Revised #1

Bilateral Changes in Ground Reaction Forces in Patients with Unilateral Anterior Cruciate Ligament Deficiency during Stair Locomotion

Hsiu-Chen Lin[1,2], Horng-Chaung Hsu[3], Tung-Wu Lu[1,*]

[1] Institute of Biomedical Engineering, National Taiwan University, Taipei, Taiwan.

[2] Department of Physical Therapy, China Medical University, Taichung, Taiwan.

[3] Department of Orthopedics, China Medical University Hospital, Taichung, Taiwan.

Running title: GRF during stair locomotion in ACL-deficient patients

Word Count: 4067

Submitted to *Journal of Mechanics*

June 2010

Key Words: Ground reaction force; Anterior cruciate ligament deficiency, Stair locomotion

Address for correspondence:
Dr. Tung-Wu Lu, Institute of Biomedical Engineering, National Taiwan University, No. 1, Sec. 1, Jen-Ai Road, Taipei 100, Taiwan, R.O.C.
Tel: (02)33653335, E-mail: twlu@ntu.edu.tw

Abstract

Stair locomotion is an important but challenging functional activity for people with lower limb pathology. This study aimed to investigate the bilateral changes in force-bearing on lower limbs during stair locomotion in patients with unilateral ACL deficiency. The ground reaction forces (GRF) were collected from three force platforms: one at ground level in front of a 5-step stair and two on the first two steps respectively. Parameters in vertical and anterior-posterior GRF were extracted and compared between the ACL-deficient (ACLD) and control groups. The ACLD group showed significantly slower stepping cadences in both stair ascent and stepping down to the ground (p<0.05). The vertical GRF in the ACLD group demonstrated smaller peak forces but larger minimum forces between the two peaks than those in the control group during both stair ascent and descent. Significantly reduced anterior propulsive forces and push-off rates in the late stance were also found in both limbs of the ACLD group (p<0.05). The slower cadences and reduced force-bearing on the affected limb suggested a protective strategy was adopted. However, the anterior loading parameters in the early stance on the unaffected limb demonstrated different adaptations with significantly larger magnitudes during stair ascent but reduced magnitudes during stair descent (p<0.05). Similar results were also found in the weight-transferring strategies between legs in consecutive steps with a significantly larger percentage of lift-up forces but a smaller percentage of impact forces on the leading unaffected limb. The results of this study indicated a cautious force-bearing strategy and bilateral adaptation were apparent in the patients with unilateral ACL deficiency. This information may provide a safety guideline for the patients and be helpful for a better use of the stair tasks as part of a rehabilitation program.

Keywords: Ground reaction force; Anterior cruciate ligament deficiency, Stair locomotion

1. Introduction

Stair locomotion is an important and common functional activity in daily life; however, it is also a hazardous activity for some populations such as older people or people with lower limb pathology. Gait analysis of stair locomotion in healthy young adults [1-4] and older individuals [5, 6] have been reported. Stair walking was shown to be more challenging and demanding than level walking [5, 7, 8]. The elderly tend to take safer strategies to negotiate with stairs than the young adults [7]. Moreover, relatively higher motor capabilities were required in stair walking because of the decline in physical capacities in the elderly [9]. The physical capacities of people with lower extremity pathology may also be compromised. Studies have demonstrated several altered movement patterns during stair walking in those patients [10-13]. Stair locomotion was therefore frequently regarded as a practical testing to reveal their functional impairments [14, 15], and also used in clinics as one of the rehabilitation exercises to restore their functional ability [16].

Stair locomotion involves progressing and ascending or descending the body to a new level, and thus requires bearing more muscle forces on the lower limbs. The propulsion of the body center of mass in upward and forward directions is associated directly with the vertical and propulsive (anterior) ground reaction forces (GRF) respectively. Though the GRF pattern in stair locomotion preserved most of the features in level walking, the magnitudes of the anterior-posterior GRF were considerably larger during level walking [17]. Moreover, a two-peak pattern of vertical GRF demonstrated larger peak in the late stance of stair ascent to push the body upward, while larger peak in the early stance of stair descent to support the downward body [4, 17]. The vertical GRF in braking phase in stair descent was 32.5% higher than seen in level walking in the asymptomatic older subjects with knee osteoarthritis. Their loading rate of stair descent was also significantly faster than in level walking [18]. The loading rate indicated the impulsive nature of the ground reaction force to the lower limb. A faster loading rate indicated larger impulses that may correlated to the degenerative changes of the weight-bearing joint. With the decline in physical capacities, the elderly would prefer a slower velocity in stair negotiation and thus demonstrated lower peak forces and slower loading rates [6]. The patients after knee arthroplasty demonstrated significantly smaller peak vertical GRF in stair ascent, and greater bilateral asymmetry in limb loading in stair descent when comparing with healthy controls [19].

Individuals with ACL injury would find stair descending more difficult because of the inability to bear anterior shear forces. Shear components of the knee contact forces were considered especially important for the stability of the joint during rehabilitation after ligament reconstruction and total knee replacement surgery.

Studies reported that the tibio-femoral forces during stair climbing were larger than those during walking, and the corresponding shear forces were 2 times more than those during walking. [20]. In comparison of normal stair ascent and descent, the resultant forces at the knee joint showed larger anterior shear forces in the late stance of stair descent [3]. The force-bearing on the structures around the knee joint showed significantly higher peak patellar tendon forces, peak flexor forces, posterior cruciate ligament (PCL) forces and joint surface contact forces during stair ascent. In contrast, a tendency of higher forces on the anterior cruciate ligament (ACL) was demonstrated during stair descent. These suggested that one should be cautious when using stair ascent and descent as a rehabilitation exercise on patients with injuries or diseases of the cruciate ligaments and articular surfaces [21].

When performing the step up and over activity, weight-bearing would change significantly in the early stage after ACL injury or reconstruction [22]. Patients with ACL deficiencies developed gait adaptations during stair ascent by reducing peak external flexion moments and also decreasing vertical GRF [13]. These studies showed that measures deriving from ground reaction forces provided an informative means of quantifying the deviations in limb loading in stair locomotion. The primary function of the ACL is the restraint on the anterior instability of the knee joint, but the information about anterior-posterior GRF is limited. Moreover, the comprehensive information about the bilateral adaptations in load-bearing during stair locomotion in the patients with ACL deficiency was still limited. The purpose of this study is to investigate the bilateral changes of GRF parameters during both stair ascent and descent in the patients with unilateral ACL deficiency.

2. Methods

2.1. Subjects

Two subject groups were enrolled in this study. Twenty patients (12 male, 8 female) with ACL deficiency were recruited from the Department of Orthopedics of China Medical University Hospital. They were diagnosed as unilateral ACL complete tear confirmed by either arthroscopic or MRI examination. The control group consisted of fourteen young healthy collegiate students (10 male, 4 female). Those with neuromuscular disorders in lower limb or low back, pain or injury over other ligaments of knee were excluded from this study. The sample size was determined by a power analysis for analysis of variance (ANOVA) with a power of 0.8 and a large effect size (f = 0.5). The study was approved by the Ethics committee at the China Medical University Hospital. All participants signed the consent form after understanding the aim, procedures, potential risks and benefits of this study. 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 [23] and the Lysholm score [24] were also recorded to understand their activity level and subjective functional status. These descriptive data for each group were listed in Table 1.

2.2. Experiment setup and testing procedures

A 5-step wooden staircase with a dimension of 18 × 40 × 120 cm (height × depth × width) for each step was created especially for this study. The staircase was placed in front of two force plates (AMTI OR6-5, Watertown, MA, USA) which were mounted on the ground as FP#0. Two other force plates (Kistler 9286AA, Winterthur, Switzerland) were integrated into the staircase on the first two steps from the ground as FP#1 and FP#2 (Figure 1). The GRF signals were collected at 960Hz via the amplifier and integrated into a VICON workstation (VICON, Oxford Metrics, UK). The subject was asked to walk toward the stair, climb up the step to the top at his or her comfortable speed as a stair ascent trial, and step down to the ground and walk away as a stair descent trial. For each participant and each test condition, both legs would take turns to lead and a total of six successful trials, three for each leg, were obtained for subsequent analysis.

2.3. Definition of GRF parameters

The GRF signals from all force plates were recorded and normalized with the individual’s body weight in order to allow for comparisons between subjects of different body weights. The vertical and anterior-posterior components of the GRF were further analyzed to extract important parameters by using a custom MATLAB program. The detected parameters in vertical components included the peak forces in the first and second halves of the stance (Fz2 and Fz4), minimum forces between these two peaks (Fz3), loading rate at the beginning (Bn), and unloading rate at the end (En) of the stance phase (Figure 2A). The loading rate was calculated as the magnitude of 80% of the first peak force (Fz2) divided by the time during which it occurred. The unloading rate was calculated as the magnitude of the second peak force reduced to 80% of the second peak force (Fz4) divided by the time from that point until the end of the stance [9]. To understand the weight-transferring strategy between legs, the vertical forces from two consecutive steps were further analyzed. The maximal summation of the vertical lifting forces exerted by the legs during stepping up was defined as the lift-up index (LUI). The maximal summation of the vertical forces transmitted through the legs when the leading leg landed on the surface of the lower step was defined as the impact index (IPI) [22] (Figure 2B). The percentages of the lift-up and impact indexes (expressed as %LUI and %IPI respectively) on the leading leg were also calculated to show the contribution from each leg. The higher the percentage, the larger the contribution of the maximum forces on the leading leg at the lift-up or the impact. In the anterior-posterior component of the GRF, the peak forces in the first and second halves of the stance (Fx2 and Fx4), and the loading and push-off rates (LRx and PRx) were also extracted (Figure 2A). The loading rate was defined as the slope from the beginning of the stance to the first peak force (Fx2), and the push-off rate is the slope from the second peak force (Fx4) to the end of the stance. Besides these force parameters, the walking speed was indicated by the cadence of each leg, defined by the inverse of the time to complete a step cycle and expressed as strides per minute. The duty factor was defined by calculating the percentage of the duration of stance phase in the entire step cycle [6].

2.4. Statistical analysis

These detected force and temporal variables were tested by using a mixed and repeated measure analysis of variance (RM ANOVA) with one between-subject factor (groups) and two within-subject factor (bilateral limbs and different steps). However, similar patterns in the left and right legs of the control group were demonstrated and thus the average of the variables of both legs was used to compare with those of the ACL deficient (ACLD) group. Significant effects of different steps were found in most dependent variables, so the data from different steps were analyzed separately. The *post-hoc* tests were performed on those variables where significance was found between groups, and the paired t-test where significance was found between the bilateral limbs. The statistical significance was set at 0.05. All statistical analyses were performed using SPSS software (Chicago, IL, USA).

3. Results

3.1. Vertical ground reaction forces

The pattern of two-peak vertical GRF was observed in the stance phases both during the stair ascent and decent. However, among these two peaks, relatively larger peak (Fz4) in the late stance during stair ascent and relatively larger peak (Fz2) in the early stance during stair descent were demonstrated across all step levels (Figure 3A). During stair ascent, the maximal peaks (Fz2 and Fz4), loading and unloading rates (Bn and En) at the ground level (FP#0) were significantly smaller on both limbs of the ACLD group than the control group, except for the second peak on the unaffected limb. Similar results were found only in the affected limb of the ACLD group at the first step (FP#1). The differences were no longer significant at the peak forces compared between groups at the second step (FP#2). Significantly smaller peaks were found only in the affected limb compared with the unaffected limb of the ACLD group. In contrast, the minimum forces between two peaks (Fz3) were significantly larger on both the unaffected and affected limbs during the mid-stance in the ACLD group than those in the control group at all three step levels, except for the unaffected limb at the first step (FP#1). During stair descent, significantly smaller first peaks (Fz2) and loading rates (Bn) in the unaffected limb of the ACLD group at all three levels and larger second peaks (Fz4) on the affected limb on stairs were found than in the affected limb and those in control group. Additionally, comparing with the control group, the Fz3 were significantly larger on both the unaffected and affected limbs of the ACLD group on the stairs (FP#1 and FP#2) (Figure 3B).

3.2 Anterior-posterior ground reaction forces

Lager magnitudes of the anterior-posterior ground reaction forces were observed during stair descent than during stair ascent (Figure 4). In the early stance of stair ascent, the unaffected limb of the ACLD group showed larger posterior loading forces (Fx2) on stairs (FP#1 and FP#2) when compared with the control group. The affected limb of the ACLD group demonstrated significantly smaller Fx2 and loading rate (LRx) at the ground level (FP#0) when compared with the control group. Similar results in the affected limb were found at all three steps when compared with the unaffected limb. In the late stance, smaller anterior push-off forces (Fx4) on stairs and smaller push-off rates (PRx) at all three steps were found in both limbs of the ACLD group (Figure 4A). During stair descent, the unaffected limb of the ACLD group demonstrated significantly smaller Fx2 and LRx in the early stance on stairs (FP#2 and FP#1) than the affected limb and the control group. Smaller Fx4 and PRx in both the unaffected and affected limbs than those in the control group were demonstrated mainly during the transition from the stair to the ground in the late stance (Figure 4B).

3.3 Weight transferring between consecutive steps

During stair ascent, the lift up indexes (LUI) were significantly smaller in both the affected and unaffected limbs of the ACLD group than those in the control group. However, no significant differences between groups were found in the impact indexes (IPI) during stair descent, except for the unaffected limb landing on the first step (FP#1) (Figure 5A). The changes of the weight-transferring strategy between the consecutive steps were evident in the unaffected limb of the ACLD group with a larger percentage of the lift up indexes (%LUI) during stair ascent and a smaller percentage of the impact indexes (%IPI) during stair descent (Figure 5B).

3.4 Cadence and Duty Factor

During stair ascent, lower cadences were found in both legs of the ACLD group than in the control group. From the ground (step#0) to the second step of the staircase (step#2), the unaffected limb of the ACLD group would have a longer stance phase when compared with the affected limb and with the control group. During stair descent, both the affected and unaffected limbs of the ACLD group showed a lower cadence from step#2 to the ground (step#0) than the control group. A longer stance phase was found from the third (step#3) to the first step (step#1) in the affected limb of ACLD group when compared with the control group (Table 2). The ACLD group demonstrated longer stance phase than the control group during the transition between ground level (step#0) and the second step (step#2) in both stair ascent and descent.

4. Discussion

This study aimed to investigate the bilateral changes in force-bearing on the lower limbs during stair walking in the patients with unilateral ACL deficiency. The vertical and anterior-posterior components of the GRF were analyzed and compared with the control subjects. The patterns of two-peak vertical GRF demonstrated a larger peak in the early stance during stair descent while a larger peak in the late stance during stair ascent, which was consistent with the results in the previous study [4]. However, most GRF parameters in the both limbs of the patients with ACL deficiency were found significantly different from the healthy controls.

The patients with ACL deficiency negotiated with stair climbing by changing to a lower cadence. A less duty factor of the stance phase was also demonstrated in the affected limb of the ACL group at the initial steps from the ground level (Table 2).

The analysis of vertical GRF also revealed smaller maximal peaks, loading rates and lift-up indexes in both the unaffected and affected limb of ACLD group during the initial steps in stair ascent (Figure 3A and 5A). The initial steps indicated the transition from the ground to the stair, when sufficient lifting forces from the anti-gravity muscles in the lower legs were generated to produce the upward acceleration of the body. However, muscle strength deficits were frequently seen in these patients. A study has reported that there was 12%-17% quadriceps strength deficit in patients with chronic ACL deficiency [25]. The decreases in Fz2 and slower cadence may also be related to the reduction in peak knee flexion moment found in the involved knee of the patients with ACL deficiency during stair climbing [13]. Therefore, the above responses in the ACLD group may result from a cautious strategy for the knee instability and from possible decreased muscle functions. The smaller maximal peaks may also be related to the slower cadence; however, the larger minimum forces between two peaks (Fz3) were found in both the affected and unaffected limbs of the ACLD group than those in the control group. This may be caused by the slower walking speed and may also indicate larger leg stiffness in both limbs of the ACLD group during the mid-stance. Similar findings were also reported by a previous study in older adults performing stair ascent. Their results of the myoelectric information showed elevated thigh muscle coactivation in the entire stance phase in elderly subjects [6]. Therefore, similar strategy to increase leg stiffness could be expected in our ACLD subjects to provide compensation for the instability of the knee joint.

During stair descent, the cadences were not changed significantly on the stairs but they slowed down when reaching to the ground with either limb of the ACLD subjects (Table 2). These results indicated that patients with ACL deficiency would slow their paces when stepping down to the ground when the descending momentum had to be braked during this transitional step. The slower cadence suggested a slower walking speed, which was consistent with the longer movement time found in the step up and over task in the patients with ACL deficiency [22]. The duty factor on the stairs was significantly increased only in the affected limb of the ACLD group, which may indicate its poorer eccentric control in lowering the body. This result could also be further supported by the smaller Fz2 in vertical GRF on the unaffected limb in all steps (Figure 3B). The smaller differences between Fz2 and Fz3 were also evident during stair descent in both limbs of the ACLD group. A study has demonstrated that the abruptly increased stiffness of the knee and lower legs on landing in a forward hop landing task may be related to the weaker thigh musculature [26].

The larger magnitudes of the GRF parameters during stair descent than during stair ascent supported the responses in ACL-deficient patients who would find it more challenging to perform stair descent than ascent. During stair ascent, significantly reduced magnitudes of the GRF parameters in the affected limb of the ACLD group were found in the late stance (Figure 3A and 4A). An in vitro study on the restraining role of the ACL during stair ascent indicated that it was significant only during the late stance, not during the early and middle segments of the stance phase [27]. In the late stance, the trailing limb would be at a more flexed position, therefore, the smaller propelling force on the affected limb could decreased the anterior shear forces at the affected knee. Meanwhile, larger magnitudes of the GRF parameters in the early stance (Figure 3A and 4A) and a larger percentage of the LUI (Figure 5B) were found in the unaffected limb. These results indicated that the patients with unilateral ACL deficiency reduced forces on the trailing affected limb successfully by transferring the loading to the leading unaffected limb. However, the relative reductions on the affected limb were not found during stair descent. Moreover, significantly larger magnitudes of the GRF parameters were found in both early and late stance phases in the affected limb than in the unaffected limb (Figure 3B and 4B). The reduced percentage of IPI in the leading unaffected limb (Figure 5B) and the longer duty factor in the affected limb during stair descent (Table 2) further confirmed the difficulties in lowering the body on the trailing affected limb in a well-controlled way. These results indicated that the adaptation made by these patients failed to reduce force-bearing in the affected limbs and thus may increase the risks when performing stair descent.

The significant changes of the percentages of LUI and IPI occurred only in the unaffected limbs of the ACL subjects (Figure 5B), which may indicate the bilateral adaptation to the ACL injury and lead to changes in the weight-transferring strategy. The results of increases in %LUI but decreases in %IPI in the leading unaffected limb may also suggest different adaptations in the motor strategy for the instability of the affected knees during stair ascent and descent. Studies have shown that the ACL would bear significantly larger strains and forces when the knee was in flexion around 10 to 40 degrees than in flexion greater than 50 degrees during rehabilitation exercises [28, 29]. Therefore, when leading with the unaffected limb in stair ascent, a larger percentage of LUI indicated that less forces would be applied to the affected limb when the knee was in a near extension position. On the other hand, a smaller percentage of IPI when leading with the unaffected limb in stair descent indicated that larger forces would be applied to the affected limb when the knee was in a flexed position. Modifications of the central somatosensory pathways caused by ACL lesions have been reported, and these modifications encouraged an alternate synergy that could minimize the instability and optimizes the functional level in situations that challenge knee stability [30].

In computerized three-dimensional motion analysis, the integration of multiple cameras and forceplates systems is required, followed by complicated preparation of the subjects and experimental procedures. The method used in the current study is relatively simple and convenient, and can be applied to study various movements of patients in a clinical setting. This study investigated the GRF parameters during stair locomotion and demonstrated the adaptations on bilateral lower limbs in patients with unilateral ACL deficiency. These patients were found to adopt a more cautious strategy during both stair ascent and decent, with smaller GRF and reduced cadence than the healthy controls. However, when compared to the unaffected limb, the affected limb was found to bear greater loadings during descent, indicating that the observed strategy was successful in protecting the affected limb during ascent but not during descent. Since stair locomotion is a common daily activity, the results of this study may provide a safety guideline for these patients when performing the task and may be helpful in promoting the use of the stair tasks as part of a rehabilitation program. One limitation of this study is that we used only one dimension of the staircase, and the influence of different inclinations could not be discussed. However, the GRF parameters and temporal gait cycle parameters were shown not significantly affected by the staircase inclination in healthy subjects [17]. Another limitation is that there is no electromyographic and kinematic information to validate the effects of the muscle coactivation on the knee stiffness changes. The detailed myoelectic and joint kinematic information from the lower limbs and the control of the body center of mass could be further investigated in future studies.

5. Conclusions

This study demonstrated substantial differences in GRF parameters between the healthy controls and the patients with unilateral ACL deficiency. The results showed that the patients with ACL deficiency would adopt slower stepping cadences during stair ascent and stepping down to the ground. The vertical GRF in the ACLD group demonstrated smaller peak forces but larger minimum forces at mid-stance in both stair ascent and descent. It may imply larger stiffness in the lower limbs of the ACLD group. Significantly reduced magnitudes of anterior propulsive forces and push-off rates in the late stance were found in both limbs of the ACLD group. The slower cadences and reduced force-bearing on the affected limb suggested a protective strategy was adopted. However, the anterior loading parameters in the early stance and the weight-transferring strategies between the affected and unaffected limbs indicated different adaptations during stair ascent and descent. During stair descent, relatively larger magnitudes of the GRF parameters were found in the affected limb than in the unaffected limb. These findings supported the responses in patients with ACL deficiency who would find it more challenging to perform stair descent. The results of this study revealed a cautious force-bearing strategy and the bilateral adaptation in patients with unilateral ACL deficiency. This information would be helpful in understanding the kinetic adaptations after ACL injury and could help promote the use of the stair tasks as part of a rehabilitation program.

Acknowledgements

The authors acknowledge the support from the National Health Research Institute (NHRI93-EX9126).

References

[1] Andriacchi, T. P., Andersson, G. B., Fermier, R. W., Stern, D., and Galante, J. O., "A study of lower-limb mechanics during stair-climbing," *Journal of Bone & Joint Surgery - American Volume.*, 62, pp. 749-57, (1980).

[2] McFadyen, B. J. and Winter, D. A., "An integrated biomechanical analysis of normal stair ascent and descent," *Journal of Biomechanics*, 21, pp. 733-44, (1988).

[3] Lin, H. C., Lu, T. W., and Hsu, H. C., "Comparisons of joint kinetics in the lower extremity between stair ascent and descent," *Journal of Mechanics*, 21, pp. 41-50, (2005).

[4] Protopapadaki, A., Drechsler, W. I., Cramp, M. C., Coutts, F. J., and Scott, O. M., "Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals," *Clin Biomech (Bristol, Avon)*, 22, pp. 203-10, (2007).

[5] Nadeau, S., McFadyen, B. J., and Malouin, F., "Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking?," *Clinical Biomechanics*, 18, pp. 950-9, (2003).

[6] Larsen, A. H., Puggaard, L., Hamalainen, U., and Aagaard, P., "Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing," *J Electromyogr Kinesiol*, 18, pp. 568-80, (2008).

[7] Christina, K. A. and Cavanagh, P. R., "Ground reaction forces and frictional demands during stair descent: effects of age and illumination," *Gait & Posture.*, 15, pp. 153-8, (2002).

[8] D.Beaulieu, F. G., Pelland, L., and Robertson, D. G., "Kinetic analysis of forwards and backwards stair descent," *Gait Posture,* 27, pp. 564-71, (2008).

[9] Stacoff, A., Diezi, C., Luder, G., Stussi, E., and Kramers-de Quervain, I. A., "Ground reaction forces on stairs: effects of stair inclination and age," *Gait & Posture*, 21, pp. 24-38, (2005).

[10] Salsich, G. B., Brechter, J. H., and Powers, C. M., "Lower extremity kinetics during stair ambulation in patients with and without patellofemoral pain," *Clinical Biomechanics.*, 16, pp. 906-12, (2001).

[11] Brindle, T. J., Mattacola, C., and McCrory, J., "Electromyographic changes in the gluteus medius during stair ascent and descent in subjects with anterior knee pain," *Knee Surg Sports Traumatol Arthrosc*, 11, pp. 244-51, (2003).

[12] Rudolph, K. S. and Snyder-Mackler, L., "Effect of dynamic stability on a step task in ACL deficient individuals," *J Electromyogr Kinesiol*, 14, pp. 565-75, (2004).

[13] Thambyah, A., Thiagarajan, P., and Goh Cho Hong, J., "Knee joint moments during stair climbing of patients with anterior cruciate ligament deficiency," *Clinical Biomechanics*, 19, pp. 489-96, (2004).

[14] Andriacchi, T. P. and Birac, D., "Functional testing in the anterior cruciate ligament-deficient knee," *Clinical Orthopaedics & Related Research.*, pp. 40-7, (1993).

[15] Andriacchi, T. P., Dyrby, C. O., and Johnson, T. S., "The use of functional

analysis in evaluating knee kinematics," *Clinical Orthopaedics & Related Research*, pp. 44-53, (2003).

[16] Meyers, M. C., Sterling, J. C., and Marley, R. R., "Efficacy of stairclimber versus cycle ergometry in postoperative anterior cruciate ligament rehabilitation," *Clinical Journal of Sport Medicine*, 12, pp. 85-94, (2002).

[17] Riener, R., Rabuffetti, M., and Frigo, C., "Stair ascent and descent at different inclinations," *Gait & Posture.*, 15, pp. 32-44, (2002).

[18] Liikavainio, T., Isolehto, J., Helminen, H. J., Perttunen, J., Lepola, V., Kiviranta, I., Arokoski, J. P., and Komi, P. V., "Loading and gait symmetry during level and stair walking in asymptomatic subjects with knee osteoarthritis: importance of quadriceps femoris in reducing impact force during heel strike?," *Knee*, 14, pp. 231-8, (2007).

[19] Stacoff, A., Kramers-de Quervain, I. A., Luder, G., List, R., and Stussi, E., "Ground reaction forces on stairs. Part II: knee implant patients versus normals," *Gait Posture*, 26, pp. 48-58, (2007).

[20] Taylor, W. R., Heller, M. O., Bergmann, G., and Duda, G. N., "Tibio-femoral loading during human gait and stair climbing," *Journal of Orthopaedic Research*, 22, pp. 625-32, (2004).

[21] Lu, T.-W. and Lu, C.-H., "Forces transmitted in the knee joint during stair

ascent and descent," *Journal of Mechanics*, 22, pp. 289-297, (2006).

[22] Chmielewski, T. L., Wilk, K. E., and Snyder-Mackler, L., "Changes in weight-bearing following injury or surgical reconstruction of the ACL: relationship to quadriceps strength and function," *Gait Posture*, 16, pp. 87-95, (2002).

[23] Tegner, Y. and Lysholm, J., "Rating systems in the evaluation of knee ligament injuries," *Clin Orthop Relat Res*, pp. 43-9, (1985).

[24] Lysholm, J. and Gillquist, J., "Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale," *Am J Sports Med*, 10, pp. 150-4, (1982).

[25] de Jong, S. N., van Caspel, D. R., van Haeff, M. J., and Saris, D. B., "Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions," *Arthroscopy*, 23, pp. 21-8, 28 e1-3, (2007).

[26] Lephart, S. M., Ferris, C. M., Riemann, B. L., Myers, J. B., and Fu, F. H., "Gender differences in strength and lower extremity kinematics during landing," *Clinical Orthopaedics & Related Research.*, pp. 162-9, (2002).

[27] Ahmed, A. M. and McLean, C., "In vitro measurement of the restraining role of the anterior cruciate ligament during walking and stair ascent," *Journal of*

Biomechanical Engineering., 124, pp. 768-79, (2002).

[28] Beynnon, B. D., Fleming, B. C., Johnson, R. J., Nichols, C. E., Renstrom, P. A., and Pope, M. H., "Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo," *Am J Sports Med*, 23, pp. 24-34, (1995).

[29] Toutoungi, D. E., Lu, T. W., Leardini, A., Catani, F., and O'Connor, J. J., "Cruciate ligament forces in the human knee during rehabilitation exercises," *Clin Biomech (Bristol, Avon)*, 15, pp. 176-87, (2000).

[30] Courtney, C., Rine, R. M., and Kroll, P., "Central somatosensory changes and altered muscle synergies in subjects with anterior cruciate ligament deficiency," *Gait Posture*, 22, pp. 69-74, (2005).

Figure Captions

Figure1. Experimental set-up of the stair walkway (X, Y, Z unit: millimeter).

Figure 2. Parameters of ground reaction forces in a representative trial (A) during stair ascent; (B) during stair descent. (The solid curves are the GRF data from three forceplates, the dashed lines are the calculated loading/unloading rates from each forceplate, and the dashed curves are the summation of vertical GRF from two consecutive forceplates)

Figure 3. Average peak values and loading/unloading rates in vertical ground reaction forces (A) during stair ascent; (B) during stair descent.

Figure 4. Average peak values and loading/push-off rates in anterior-posterior ground reaction forces (A) during stair ascent; (B) during stair descent.

Figure 5. (A) Average maximal forces, lift-up index (LUI) in stair ascent and impact index (IPI) in stair descent; and (B) the percentages on the leading limb in transition between steps during stair locomotion in different subject groups.

Table Captions

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

Table 2. Average cadence and duty factor in various steps during stair ascent and descent.

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

	Control (N = 14)	ACLD (N = 20)	
Gender, men/women, n	10M / 4W	12M / 8W	
Age, years	21.8 (4.2)	23.8 (5.8)	
Body height, cm	167.5 (9.6)	168.4 (8.2)	
Body weight, kg	68.0 (12.5)	66.5 (13.7)	
BMI, kg/m^2	24.1 (3.4)	23.1 (3.7)	
Post-injury duration, months [range]	—	42.9 (53.0) [1-157]	
Lysholm score [range]	100	71.3 (15.5) [45-99]	
		Before injury	Before injury
Tegner activity level scale [range]	6.2 (3.0) [1-9]	6.8 (2.5) [2-9]	3.4 (2.3) [1-9]

BMI: body mass index

Figure1. Experimental set-up of the stair walkway (X, Y, Z unit: millimeter).

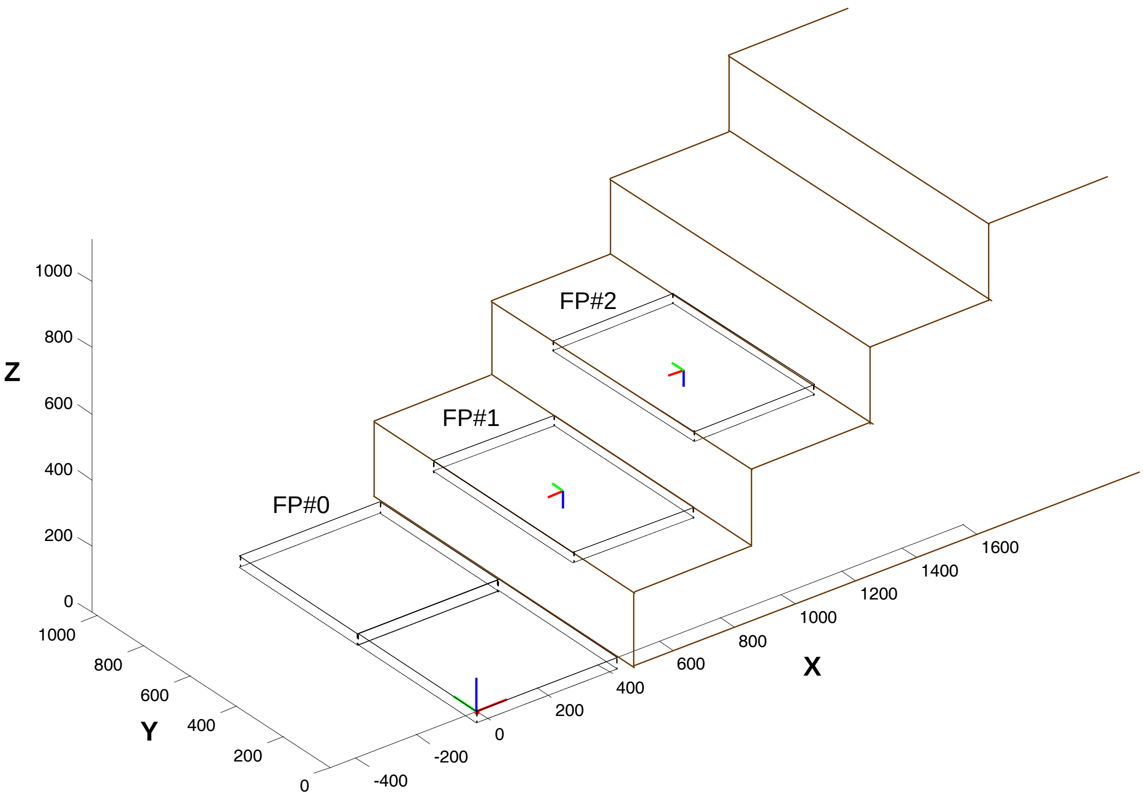
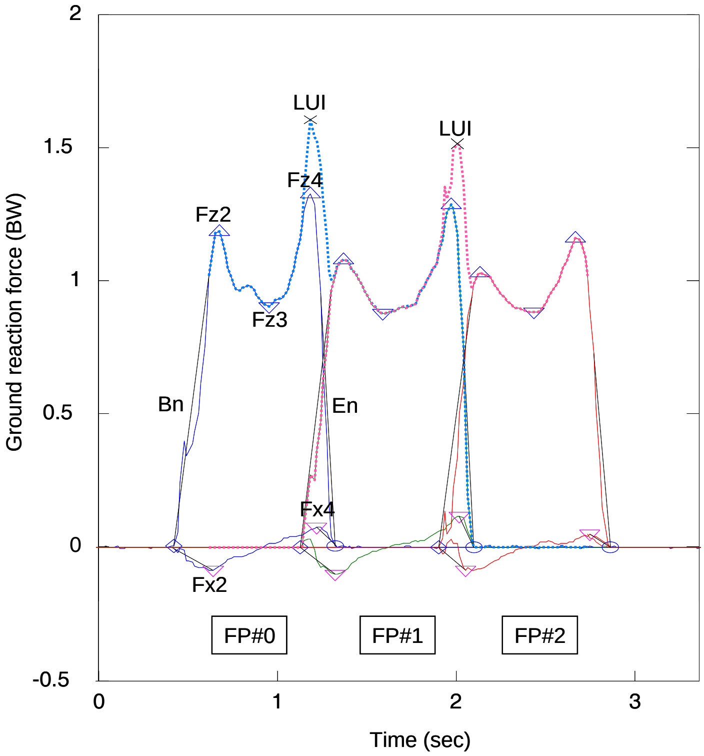
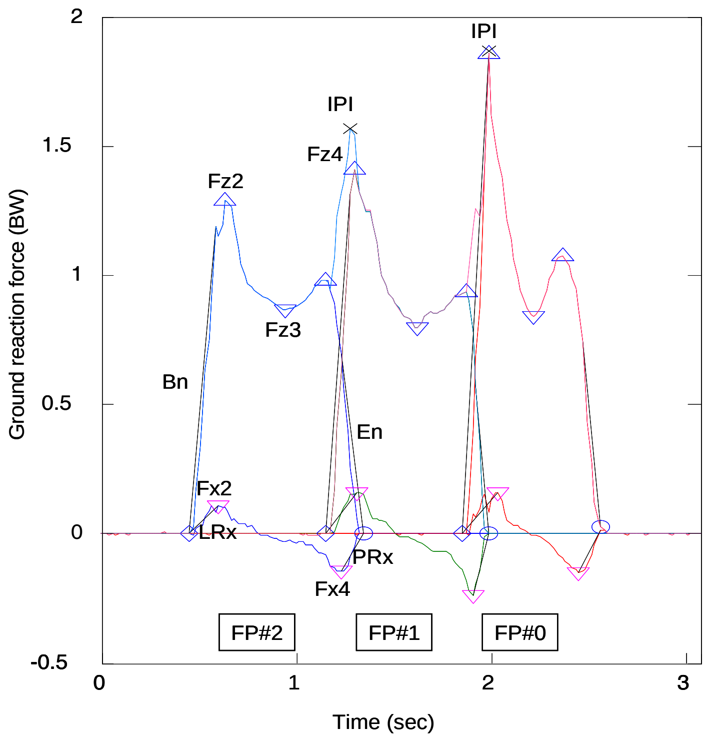


Figure 2. Parameters of ground reaction forces in a representative trial (A) during stair ascent; (B) during stair descent. (The solid curves are the GRF data from three forceplates, the dashed lines are the calculated loading/unloading rates from each forceplate, and the dashed curves are the summation of vertical GRF from two consecutive forceplates)

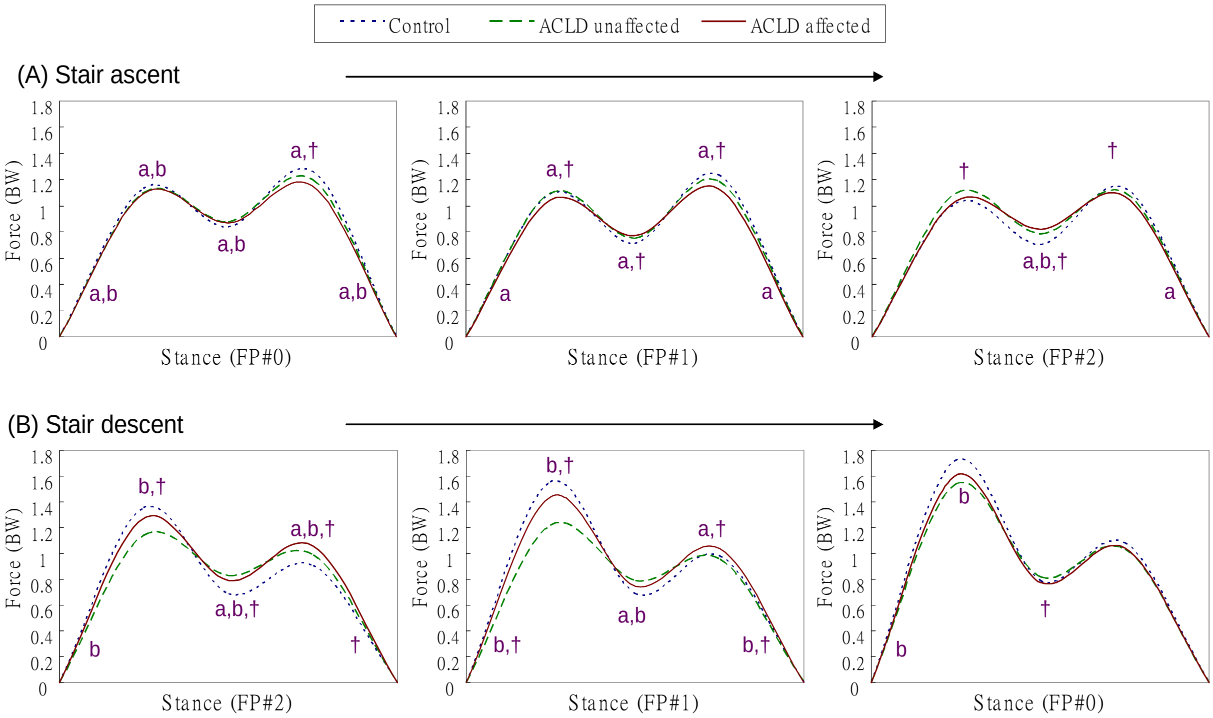


(A)



(B)

Figure 3. Average peak values and loading/unloading rates in vertical ground reaction forces (A) during stair ascent; (B) during stair descent.

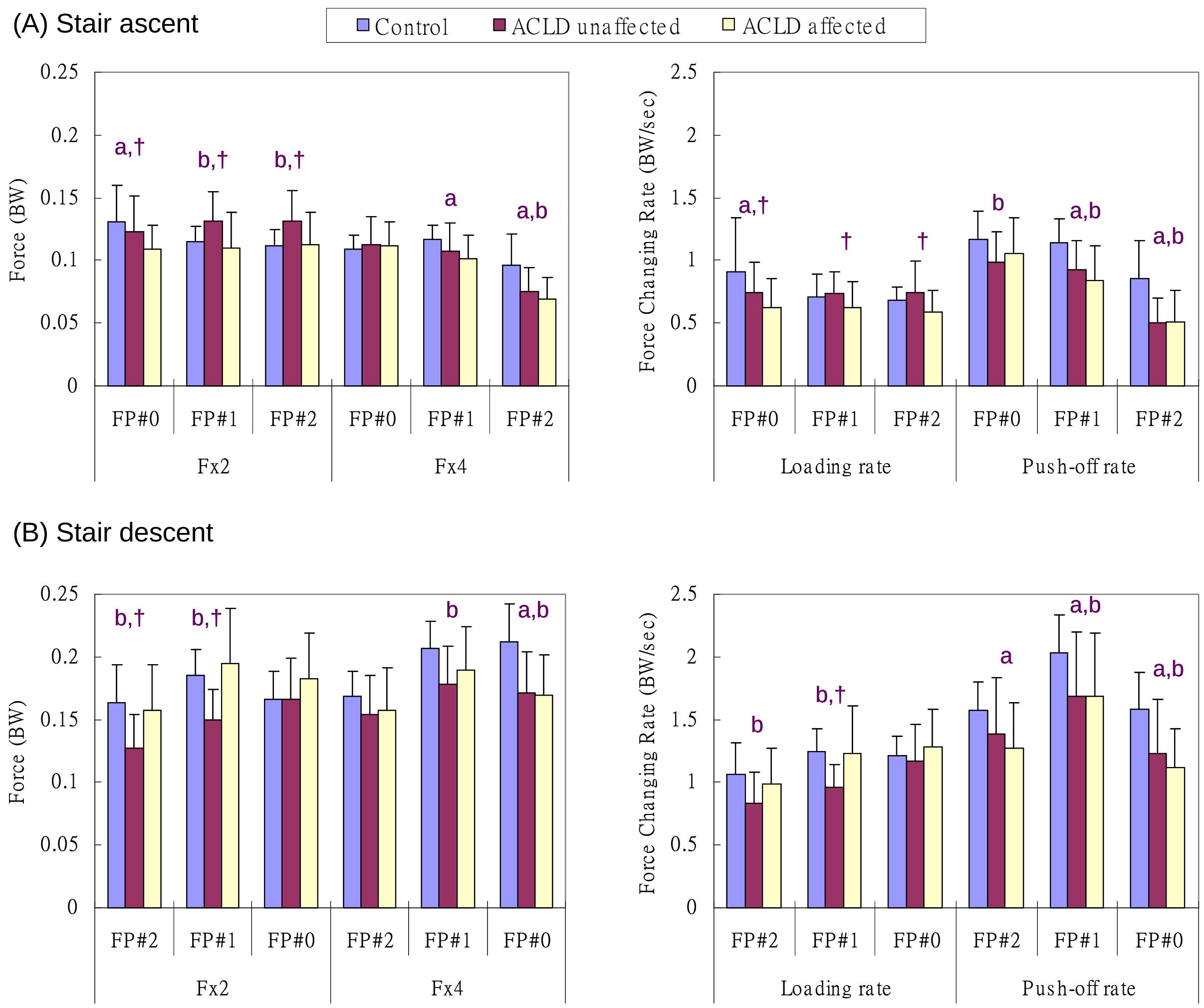


a: significant difference in the comparison of the control group with the affected limb of the ACLD group

b: significant difference in the comparison of the control group with the unaffected limb of the ACLD group

†: significant difference in the comparison between the affected and unaffected limb of the ACLD group

Figure 4. Average peak values and loading/push-off rates in anterior-posterior ground reaction forces (A) during stair ascent; (B) during stair descent.

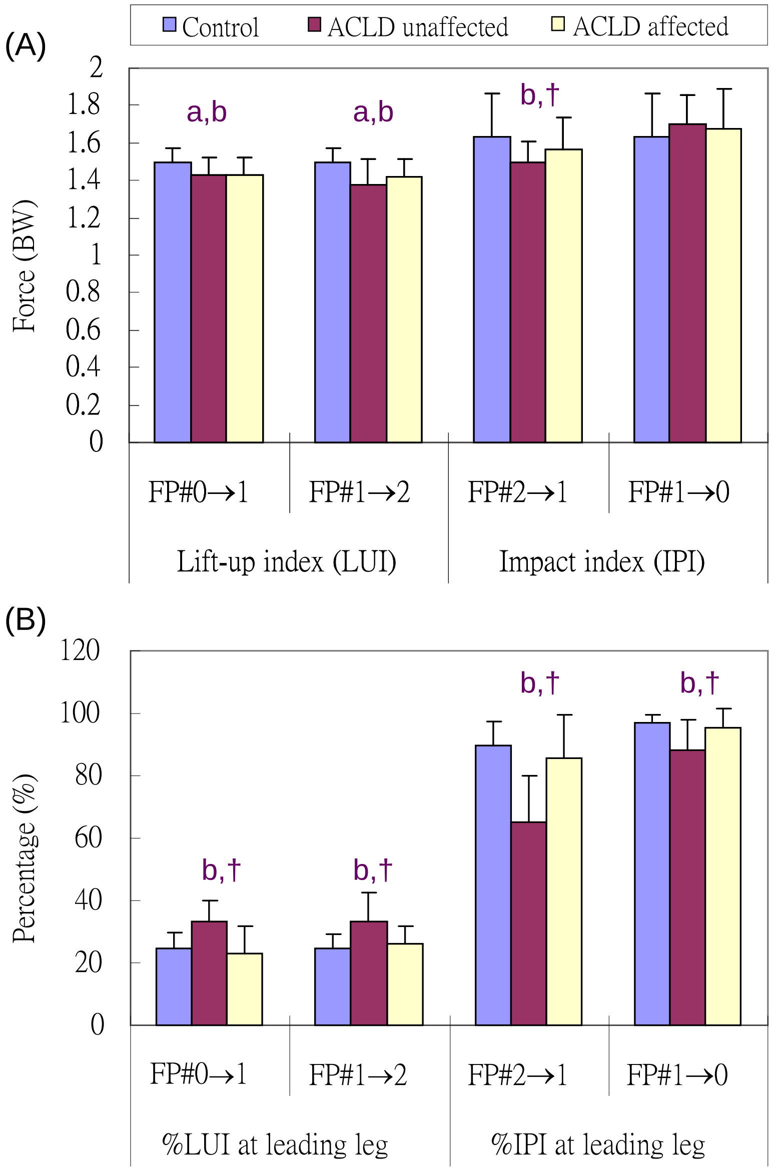


a: significant difference in the comparison of the control group with the affected limb of the ACLD group

b: significant difference in the comparison of the control group with the unaffected limb of the ACLD group

†: significant difference in the comparison between the affected and unaffected limb of the ACLD group

Figure 5. (A) Average maximal forces, lift-up index (LUI) in stair ascent and impact index (IPI) in stair descent; and (B) the percentages on the leading limb in transition between steps during stair locomotion in different subject groups.



a: significant difference in the comparison of the control group with the affected limb of the ACLD group

b: significant difference in the comparison of the control group with the unaffected limb of the ACLD group

†: significant difference in the comparison between the affected and unaffected limb of the ACLD group

Table 2. Average cadence and duty factor in various steps during stair ascent and descent.

Group	Control group		ACLD group					
Side			unaffected			affected		
Parameters	Mean	(SD)	Mean	(SD)		Mean	(SD)	
	Stair ascent							
Cadence (stride/min)								
step#0 → step#2	42.3	(3.8)	35.0	(4.9)	*	35.7	(4.5)	*
step#1 → step#3	42.6	(3.8)	37.1	(4.6)	*	37.5	(4.9)	*
Duty factor (%cycle)								
step#0 → step#2	62.0	(1.9)	64.5	(2.5)		61.1	(2.1)	†
step#1 → step#3	57.8	(1.9)	57.6	(3.4)		56.2	(3.9)	
	Stair descent							
Cadence (stride/min)								
step#3 → step#1	44.6	(5.0)	41.4	(8.1)		43.4	(7.3)	
step#2 → step#0	48.5	(8.6)	37.3	(4.3)	*	37.7	(6.0)	*
Duty factor (%cycle)								
step#3 → step#1	56.2	(5.9)	62.6	(5.3)		67.0	(5.9)	*
step#2 → step#0	68.6	(4.1)	70.0	(4.6)		69.5	(6.6)	

*: significant difference in the comparison of the control group with the unaffected or affected limb of the ACLD group

†: significant difference in the comparison between the affected and unaffected limb of the ACLD group