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Original article

# Use of a portable motion analysis system for knee dynamic stability assessment in anterior cruciate ligament deficiency during single-legged hop landing

Man-Yi Yeung, Sai-Chuen Fu, Eldrich Norwin Chua, Kam-Ming Mok, Patrick Shu-Hang Yung, Kai-Ming Chan*

*Department of Orthopaedics and Traumatology, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China*

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## Abstract

*Background/objective*: Anterior cruciate ligament (ACL) rupture results in knee instability, and patients are often unable to return to their previous level of activity. Current assessments rely on passive laxity tests, which do not correlate with function. Dynamic stability may be a better indicator for return to sport. However, equipment for measuring dynamic stability is ill suited for clinical use. The purpose of this study is to evaluate knee kinematics in ACL-deficient patients with a single-legged hop task using a portable motion analysis system. We hypothesize that the assessment task is able to differentiate ACL-deficient knees from healthy knees.

*Methods*: Ten ACL-deficient patients and 10 healthy controls were recruited. Participants were instructed to perform a single-legged hop, while kinematics was measured using a portable motion capture system (Opti-Knee; Shanghai Innomotion Inc., Shanghai, China). Kinematic changes after initial contact were examined. Repeatability of the results was examined by calculating the coefficient of variations of the pooled standard deviation of the tibiofemoral displacements. Side-to-side differences were calculated and compared between the two groups.

*Results*: One patient could not perform the task. Intraindividual variability was small after initial contact; the coefficient of variation in this region was 13–26%. ACL-deficient knees demonstrated lower flexion range of motion ($p = 0.008$) and increased internal/external rotation range of motion after landing ($p = 0.038$), while no significant differences were detected in the healthy group. Only the side-to-side difference in flexion was significantly different between the two groups ($p = 0.002$).

*Conclusion*: The altered knee kinematics in ACL-deficient patients can be revealed by a portable motion capture system, which may enable the clinical application of kinematic assessment in the evaluation of ACL deficiency.

*Keywords:* anterior cruciate ligament injury; biomechanics; kinematics; knee function; movement task

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## Introduction

Rupture of the anterior cruciate ligament (ACL) is one of the most common sport-related injuries in the lower extremities.[1] The ACL is one of the main stabilizers in the knee joint, and its disruption often results in deterioration in everyday function.[2] Joint stability influences knee function.[3] However, current assessment on knee stability relies on manual passive clinical tests that do not correlate well with functional outcomes.[4] A reason for this is that stabilization of the knee is dependent on two systems: static stabilizers, for which the ACL and the other knee ligaments are the main components, and dynamic stabilizers, which pertain to the

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* Corresponding author. Department of Orthopaedics and Traumatology, The Chinese University of Hong Kong, Room 74034, 5/F, Lui Che Woo Clinical Science Building, Prince of Wales Hospital, Shatin, Hong Kong, China.

*E-mail address:* kaimingchan@cuhk.edu.hk (K.-M. Chan).

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muscular activity surrounding the knee joint.[5,6] In passive laxity tests, only the static stabilizers are engaged. Hence, the lack of a correlation between passive laxity tests and functional outcomes suggests that the integrity of the dynamic stabilizers may be a better indicator of knee function. In light of these, several studies have been conducted to assess and measure dynamic stability.[7,8]

Motion capture systems such as optical motion capture and biplanar fluoroscopy have allowed for objective and quantifiable assessment of dynamic knee stability. Results have shown that patients with knee joint laxity during the performance of motion tasks have worse functional outcomes.[9] This assessment may, therefore, prove to be clinically relevant in decision making. However, commonly used motion capture systems often require substantial resources that make it impractical for clinical use. Biplanar fluoroscopy is the gold standard for kinematic assessment, but the invasive nature makes this system unsuitable for regular clinical use to monitor treatment progress. Laboratory-based optical motion capture systems typically require sizable laboratories and intensive labour, which render it unfeasible for use in clinics. A portable motion capture system uses two infrared cameras attached to a portable workstation and has previously been used in a study to assess normal gait.[10] Several motion tasks may have been able to elicit an observable kinematic response; it has been shown that single-legged hop landing (SLHL) is sufficient to distinguish ACL-deficient (ACLD) knees from healthy knees.[11] Thus, development of SLHL assessment task using a portable motion capture system would enable the transition from research to clinic.

The purpose of this study is to evaluate tibiofemoral joint kinematics in ACLD patients with an SLHL assessment task using a portable motion capture system. Based on previous kinematic studies, we hypothesize that this system is able to differentiate ACLD knees from uninjured knees.

## Materials and methods

### *Participants*

Ten unilateral ACLD patients were recruited from the outpatient clinic of the department of Orthopaedics and Traumatology, Prince of Wales Hospital, Shatin, Hong Kong. Patients (age range, 18—50 years; no restriction on sex) were included if the injury was sustained at least 4 months prior to testing. Patients with pain or swelling at the knee joint and rerupture of a previous ACL reconstruction were excluded. All patients were scheduled for ACL reconstruction, and assessments were scheduled 3 months before ACL reconstruction. Ten personnel from the same department (age range, 18—50 years; no restriction on sex) with no previous history of injuries of the lower extremities were recruited as healthy controls.

Demographic data and medical history of the participants were collected. All the participants completed the International Knee Documentation Committee subjective knee evaluation form, Lysholm score, and postinjury Tegner activity level scale. For ACLD patients, concomitant injuries identified during the reconstruction surgery were documented. Prior to participation in the study, all the participants were provided with the study information and they signed a consent form. The study protocol was approved by The Joint Chinese University of Hong Kong—New Territories East Cluster Clinical Research Ethics Committee (Ref. No.: 2014.540). All experimental procedures were performed in accordance with the approved procedures.

### *Kinematic assessment*

Tibiofemoral joint kinematics was acquired using a portable infrared optoelectronic motion capture system (Opti-Knee; Shanghai Innomotion Inc.). The system comprised two infrared cameras placed ~50 cm apart and a high-speed camera attached to a portable workstation. A set of eight reflective markers were used according to a standardized protocol provided by the developer. Two sets of markers were attached on the test limb according to premade grids, with each set consisting of four markers (Figure 1). A set of markers was attached 6—10 cm above the lateral epicondyle of the test leg, while a second set of markers was attached 1—5 cm below the fibular head. After fixing the markers, calibration was performed by marking specified body landmarks with the use of a pointer fixed with four reflective markers. With the participants in a level standing position and the lateral test side facing the cameras, the tip of the pointer was placed on the following points of the test leg: greater tuberosity, lateral epicondyle, medial epicondyle, lateral tibial plateau, medial tibial plateau, tibial tuberosity, fibular head, lateral malleolus, and medial malleolus. Three points on the ground were also captured. Data were collected at 60 Hz. Knee kinematics, including rotations and translations, were calculated for each frame using the geometric relationships between the reflective markers under the femur and tibia coordinate systems that were established during calibration.[10] The high-speed camera was also used to capture a video of the task and synchronized with the motion analysis data.

Participants were positioned within the capture area of the system, with all eight reflective markers being clearly detectable by the system throughout the task. They were asked to place both arms across the chest to prevent potential counterbalance attempts. A demonstration was given by the assessor on how to perform an SLHL task. A trial was considered successful if an individual was able to stand on the test leg, hop forward on the test leg over a distance of 1 m, land on the test leg, and maintain the single-legged stance until instructed by the assessor. Participants who were unable or unwilling to perform the task at the given distance of 1 m were allowed to perform it at their self-selected distance. Five successful trials were acquired for each participant on each limb.

### *Data analysis*

For each successful trial, initial contact (IC) was identified using the captured video by manually identifying the instance

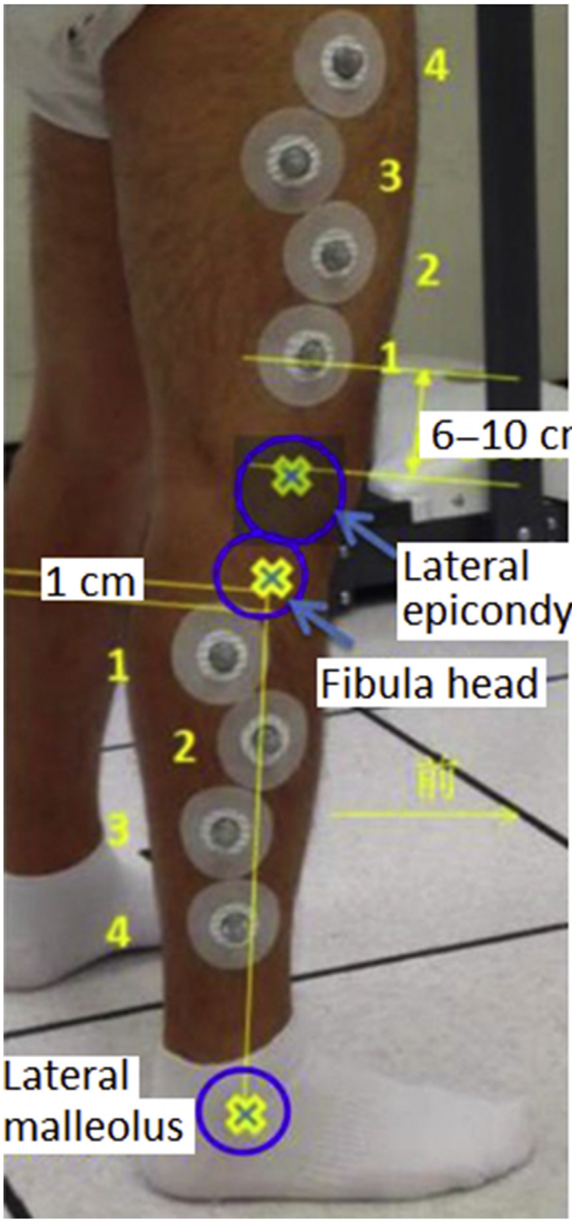

Fig. 1. Marker cluster design.

when any part of the foot made contact with the ground. Data were extracted for the period between IC and maximum knee flexion after landing. The changes in values of internal/external rotation of the knees, varus/valgus, anterior/posterior (AP) translation, medial−lateral translation, and proximal/distal translation were quantified, as shown in the representative time−displacement curves (Figure 2). The data on proximal/distal translation were not included for further analysis because it was shown to be highly influenced by the movement of soft tissue artefacts.[12,13]

### *Statistical analysis*

A comparison of demographics was performed using *t* test. Intrapersonal repeatability of the SLHL test was evaluated by calculating the intraclass correlation coefficients of the kinematic data from repeated trials. Pooled standard deviations from the repeated trials of all test participants were used to calculate the coefficient of variations for the kinematic data in the 6 degrees of freedom of femoral−tibial movement. The mean values of repeated trials were used for comparisons of both limbs between the ACLD patient and healthy control groups. Side-to-side differences (SSDs) in the mean kinematic data were calculated as injured−noninjured side in the ACLD group, and dominant−nondominant side in the control group. Nonparametric two-related-sample Wilcoxon signed-rank test was used to detect the bilateral difference and the difference between the two groups. Mann−Whitney *U* test was used to compare SSDs between the ACLD knees and the healthy knees. All tests were performed using SPSS (version 20.0; IBM, Chicago, IL, USA). Statistical significance was denoted at an alpha level of 0.05.

## Results

The demographic characteristics and comorbidity of 10 ACLD patients are shown in Table 1. ACLD patients have significantly lower International Knee Documentation Committee subjective knee evaluation form, Lysholm, and Tegner activity scores than the control groups, but there were no significant differences in sex, age, body weight, and body height (Table 1). The time from injury to assessment in ACLD patients ranged from 2 months to 90 months. One ACLD patient could not perform the SLHL task. Kinematic data showed characteristic landmarks of knee flexion−extension pattern during SLHL (Figure 2). Immediately following IC, sudden changes in internal rotation, AP translation, and medial/lateral displacement were detected; these changes occurred prior to the maximum knee flexion post-IC. The intrapersonal variation in performing the task was good in the curve region immediately after IC, while the kinematics before takeoff and after maximum knee flexion post-IC entailed large variations. Intraindividual repeatability is shown in Table 2.

ACLD patients demonstrated a lower knee flexion range of motion ($p = 0.008$) and internal/external rotation range of motion ($p = 0.038$) after landing when the injured side was compared with the contralateral side, while no significant bilateral differences were detected in the healthy group (Table 3). The median SSD (injured−noninjured) in knee flexion range of motion after landing was −8.2°, which is significantly lower than that of the healthy group (dominant−nondominant = 2.2°). There was a trend towards a difference in the SSD of internal/external rotation between the two groups (−2.24° in the ACLD group and −0.22° in the control group), but due to lower intraindividual repeatability in the measurement of internal/external rotation (pooled standard deviation = 3.14°), no significant difference was seen.

## Discussion

The results of this study indicate that the portable motion capture system is able to detect kinematic differences

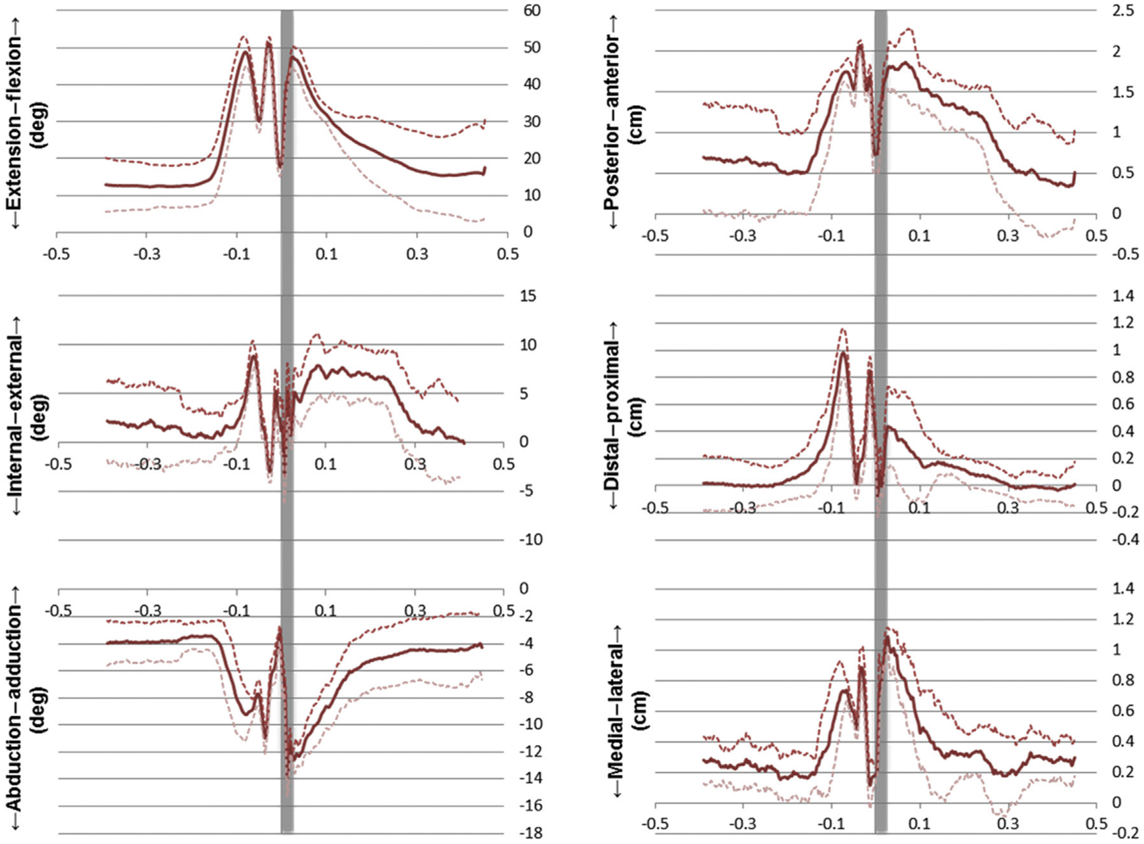

Fig. 2. The tibiofemoral kinematics (mean and standard deviation) measured in an ACLD patient during the SLHL task. The grey area time in seconds shows the between the initial contact (when any part of the foot touches the floor) and the absorption phase (maximum flexion). ACLD = anterior cruciate ligament deficient; SLHL = single-legged hop landing.

Table 1
Demographics of ACLD patients.

| Patient ID | Sex | Age | Body weight | Body height | Injured side | Comorbidity | Time from injury to assessment |
|---|---|---|---|---|---|---|---|
| ACLD101 | M | 20 | 62 | 174 | Left | Healed previous meniscal injury | 5 mo |
| ACLD102 | F | 27 | 54 | 158 | Left | Meniscal injury | Unknown |
| ACLD103 | M | 18 | 74 | 179 | Right | Meniscal injury, chondral defect | 2 mo |
| ACLD104 | M | 30 | 82 | 172 | Left | Meniscal injury, chondral defect, osteophyte | 2—3 y |
| ACLD105 | M | 38 | 74 | 177 | Right | Meniscal injury, chondral defect | 7—8 y |
| ACLD106 | M | 27 | 80 | 173 | Right | Meniscal injury | 2 y |
| ACLD107 | M | 33 | 72 | 172 | Right | None | 21 mo |
| ACLD108 | M | 36 | 67 | 169 | Right | Meniscus injury, chondral defect | 6 mo |
| ACLD109 | M | 32 | 82 | 165 | Left | Right ACL + meniscus injured in 2004 (ACLR in 2006) | 3—4 y |
| ACLD110 | F | 19 | 60 | 175 | Left | Meniscal injury | 15 mo |

ACL = anterior cruciate ligament; ACLD = anterior cruciate ligament deficient; ACLR = anterior cruciate ligament reconstruction.

Table 2
Tibiofemoral kinematics after initial contact.

| Femoral—tibial displacement after landing | Pooled SD | CV (%) | *p* Bilateral difference Control | *p* Bilateral difference ACLD | SSD ACLD vs. control |
|---|---|---|---|---|---|
| Varus/valgus | 2.39° | 16.86 | 0.169 | 0.051 | 0.653 |
| Internal/external rotation | 3.14° | 24.42 | 0.959 | 0.038* | 0.131 |
| Flexion/extension | 5.62° | 12.823 | 0.386 | 0.008* | 0.002* |
| Anterior/posterior translation | 0.36 cm | 25.67 | 0.646 | 0.441 | 0.744 |
| Medial/lateral translation | 0.27 cm | 21.37 | 0.285 | 0.086 | 0.744 |

*Statistically significant difference ($p < 0.05$).
ACLD = anterior cruciate ligament deficient; CV = coefficient of variation; SD = standard deviation; SSD = side-to-side difference.

Table 3
Patient demographics.

| | Control ($n = 10$) | ACLD ($n = 10$) | $p$ |
|---|---|---|---|
| Sex ratio (M:F) | 8:2 | 8:2 | |
| Age (y) | 25.0 (4) | 28.5 (14) | 0.340 |
| Body weight (kg) | 65.2 (19.92) | 74.0 (16.7) | 0.131 |
| Body height (cm) | 167.75 (16.73) | 172.40 (7.25) | 0.705 |
| IKDC score | 100 (0.85) | 73 (19.25) | <0.001* |
| Lysholm score | 100 (1.25) | 78 (16.25) | <0.001* |
| Tegner activity score | 5.5 (3.75) | 7.0 (0.75) | 0.014* |

*Statistically significant difference ($p < 0.05$).
ACLD = anterior cruciate ligament deficient; IKDC = International Knee Documentation Committee subjective knee evaluation form.

between ACLD and healthy contralateral knees when the SLHL task was performed. The SLHL test is a commonly used clinical tool for knee function assessment after ACL injuries. Interpretation of the test result is based on the ratio of the hop distance between the two limbs. Although other motion tasks may have been able to provide greater challenges and elicit a more observable kinematic response, it has been shown that the SLHL task is sufficient to differentiate ACLD knees from healthy knees.[11] Previous studies on knee kinematics during SLHL have been performed in ACLD patients using optoelectronic cameras and force plates, and in ACL-reconstructed patients using biplane radiography.[7,14] Compared with these complex set-ups, the motion analysis system used in the current study does not measure kinetic data and is unable to reach the same level of accuracy as biplane radiography, a trade-off for the system's portability and ease of use.

Our results revealed observable kinematic differences between ACLD and healthy knees. Decreases in the knee flexion range of motion (median SSD, 14°) and tibial rotation range of motion (median SSD, 2.2°) were detected during the SLHL task using the portable motion capture system. A recent similar study reported that ACLD knees produced greater average external tibial rotation and maximum anterior tibial translation compared with uninjured knees.[7] However, our results failed to show the same response in anterior tibial translation. There are stark differences between our results, which may explain the discrepancy. First, in contrast to our study, Oberlander et al[7] recruited a more homogeneous group of patients who were able to perform high-demand activities despite the injury and excluded those with other knee injuries. Although our sample size was not large enough to account for the influence of meniscal tears on knee joint kinematics, most of the ACLD patients in our study have had concurrent injuries on the ipsilateral limb that may have affected the results.[15] Second, our protocol differed in execution of the motion task. Oberlander et al[7] used a hop distance equal to 75% of the patient's body height. This was achievable because the study participants were all active in sports with high knee joint loading. By contrast, we did not use a strict protocol as our study participants were heterogeneous in the activity level. Hence, those who were hesitant or unable to reach the 1 m target were allowed to hop at their self-selected distance. Apprehension to perform the task, resulting in a smaller hop distance, may have been a protective response to control for excessive motion during landing, in effect minimizing the kinematic outcome of instability. It is also worth mentioning that despite the drawbacks of skin-marker-based motion analysis, Oberlander et al[7] were able to achieve a low degree of variability, whereas our study has a coefficient of variation of approximately a quarter in both AP translation and transverse rotation. The explanation may lie in the homogeneity of the participants, as mentioned previously.

Deneweth et al[14] used biplane fluoroscopy, a system that is considered to be the gold standard in kinematic analysis, in ACL-reconstructed knees while performing the SLHL task. In contrast to the current study, they reported changes in the maximum values of knee flexion and external tibial rotation, which we did not observe in ACLD patients.[14] It is likely that the observed changes in maximum values in the ACL-reconstructed individuals were due to a shift in the femoral-tibial position after surgery, which restored knee stability as no difference in range was produced. They also reported a difference in anterior translation in ACL-reconstructed patients, but no significant change was observed in ACLD patients in the present study.

Our results may also be explained by the intrinsic and extrinsic factors that affect knee stability. AP translation in weight bearing was seen to be half the amount of that seen in non-weight bearing activities.[16] Increased joint compression during SLHL may contribute to stabilization. Furthermore, Shelburne et al[17] concluded that an increase in the hamstring—quadriceps co-contraction ratio might be sufficient to stabilize the knee in sagittal plane translation. It has also been suggested that an insult to the knee results in joint stiffening or an increase in muscle co-contractions, which leads to compression at the joint and protects the knee from excessive rotation and translation.[18] The development of muscular compensatory mechanisms is seen in ACLD patients and, in some cases, may even lead to overcompensation in an attempt to stabilize the knee without the ACL.[19]

Two clear outliers are observable in our data: ACLD105 in internal rotation (Figure 3B) and ACLD109 in knee flexion (Figure 3A). A quick look at Table 1 reveals that ACLD105 has a substantially longer time since onset of injury at 7—8 years. This may have allowed the individual ample time to cope with the injury, and hence perform better. ACLD109 has had an ACL reconstruction of the contralateral knee prior to the commencement of the study, which may have affected the performance of the contralateral limb, as stability may not have been fully restored after the surgery.[14]

## *Limitations*

Our study has a heterogeneous group of patients. There is a large time gap between injury and assessment. Patients with meniscal injury or contralateral joint injuries that could have affected joint kinematics were not excluded. A larger sample size may have been able to reveal more information on the influence of meniscal injuries and decrease interindividual variability.

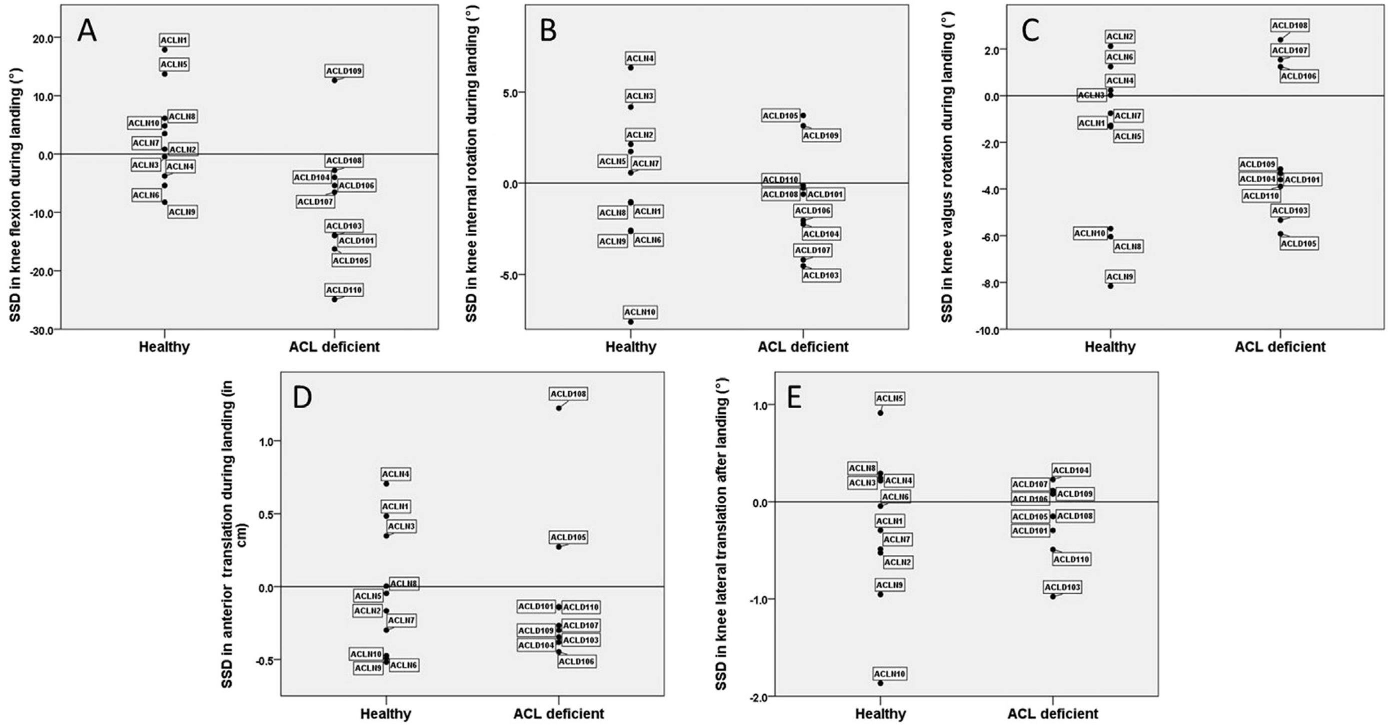

Fig. 3. SSDs in healthy and ACLD individuals: (A) knee flexion; (B) internal rotation; (C) varus/valgus; (D) anterior–posterior translation; and (E) medial–lateral translation. ACL = anterior cruciate ligament; ACLD = anterior cruciate ligament deficient; SSD = side-to-side difference.

An observable pattern can be seen in the graphs. There seems to be a link among flexion, AP translation, and varus/valgus curves, suggesting potential cross-talk in the 6 degrees of freedom. This may influence the results of smaller movements such as AP translation and transverse rotation since flexion may directly affect their measurements.

Compensatory changes in the contralateral knees of patients with ACLD may also be a factor that was not accounted for. As data were calculated using the side-to-side difference and by comparison with the contralateral limb, compensation of the contralateral limb would dampen the true change from normal of the injured limb.

The limitation of skin marker-based motion analysis is well known.[20] Soft tissue artefact may be influential in our protocol due to the high impact of the motion task. The SLHL task may be too challenging for some patients with ACLD, as evidenced by one of our participants refusing to perform the task. Further studies using tasks with lower demand, such as stair negotiation, are suggested.

## Conclusion

ACLD patients have demonstrated altered knee kinematics in their injured limbs, suggesting the potential use of the SLHL assessment task using a portable motion capture system in clinical applications. Further study with correlation made to muscular strength and other dynamic motion analysis system is recommended for further improvement. Nevertheless, development of the current system has a high clinical value, as functional stability is one of the key players in knee function. This may be crucial in the management of ACL injury and may potentially be used as a first screening for a suspected ACL-injured patient. In addition, the assessment task can assess the restoration of knee function, which can be regarded as an indicator of rehabilitation progress after the ACL reconstruction. The portability and ease of use of the portable motion capture system add a high clinical value to what would otherwise have been appropriate for use in research only.

## Conflicts of interest

The authors have no conflicts of interest relevant to this article to declare.

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