantly larger lateral translation in the ACL deficient knees than those in the contra-lateral knees ($n = 18$, $p < 0.01$). For the ACL injured knees, ten ACL deficient knees were graded as a pivot-glide with a mean lateral translation of 2.7 ± 0.6 mm. The remaining 10 knees were graded as a pivot-clunk with a mean anterior translation of 3.6 ± 1.2 mm, which was significantly larger than the pivot-glide knees ($p < 0.05$). However, there was no statistically significant difference in the side-to-side difference of the lateral translation between pivot-glide versus pivot-clunk patients (n.s.) (Table 1).

Discussion

The most important finding of this study was that the increase in the lateral translation was detected by the image analysis using the newly developed iPad application in the ACL deficient knees compared to the contralateral knees and in relation to the higher grading of the pivot shift test. However, the side-to-side difference of the lateral translation during the pivot shift test was not different between differently graded patients. The detection rate of the tibial reduction movement during the pivot shift test was moderate, but there is still room to improve the iPad system by both technical adjustment, for example, angle and position of image acquisition, and hardware improvement, for example, image resolution, sampling rate and noise cancelling. Therefore, the current results from using this novel technique are promising for quantitative measurement of the pivot shift test.

Variation in performance of the pivot shift test manoeuvre has long been regarded as the obstruction to achieve objective and quantitative measurement [30]. At the recent Panther Global Summit (Pittsburgh, USA, August 2012), a standardized manoeuvre of the pivot shift test was introduced, which was developed based on the technique introduced by Galway et al. [11]. The standardized procedure of the pivot shift test can be easily acquired by experienced ACL surgeons who are accustomed to perform the test in their own technique (please see the supplementary material on this website: http://www.springerlink.com/content/k377885587185016/167_2011_Article_1862_ESM.html).

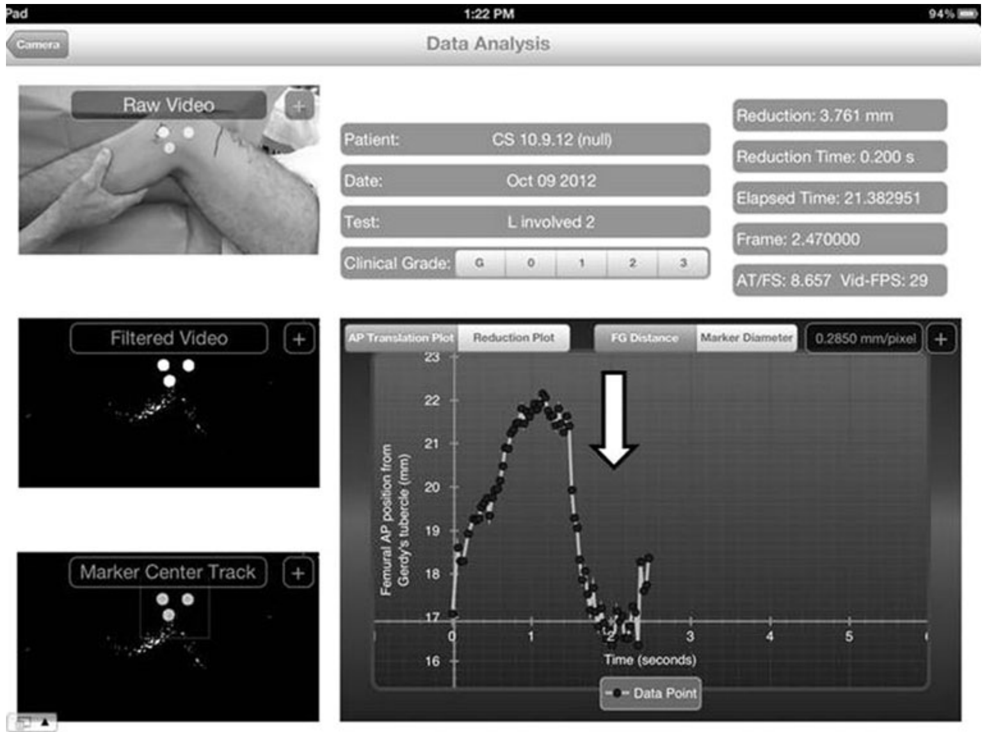

Fig. 3 A screenshot of the iPad application. The raw video data are on the top left; the marker tracking process is displayed below. The femoral AP position from Gerdy's tubercle (in mm) over time (in sec) is plotted on the graph (*lower right*); the sudden decrease (femoral anterior translation or tibial reduction) is displayed (*arrow*). The calculated results are listed on the *top right* (note the elapsed time for video processing—in this case 21.4 s)

Table 1 The lateral translation measured by iPad application (mm)

	ACL deficient	Contra-lateral	Side-to-side difference
Patients graded as glide	2.7 ± 0.6 (n = 10)	1.4 ± 1.9 (n = 9)	1.3 ± 2.0 (n = 9)
Patients graded as clunk	3.6 ± 1.2* (n = 10)	1.0 ± 1.5 (n = 8)	2.5 ± 2.0 (n = 8)
Total (n = 17)	3.2 ± 1.0^{+}	1.3 ± 1.7	1.9 ± 2.1

* Significantly larger compared to that in the patients graded as glide ($p < 0.05$)

$^{+}$ Significantly larger compared to that in the contra-lateral knees ($p < 0.01$)

This will improve the consistency of quantitative evaluation of the pivot shift test [14]. We used the standardized technique for this study, performed by the senior author (VM). However, because of the consistency of the standardized pivot shift test, the current result might be repeatable with another examiner or multiple examiners.

Several systems have been developed to provide quantitative evaluation of the pivot shift test such as a navigation system [6, 8, 16, 24, 26, 32], an electromagnetic system [7, 9, 12, 23] and an accelerometer [20, 25, 27, 28], but these systems are not usable in the clinical setting with the exception of the accelerometer. Some systems require rigid fixation using bone pins [6–9, 16, 24, 26, 28, 32]. Also, most of these systems are available only for research facilities and are expensive. Even when those monitoring systems are available, the final data must be calculated through a complicated process. The image analysis technique for lateral translation during the pivot shift test has been developed to provide a non-invasive and widely affordable measurement system using a digital camera and stickers [13], but it still requires labour-intensive image analysis processing using a computer. The iPad is a computer tablet, which contains a video capture and a computer function. Thus, the iPad can be an all-in-one measurement device with help from the application programmed to perform the image analysis processing.

This iPad application system could have more clinical benefit than the other pivot shift test measurement systems. Obviously, non-invasiveness is a requirement for clinical application. Of the non-invasive systems, the electromagnetic system is limited by interference from metal objects [7, 12, 23]. Compared to the accelerometer measurement, the translation measurement is less susceptible to differences in performing the pivot shift manoeuvre [14]. Furthermore, the iPad application is completely ready-to-use and can provide estimates of lateral tibial translation result without a complex calculation process. Also, this measurement system is portable, requiring only the iPad and small stickers, so this quantitative evaluation of the pivot shift test can be performed in an exam room, an operation room and even on a sports field.

There are limitations to this measurement system. The reasons for the low sensitivity in detecting the pivot shift reduction reported in this study (59 % of ACL deficient knees) are (1) marker movement outside of the field of view of tracking; (2) camera angle less than perpendicular to the lateral aspect of the knee joint; and (3) performing of the pivot shift test too fast for the camera speed. The image capturing technique has been refined since the reporting of results in this study, including enlarging the field of view for marker tracking and refining the speed of the pivot shift test. We currently achieve detection of valid data sets (detection of reduction curve with iPad and intraoperative validation of ACL tear) in greater than 90 % of tests. Further improvement of the camera device in the iPad, such as noise cancelling and/or higher resolution, will aid in improving the iPad app in the future. The clinical pivot shift test has just 74 % of sensitivity for diagnosing the ACL deficiency [5]. Thus, the iPad application might be still usable for the detection of the ACL deficiency similarly to the clinical pivot shift test. Second, the sample size is small, especially for the comparison of side-to-side difference between different pivot shift grades. As joint laxity is highly independent between subjects, the side-to-side difference of laxity measurements is more suitable for an objective measurement by cancelling baseline joint laxity. Although this study found a significant difference of the lateral translation between different grading of the ACL injured knees, more subjects should be tested. Lastly, the lateral translation measured on the skin surface may not be an accurate evaluation of general knee joint movement. Lateral translation measured by image analysis was only poorly correlated to the tibial anterioposterior translation measurement based on the general knee kinematics coordinate system [1, 2]. Nevertheless, appropriate validation studies, for example, basic validation of the iPad measurement versus bony movement and clinical validation using actual ACL deficient and reconstructed patients, are planned.

This iPad application can be delivered through the Internet so that this measurement can be widely accessible for orthopaedic surgeons worldwide to perform and objective compare pivot shift test results.

Conclusion

The sudden shift of the lateral compartment of the knee joint was successfully detected by this newly developed video-based image analysis measurement method. This image analysis technique facilitates a simple, reliable and affordable measurement to evaluate the lateral pivot shift test.

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