

Research article

Alterations of kinetic characteristics in step up and over test in patients with anterior cruciate ligament deficiency

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Abstract

The purpose of this study is to investigate the alterations of kinetic characteristics in the step up/over test in patients with acute and chronic anterior cruciate ligament (ACL) deficiency. Twenty acute, twenty chronic ACL-deficient (ACLD) patients, and forty healthy controls participated in this study. The step up/over test was performed on a clinical force platform system to obtain the following variables: movement time, lift-up index and impact index. The percentages of the indexes from the stepping leg and time of step-up and swing-over were further calculated. These variables were examined statistically by using mixed repeated measure analysis of variance to reveal the differences between groups and between limbs. Smaller lift-up forces and longer swing-over time in both ACLD groups than those in the control group were found. One exception was the lift-up index in the affected side condition of the acute ACLD group, which was not significantly different from the controls. A reduced contribution to the impact index from the affected stepping leg was also found in the acute ACLD group. The acute ACLD group showed no significant change in their step-up strategy at the affected limbs, but they may have a poorer eccentric control of the affected knees on the step and thus put a larger portion of loading onto the unaffected landing leg. Our results indicated the lift-up index, swing-over time and load-distributing strategy at impact may be important parameters in monitoring functional recovery in patients with ACL deficiency. The detected alterations in these parameters could be used as a reference to design proper rehabilitation exercises for these patients.

Key words: Knee, ACL deficiency, kinetics, locomotion, step activity.

Introduction

Anterior cruciate ligament (ACL) plays an important role in maintaining anterior knee stability. However, it is unfortunately the most frequently injured structure of the knee joint, especially for sports persons (Noyes et al., 1980). Altered kinetics and kinematics in lower extremities during walking, running, cutting and stair climbing in patients with ACL deficiency have been observed, such as smaller knee extensor moments and flexion angle during stance. (Czerniecki et al., 1988; Berchuck et al., 1990; Patel et al., 2003; Thambayah et al., 2004; Waite et al., 2005). A study on the natural course of functional recovery after ACL rupture has suggested that returning to near normal levels in gait and hopping may take 5 months in average (Button et al., 2005). Nevertheless, the patients

with chronic ACL deficiency (with an injury duration of more than one year) have also been reported have impaired functional performances (Barber et al., 1990; Berchuck et al., 1990; Patel et al., 2003; Button et al., 2005; Lindstrom et al., 2010). Some of the altered functions were even suggested to be due to central adjustments of motor control (Gauffin et al., 1990). Therefore, patients with ACL deficiency could be further divided into copers, non-copers and adapters by functional outcomes (Button et al., 2006). The non-copers demonstrated significantly poorer performances than the copers in gait, hopping and step task (Rudolph et al., 2000; Rudolph and Snyder-Mackler, 2004; Button et al., 2008). These studies demonstrated that functional recovery for patients with ACL deficiency could be diverse and thus implied that careful monitoring of functional retraining was essential before returning to sport activities.

Researchers have discussed the musculoskeletal deficits that may lead to the alterations in functional activities in the patients with ACLD deficiency. The deficits included knee instability (Maitland et al., 1995), laxity during dynamic activities (Eastlack et al., 1999; Kvist, 2006), muscle strength adaptation (Rudolph et al., 2000; St Clair Gibson et al., 2000; Zhang et al., 2002; von Porat et al., 2006) and neuromuscular reprogramming (Rudolph and Snyder-Mackler, 2004). Functional tests were usually used to monitor the patients' recovery and the outcome of rehabilitation. One-leg hop test for distance was most commonly used to evaluate functional impairments in patients with ACL deficiency (Barber et al., 1990; Gauffin et al., 1990; Itoh et al., 1998; Rudolph et al., 2000). This test may be sensitive enough for evaluating lower limb functions (Itoh et al., 1998), but the movements may not be acceptable to all patients. For example, in Rusolph et al. study, 60% of non-copers would not consent to perform the hop test because of possible further damage (Rudolph et al., 2000).

Stepping up and down, another common test for evaluating lower limb functions, is less challenging and performed more frequently than hopping in daily life. It is also considered an important close kinetic chain exercise in the rehabilitation program after ACL injury (Risberg et al., 2004; Risberg et al., 2007), and has been proved to be effective in muscle strength enhancement (Tovin et al., 1994; Meyers et al., 2002) and also sensorimotor integration through motor learning (Ageberg, 2002). Stair locomotion involves coordination and inter-

action of bilateral legs, and understanding the controlled movements between legs would be helpful to perform the step activities correctly and efficiently. Rudolph and Snyder-Mackler investigated the kinetic and kinematic alterations in patients with ACL deficiency when stepping up and over a 26 cm step. They found larger hip flexion at the transition from step-up to step-down when comparing these patients with healthy controls (Rudolph and Snyder-Mackler, 2004). Similar experimental setup was used in the study of individuals with 16-year-old ACL injuries. The study showed no significant statistical differences between the ACL and control groups, but found larger variability of performances in patients with ACL deficiency (von Porat et al., 2006). The results supported the use of step activity in evaluating the recovery of the lower limb functions in individuals with ACL injuries. Both these studies used a motion capture system combined with a six-component force plate to obtain the joint kinematics and internal knee joint moments during the step activity (Rudolph and Snyder-Mackler, 2004; von Porat et al., 2006). Chmielewski et al. and Mattacola et al. used a computerized dynamic posturogram system to evaluate the performances of the step up/over test in both the acute ACL-deficient and ACL-reconstructed patients (Chmielewski et al., 2002; Mattacola et al., 2004). This system used a dual long force plate to measure vertical ground reaction forces, and provided outcome variables, such as lift-up index, impact index and movement time, immediately after testing. This clinical force platform system made the step test easily applicable and also understandable to the clinicians. The results of the previous studies also proved that the step test is sensitive to disability and thus is a promising test for rehabilitative and evaluative purposes.

Stepping up and over requires weight bearing and weight shifting between lower limbs (Rudolph and Snyder-Mackler, 2004). It is a closed kinetic chain activity involving both the movements at joints of each limb and the interaction between both limbs. Previous studies have demonstrated some changes in both affected and unaffected limbs of patients with ACL deficiency, but the contribution from individual leg in different phases of the stepping up/over activity has not been revealed (Chmielewski et al., 2002; Rudolph and Snyder-Mackler, 2004). In addition, the information regarding changes of kinetic characteristics in the step up/over test at different post-injury recovery stages is still limited. Therefore, the purpose of this study was to investigate the kinetic characteristics of the leading (stepping) and trailing (swing-over) legs during the step up/over test in patients with acute and chronic ACL deficiency. The first hypothesis of this study was that differences in the kinetic characteristics in performing step up/over test would be observed in different recovery stages of post-ACL injury group and in comparison to the control group. The second hypothesis was that the contribution from the affected and unaffected limbs of the ACL-deficient patients would be different by reducing the loading on the affected limb when performing stepping up/over activity.

Methods

Participants

Forty patients with ACL deficiency were recruited from the Department of Orthopedics of China Medical University Hospital. They were firstly physical examined by an experienced physician and diagnosed as unilateral ACL complete tear, and then further confirmed by either arthroscopic or MRI examination. Twelve months after ACL injury was used to divide these patients into the acute ($n = 20$) and chronic ACL-deficient (ACL D) groups ($n = 20$). Forty healthy volunteers were recruited from university campus as the control group. Participants with neuromuscular disorders in lower limb or low back, pain or injury over other ligaments of knee were excluded from this study. The participants signed the consent form after understanding the aim, procedures, potential risks and benefits of this study. This study has been approved by our Institutional Review Board.

Instrumentation and data acquisition

Basic data of each participant, including age, body weight, body height, body mass index (BMI) and post-injury duration, was collected upon enrollment. The Tegner activity level scale and the Lysholm score were also recorded to understand their activity level and subjective functional status. The step up/over test was performed on a 30-cm (12-inch) height wooden step placed in the middle of the long force platform of PRO Balance Master[®] (NeuroCom[®] International, Inc.). During the test, the force data from bilateral legs were sampled at 100 Hz and acquired by the PRO Balance Master[®].

Study design and testing procedures

Each participant in all subject groups first became familiar with the test by watching a video demonstration and performing several practice trials. The step up/over test began with the subject standing evenly in front of the step at a comfortable distance. When prompted by the "GO" signal, the subject started to step up onto the step with the leading leg (defined as the stepping leg), lift up the body, swing the trailing leg (defined as the swing-over leg) over to the platform, step the stepping leg down, and then stand steadily with both legs (Figure 1). The participant was asked to perform the task as quickly as possible and complete the movement showed in the video demonstration. Each leg led as the stepping leg and preformed for three times. By doing so, two conditions formed in the ACL groups as defined by which one was the stance leg: the affected and unaffected side conditions; and two conditions in the control group: the right and left side conditions.

Definitions of the kinetic and temporal variables

Three variables were calculated by the PRO Balance Master[®] system immediately after the test: lift-up index, impact index and movement time. The lift-up index was defined by the maximum lifting force exerted by both legs and defined as the force exceeding the individual's body weight (BW) expressed as a percentage of BW (%BW). The impact index was defined by the maximum vertical force transmitted through the legs as the swing-over leg landed on the surface and also defined as the force

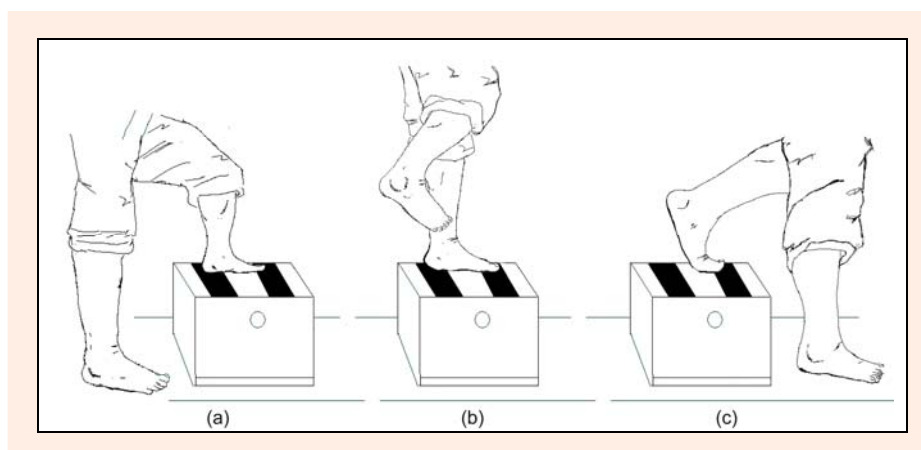


Figure 1. The step up/over test. **a)** step up with the stepping leg onto the step; **b)** swing the trailing leg (the swing-over leg) over the step; **c)** land the swing-over leg onto the platform.

exceeding the individual's BW expressed as a percentage of BW (%BW). The temporal variable, movement time, was the amount of time to complete the step-over and expressed in seconds, defined by the moments of movement initiation and the impact index occurrence (Figure 2). To understand the contribution from each leg in the step-up and the swing over phases, raw data from the dual long force plate of the PRO Balance Master[®] was exported and then analyzed off-line with a self-written MATLAB program (MathWorks, USA). The movement time was then divided further by the moment of lift-up into the time of step-up and swing-over (Figure 2). The contributions from the stepping and swing-over legs were also calculated at the lift-up and the impact (Figure 2), expressed as percentages of the maximum lift-up and impact forces from the stepping or swing-over legs.

Statistical analysis

The ANOVA was first used to compare the difference of demographic data between three groups. Those variables showed significant differences would be considered the covariance in following comparison between groups. The kinetic and temporal dependent variables were tested using mixed repeated measure analysis of variance (RM ANOVA) with one between-subject factor (group) and one within-subjects factor (bilateral limbs). If the significant difference showed in the ANOVA, these variables would be analyzed further by *post-hoc* test and paired t-test to reveal the differences between groups and between the unaffected and affected sides. The statistical significance was set at $p \leq 0.05$. All statistical analyses were performed using SPSS version 11.0 (Standard Version, SPSS Inc., Chicago, IL, USA).

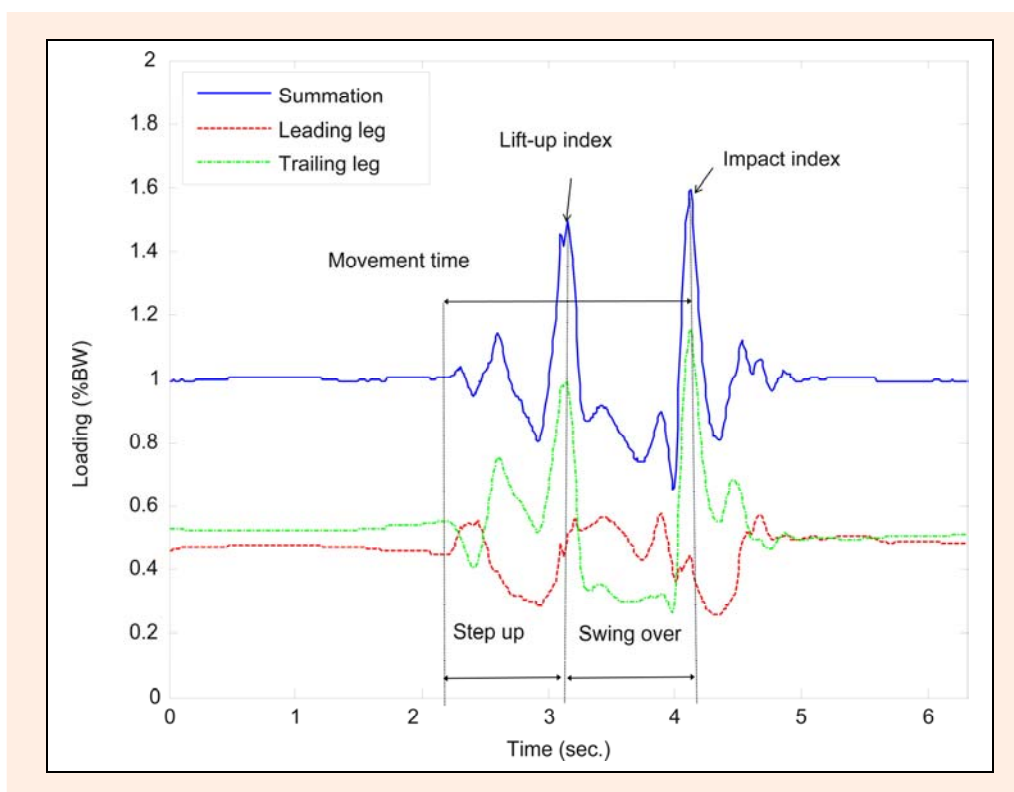


Figure 2. Normalized force data of a single trial in a healthy control subject.

Table 1. The descriptive data (mean (standard deviation)) of the subject groups.

	Control	ACLD			
		Acute		Chronic	
Gender, men/women, n	22/18	13/7		16/4	
Age, years	21.8 (4.2)	24.9 (6.7)		26.2 (6.5)	
Body height, m	1.66 (.08)	1.71 (.09)		1.73 (.07)	
Body weight, kg	64.6 (13.6)	71.3 (15.8)		69.5 (11.8)	
BMI, kg/m ²	22.6 (5.27)	24.0 (4.0)		23.2 (3.1)	
Post-injury duration, months	-	4.0 (2.9)		60.0 (72.2)	
Lysholm score [range]	100	68 (14) [42-94]		65 (18) [36-98]	
		Before injury	After injury	Before injury	After injury
Tegner activity level scale [range]	6 (3) [1-9]	6 (3) [2-9]	2 (2) [1-7]	8 (2) [1-9]	4 (3) [1-8]

Results

Demographics

Most of the demographic data was similar between these subject groups (Table 1). The age of the control group was younger than that of the chronic ACLD group ($p = 0.02$), and the body height of the control group was shorter than those of the acute and chronic ACLD groups ($p = 0.03$ and 0.02). These two variables were therefore considered covariate in the following statistical analysis.

Functional scores and activity levels

No significant difference ($p = 0.48$) existed between the acute and chronic ACLD groups in the Lysholm score with the median at 69 (range: 42-94) and 62 (range: 36-98) respectively, but the scores were significantly smaller when compared with the controls. The Tegner activity level scales showed that most of the patients with ACL deficiency exercised regularly before injury but not afterwards (Table 1).

Temporal variables

In the control group, the comparisons of the dependent variables between left and right side conditions showed no significant differences, and thus the average of the variables of both legs was used to compare with those of the ACL groups. The RM ANOVA tests showed statistical main effects among groups in movement time ($p = 0.006$) and time of swing-over ($p=0.003$). The *post hoc* tests revealed that the control group had shorter movement time (1.47 ± 0.30 sec) than both the acute and chronic ACLD groups with both the unaffected (1.80 ± 0.45 and 1.80 ± 0.34 sec) and affected side conditions (1.69 ± 0.46 and 1.70 ± 0.30 sec in acute and chronic ACLD groups) (Figure 3a). Looking further into the movement time, same results were found for the time of swing-over (Figure 3c) but there was no significant difference for the time of step-up (Figure 3b).

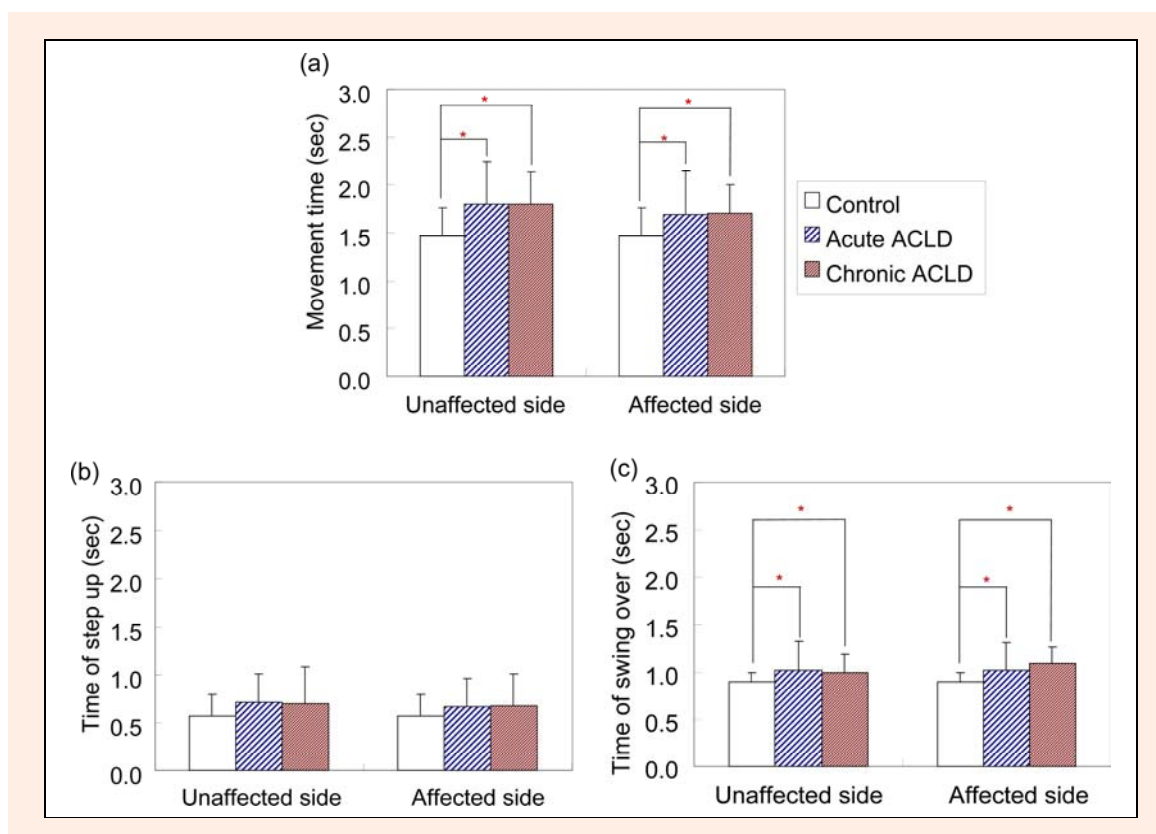


Figure 3. a) Mean movement time; b) mean time of step-up; c) mean time of swing-over in the unaffected side and affected side conditions of the control group, acute and chronic ACLD groups. * $p < 0.05$.

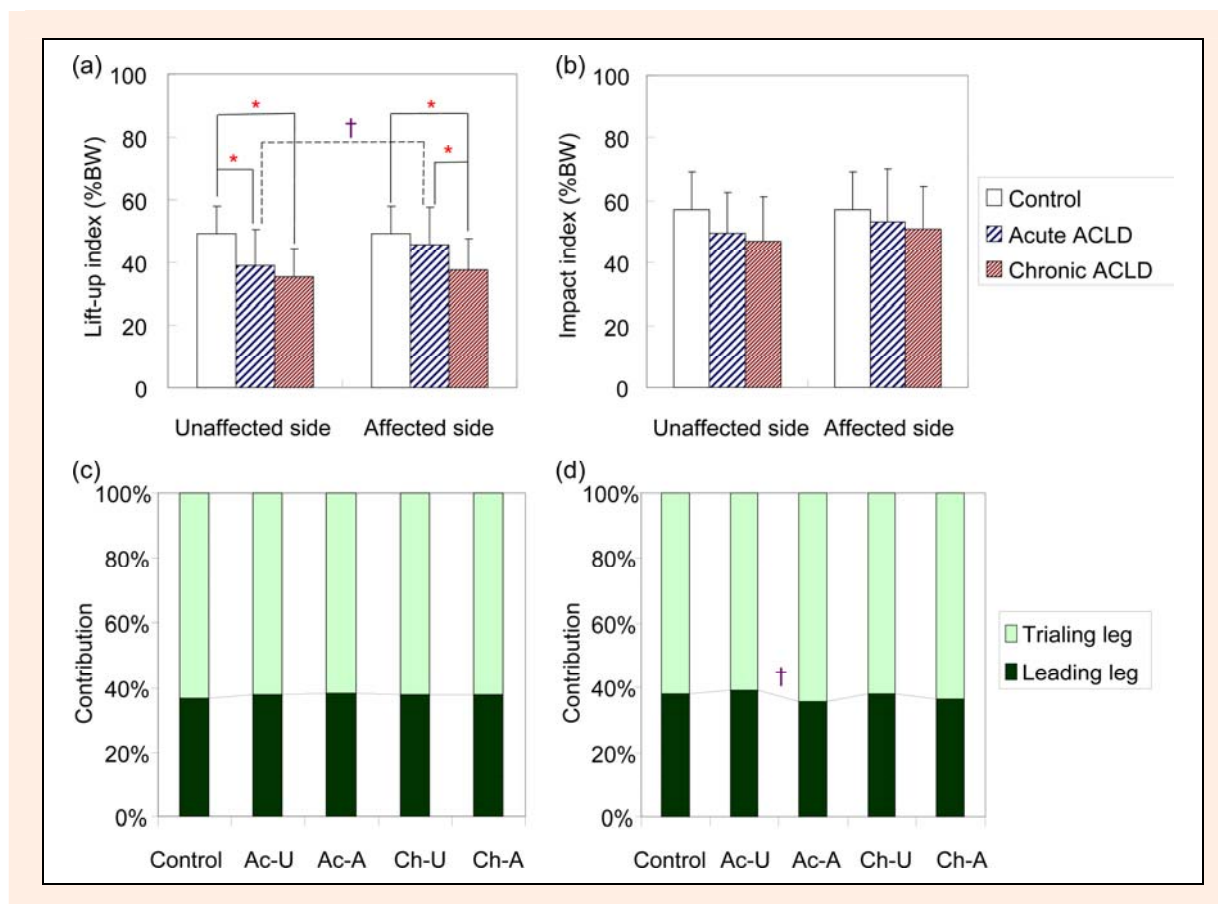


Figure 4. a) Mean lift-up index; b) mean impact index in the unaffected side and affected side conditions of the normal control group, acute and chronic ACLD groups. c) Contribution to the lift-up index; d) contribution to the impact index of bilateral legs in the normal control and both ACLD groups. The abbreviation legend: Ac-U: acute ACLD group in the unaffected side condition; Ac-A: acute ACLD group with affected side condition; Ch-U: chronic ACLD group with unaffected side condition; Ch-A: chronic ACLD group with affected side condition. *: $p < 0.05$ in ANOVA; †: $p < 0.05$ in paired t-test.

Kinetic variables

The RM ANOVA tests showed statistical main effects among groups in lift-up index ($p < 0.001$), and a group \times limb interaction was also found in lift-up index ($p < 0.001$). The *post hoc* tests also showed that the lift-up index in the control group (49.4 ± 8.8 %BW) was significantly larger than that in unaffected condition of the acute ACLD group (38.8 ± 11.8 %BW) ($p < 0.001$) and that in both conditions of the chronic ACLD group (35.3 ± 9.0 and 37.6 ± 10.0 %BW in unaffected and affected side conditions) ($p < 0.001$). The lift-up index in the affected side condition of the acute ACLD group (45.8 ± 12.1 %BW) was not significantly different from the controls, but it was significantly larger than that of the chronic ACLD group (35.3 ± 9.0 %BW) ($p = 0.03$) (Figure 4a). When comparing within the acute ACLD group, the affected side condition had a significantly larger lift-up index (45.8 ± 12.1 %BW) than the unaffected side condition (38.8 ± 11.8 %BW) ($p = 0.002$). No statistical significance was found in the impact index (Figure 4b).

Load distribution between legs

The RM ANOVA tests showed no statistical main effects among groups in percentages of lift-up and impact indexes ($p = 0.04$ and 1.00 respectively), but a group \times limb interaction was found in the percentage of impact index ($p = 0.01$). The contribution of the lift-up index from the

stepping and swing-over legs showed a consistent pattern of a larger portion coming from the swing-over leg in all groups. In addition, no significant difference was found in the comparison between limb conditions or between groups (Figure 4c). Similar contribution pattern for the impact index was demonstrated, but there was altered contribution in the acute ACLD group with a smaller percentage (35.6 ± 4.8 %) when leading (stepping) with the affected limb than with the unaffected limb (39.2 ± 5.4 %) (Figure 4d).

Discussion

This study aimed to investigate the kinetic changes in performing the step up/over test in patients with acute and chronic ACL deficiency. This test was performed on the clinical force platform system and several temporal and kinetic parameters from the system were obtained to represent general performances in different subject groups. The control subjects had comparable mean value in movement time (1.47 ± 0.30 sec) with those in previous studies (Chmielewski et al., 2002; Mattacola et al., 2004). One of the previous studies did not find significant difference in movement time between the acute ACLD group and control group (1.49 ± 0.24 sec), but slightly longer movement time (1.63 ± 0.29 sec) in the unaffected side condition (Chmielewski et al., 2002). Our ACLD partici-

pants used slightly more time in both affected and unaffected side conditions (1.70 ± 0.38 sec and 1.80 ± 0.39 sec respectively) than the finding in the previous study and also demonstrated significantly longer when compared with the control group (Figure 3a). These results indicated that our ACLD participants may be more conservative in performing strenuous activities than those in the previous study. Moreover, the decreases in exercise participation and functional score for these patients after ACL rupture showed that the injury caused significant impacts on their sport-related and functional abilities. The step up/over test involved the activities used frequently in daily life and can be used to evaluate the functional ability for patients with lower limb pathology. Unlike hopping or running that may involve patients' maximal exertion, the step up/over test is simpler and less risky for patients with ACL deficiency. To perform stepping up/over, it was essential to have skilled control of weight shifting between limbs and to have sufficient muscle strength in concentric and eccentric contractions. The longer movement time in both acute and chronic ACL groups suggested that the adaptation may occur soon after ACL injury. The difference in movement time resulted mostly from the slower swing-over suggested that the adaptation strategy could be different in the step-up and swing-over during the step up/over activity. This study demonstrated certain altered characteristics in the different parts of the step up/over test for these patients. Therefore, in this study, the test was divided into two phases to discuss the different functional alterations. Additional parameters from the ground reaction force data were extracted to understand the composition of this task and the kinetic contribution from each leg.

In the first phase, the step-up required sufficient concentric forces generated from the legs in order to lift and transfer the body up and onto the step effectively. A larger lift-up index was found in the control group when compared with the ACLD groups, except in the affected side condition of the acute ACLD group. The lift-up index in the affected side condition of the acute ACLD group was larger than that in their own unaffected side condition and also larger than that of the chronic ACLD group (Figure 4a). Interestingly, the only similar lift-up index was found in the affected side condition of the acute ACLD group when compared with the controls. Studies have shown that the ACL would bear significantly larger strain and forces when the knee was in flexion around 10 to 40 degrees than in flexion greater than 50 degrees during rehabilitation exercises (Beynon et al., 1995; Toutoungi et al., 2000). The step activity required the stepping leg to flex the knee to about 50 degrees (von Porat et al., 2006), and thus would not cause the instability of the ACLD knees. On the other hand, the swing-over leg would be in a relatively extended position, which may easily cause the instability of the ACLD knee. This may explain why the affected stepping legs in the acute ACLD group could bear similar loads to those on the healthy legs in the control group, but the loads on the affected swing-over legs would be reduced.

The similar contribution pattern of the lift-up index between the control and ACLD groups suggested that these patients may use the same weight-transferring strat-

egy during their step-up after injury. Nevertheless, this study demonstrated an interesting result that larger contribution came from the trailing (swing-over) limb for all participants. At the moment of lift-up, when the maximum vertical forces were generated, the body was lifted and the body weight was transferred rapidly with a larger contribution from the trailing (swing-over) leg on the ground rather than the leading (stepping) leg on the step. Kvist et al. (2006) found greater tibial translation at the ACL-injured knees than at the uninjured knees simply by performing body weight shifting exercises. The weight acceptance on the leg in the front would require quadriceps contraction in order to provide stability and control of the knee movements, and thus may increase the tibial translation. Therefore, the patients with ACL deficiency were expected to adjust their movement strategy to obtain a stable knee. Our results indicated the ACLD participants may not change their strategy of loading the stepping and swing-over limbs; rather, they would generally decrease the supporting forces (Figure 4a) and slow the movement pace which was demonstrated in their longer movement time (Figure 3a).

In the second phase, the stepping leg on the step would control the body and let the swing-over leg swing over and land on the ground. Sufficient eccentric contraction of the quadriceps in the stepping leg would be required to descend the body. However, the patients with ACL deficiency were reported to have muscle strength deficit in eccentric contraction (Kvist et al., 2001) and larger anterior knee translation during eccentric contraction of quadriceps (St Clair Gibson et al., 2000). The results of this study indicated that the ACLD participants would spend more time completing this step task than the control group, and the difference occurred mainly in the swing-over phase (Figure 3). The result may be explained by the deficit of eccentric quadriceps strength and also the alteration of their kinematic strategy. In the previous study, the stepping legs on the step showed larger hip flexion angles at the top of swing-over in the ACLD participants than those in the control subjects (Rudolph et al., 2000). The strategy of increased hip flexion in swing-over may put the hamstrings at a better mechanical advantage and thus provide a balancing force to the tibia during a strong quadriceps contraction. The flexed position of the hip may also result in more excursions at knee and hip joints to complete the step task and lead to longer movement time.

However, slower swing-over did not necessarily lead to a smaller impact index. No significant difference was found in the impact indexes between groups or between limbs (Figure 4b). The study on the patients with an average of 1.5-month ACL injury showed larger impact indexes in both affected side (78.1 ± 27.9 %BW) and unaffected side conditions (69.9 ± 19.5 %BW) than those in the control group (52.7 ± 16.2 %BW) (Chmielewski et al., 2002). However, in another study on patients with older ACL injuries, similar vertical impact forces when landing on both affected (66 ± 15 %BW) and unaffected legs (66 ± 18 %BW) with the control subjects (59 ± 17 %BW) were shown (von Porat et al., 2006). Compared with the previous studies, our control subjects showed a similar value of impact index (57.2 ± 11.9 %BW) and the

ACLD groups showed a similar or slightly smaller impact index (Figure 4b). The swing-over leg demonstrated consistently a larger portion in the contribution to the impact index, indicating the acceptance of the majority of the proceeding and descending body weight when swung over to the ground. The acute ACLD group showed a significant difference in load-distributing strategy between limbs. A smaller percentage from the stepping limb in the affected side condition was observed than in the unaffected side condition (Figure 4d). The results indicated that the acute ACLD participants may have a poorer eccentric control of the affected knees on the step and were forced to put a larger portion of loading onto the unaffected landing leg. The results in this study suggested the retraining of the eccentric muscle strength in a fast weight-transferring fashion during dynamic exercises should be emphasized for the recovery of their functional abilities for the patients with acute ACL deficiency.

One limitation of this study was the selection of participants. Unmatched age, height and gender between groups were found, but using the analysis of covariate reduced the effects of these inequalities on the results. Another limitation is that we did not conduct any kinematic measures or do inverse dynamics calculation because of the instrument and space restraint. This study aimed to explore the feasibility of getting more information by using the clinical forceplate system. The results of this study showed reduced lift-up index and longer swing-over duration in performing the step up and over activity in the acute and chronic ACLD groups. A reduced loading contribution on the acute affected limb when stepping down with unaffected limb was also demonstrated. The changes in the kinetic and temporal variables found in this study helped understanding the adaptation strategy of performing the step tasks in these patients. The limitation of the cross sectional study design due to the difficulty in long-term follow-up with the patients with ACL rupture made it difficult to directly correlate the results to the rehabilitation effects. However, the alterations found in this study for the patients in different recovery stages could still be used as a reference of instructing or designing appropriate treatments. In future study, a force feedback system can be developed to provide real-time force and center of pressure information during performing the dynamic strength trainings. Hopefully, a more efficient and correct movement pattern could be adopted during the retraining for the patients with ACL deficiency.

Conclusion

The results of this study demonstrated the kinetic changes in the patients with acute and chronic ACL deficiency. The major changes in the step up/over test were shown in the lift-up index and the time of swing-over. Alteration of load-distributing strategy between limbs was found only in the acute ACLD group when descending from the step. Therefore, the lift-up index, the time of swing-over and load-distributing strategy at impact could be important parameters in indentifying functional impairments for patients with ACL deficiency. This study confirmed that the step test on the clinical force platform system could provide information in the recovery of the functional

ability of the lower limb. The detected changes in these parameters could be used as a reference to design proper rehabilitation exercises for the patients with ACL deficiency.

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Key points

- The lift-up index and the time of swing-over could be important parameters for indentifying functional impairments in patients with ACL deficiency.
- The differences between limbs were found only in the acute ACLD group with a larger lift-up index and smaller load-distribution at impact on the affected limb.
- The step up/over test on the clinical force platform system could be helpful in providing a reference to design proper rehabilitation exercise and to monitor the recovery of the functional ability in patients with ACL deficiency.

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