Alterations in medial-lateral postural control after anterior cruciate ligament reconstruction during stair use

Michelle Hall[1], Luke G. Perraton[2], Catherine A. Stevermer[3], Jason C. Gillette[4]

Affiliations:
[1]Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, School of Health Sciences, Melbourne, The University of Melbourne, VIC Australia
[2]Department of Physiotherapy, Monash University, Frankston, VIC, Australia
[3]Department of Physical Therapy, Des Moines University, Des Moines, IA USA
[4]Department of Kinesiology, Iowa State University, Ames, IA USA

Corresponding author:
Dr Michelle Hall
Centre for Health Exercise and Sports Medicine
Physiotherapy
The University of Melbourne
Victoria, 3010, Australia
Tel: +61 3 8344 40556
Email: halm@unimelb.edu.au

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INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) is commonly performed to restore the mechanical stability to the knee joint. Individuals who sustain an anterior cruciate ligament injury and have subsequent surgical reconstruction often fail to achieve optimal functional recovery [1]. Although ACLR is thought to restore mechanical stability of the knee, bilateral changes including strength deficits [2], altered biomechanics [3], and altered postural control [4] have been reported. These alterations are thought to contribute to functional alterations. Following ACLR, postural stability deficits during demanding tasks such as jumping have been found to be predictors of a second ACL injury after return to sport [5] and joint instability is linked to development of knee osteoarthritis [6].

The majority of studies evaluating postural control after ACLR using instrumented assessments have utilized static single limb stance postures. Indeed, a systematic review tentatively concluded static postural control impairments are present in ACL individuals when compared to controls [4]. However, studies investigating dynamic postural control in people following ACLR report inconsistent findings [4]. These studies have assessed single-leg balance on an unstable platform [7-8] and with perturbation [9]. Furthermore, static single limb balance appears to be comparable between the ACL injured leg and non-injured leg beyond 6 months post-ACLR [9-11]. There is no research examining postural control during a challenging everyday task, such as stair use, which may provide further insight into postural control following ACLR.

Postural control is maintained by integrating somatosensory, vision, and vestibular sensory information on position and movement of the body and surrounding environment [12]. Sensory nerve fibres and mechanoreceptors enable the ACL to have a sensory function that affects excitatory and inhibitory activity of the muscles around the knee [13] and influences balance control. Following ACL injury, the sensory function of the ACL is impaired and restoration of sensory function using patellar tendon graft, iliotibial band graft or autogenous semitendinosus and gracilis tendons reconstruction is doubtful [14-15]. People following ACL injury are thought to compensate for the absence of sensory information from the ACL tissue by developing extra-articular sensation and control of the knee joint through the mechanoreceptors and sensory nerve fibres in peri-articular tissue [1].

Postural control is typically assessed using centre of pressure (COP), with the expectation that COP movements are indicative of centre of mass movements [16]. Traditionally, increased COP movement is associated with poor balance control and may indicate the need to adopt an alternate postural control strategy. Time-to-boundary (TTB) is a spatiotemporal analysis that provides an estimate of the time an individual has to make a postural correction in order to maintain balance [17]. Specifically, TTB measures provide information about COP excursions in relation to the boundaries of the base of support not addressed by traditional measures.

The purpose of this study was to compare COP measures of postural control between ACL reconstructed individuals and healthy controls during a functional dynamic task, i.e., stair negotiation. We hypothesised that COP excursion and velocity would be higher and medial-lateral TTB would be lower in the ACLR limb as compared to the non-ACLR limb and to healthy controls during stair ascent and descent.

2. METHODS

2.1 Participants

Seventeen participants with unilateral ACL reconstruction (≥ one-year post-surgery) and sixteen healthy controls between 18 and 35 years old were recruited from a university setting, via advertisements on noticeboards and class announcements. Participants were excluded if they had any previous ACL reconstructions, or any history of musculoskeletal or neurological conditions precluding safe walking or stair ambulation. Healthy controls were excluded if they had a previous knee injury or surgery. We aimed to match control participants to ACL participants (i.e., age and sex) at the group level. The Institutional Review Board at Iowa State University approved this study, and all participants provided written informed consent. Participants recalled and provided clinical information regarding time from surgery, type of reconstruction graft, presence of meniscal damage and whether the ACL injury was contact or non-contract in nature. The ACL group was on average 5 years from reconstruction surgery (range 2 –18 years) and reconstruction grafts included hamstring (n = 10), patellar tendon (n = 5), or a combination of hamstring and patellar tendon (n = 1), with one participant having an unknown graft. The majority of the ACL group had concurrent meniscal damage at the time of ACL injury (71%) and 59% of the ACL injuries were considered non-contact in nature.

2.2 Experimental protocol

A three-step staircase (step height 18.5 cm, tread depth 29.5cm) with banisters on both sides was used. Kinetic data were collected using two portable force platforms positioned on the first and second steps of the stairs, and an in-ground force platform at the base of the stairs (AMTI, Watertown, MA). Kinematic data were collected using an 8-camera motion capture system (Vicon, Oxford, UK). Kinetic and kinematic data were captured at sampling rates of 1600 Hz and 160 Hz. Reflective markers (19mm) were placed bilaterally on the medial and lateral malleoli, heel, fifth metatarsal head, and toe. Following a static trial, heel and medial malleoli markers were removed. Participants performed three trials leading with each leg, for a total of six trials each for stair ascent and descent. Participants wore self-selected shoes and performed tasks at a self-selected pace, using a step-over-step technique to ascend and descend stairs. Participants were permitted to use the banisters if required for balance, however no participants used the banisters during ascent or descent.

2.3 Data reduction

COP measures were determined during the single stance phase for the first step of stair ascent and second step of stair descent (lowest step of staircase). The first step of stair ascent and the second step of stair descent were selected for analysis due to positioning of the force platforms (mounted in the floor and on the lowest and middle step of a three-step staircase). For stair ascent, we determined single-leg stance on the lowest step since (i.e. first step of stair ascent) using the floor force platform to detect the beginning of the single-leg stance and the force plate on the second step to detect the end of single stance. For stair descent, we determined single-leg stance timing on the lowest step since (i.e. second step of stair descent) using the middle step force platform to detect the beginning of single-leg stance and the floor force platform to detect the end of the single-leg stance. Anterior-posterior (AP) and medial-lateral (ML) COP excursions were calculated as the difference between the maximum AP and ML COP positions during the single stance phase. AP and ML COP velocities and accelerations were calculated using the first central difference method [18]. AP and ML COP velocities were reported as mean values during the single stance phase. Rectangular bases of support were determined for each foot using the toe and fifth metatarsal markers, recreated heel marker, and measured foot width.

AP and ML COP positions, velocities, and accelerations were used to calculate AP and ML TTB. A dynamic TTB analysis [19] was used since the COP shifted between alternating feet during stair negotiation. AP and ML TTB were calculated during each time point of single stance and compared to the remaining single stance time. If the TTB was less than the remaining single stance time, then the TTB value was retained for that time point. If the TTB was greater than the remaining single stance time, then the TTB was set to the remaining single stance time. For example, if the TTB was 150 ms and the remaining stance time was 200 ms, then the TTB value would be retained since a postural adjustment was required during the single stance phase. In contrast, if the TTB was 200 ms and the remaining stance time was 150 ms, then the TTB value would be set to the remaining stance time since the foot would leave the ground prior to the postural adjustment. Mean AP and ML TTB were calculated during single stance, with a smaller value indicating a more rapid postural adjustment. TTB percentage was calculated by dividing TTB by half the stance time to adjust for potential changes in velocity. A TTB of 100% indicated that no adjustment was needed during single leg stance, while a percentage below 100% indicated that an adjustment was required during single leg stance.

2.4 Statistical Analysis

Independent t-tests and chi-square tests were used to determine differences in group characteristics as appropriate. The dependent variables included single stance time, AP and ML COP excursions, AP and ML COP mean velocities, and AP and ML dynamic TTB, and AP and ML dynamic TTB percentage. These COP measures were inspected for normal distribution. In the event where the COP measures did not conform to normal distribution, data were squared and log-transformed prior to analysis. Using a mixed linear model, differences between legs (ACLR leg, non-ACLR leg, and an average of the right and left legs of healthy controls) were compared with participant entered as a random effect and 'leg' as a fixed effect. Statistical analyses were performed using Stata 13.1 (Statacorp, College Station, TX). Statistical significance level was set at $p < 0.05$. For comparisons that reached statistical significance, Cohen's d effect sizes were calculated and interpreted as follows [20]: 0.20-0.49 = small effect; 0.50-0.79 = medium effect and ≥ 0.8 large effect.

3. RESULTS

There were no significant differences in participant characteristics when comparing the ACLR group and healthy controls (Table 1).

3.1 Stair Ascent

There were no statistically significant differences in stance time or COP variables when comparing the ACLR leg, non-ACLR leg, and healthy controls during stair ascent (Table 2).

3.2 Stair Descent

ML COP excursion was significantly higher in the ACLR leg compared to the non-ACLR leg (mean difference 1.06 cm [95%CI 0.08 to 2.06 cm], p=0.036; effect size = 0.38) during stair descent (Table 2). In addition, ML TTB was significantly lower in the ACLR leg compared to the non-ACLR leg (mean difference -13 ms [95%CI -38 to 2 ms], p = 0.005; effect size = 0.49) during stair descent. Similarly, ML TTB percentage was significantly lower in the ACLR leg compared to the non-ACLR leg (mean difference -5.8% [95%CI -10.3 to 1.3 %], p = 0.012; effect size = 0.80). There were no significant differences in stance time, AP COP measures, and ML COP velocity when comparing the ACLR leg and the non-ACLR leg. In addition, there were no significant differences between the ACLR leg and healthy control leg for stance time for any COP measures.

4. DISCUSSION

The aim of this study was to determine if individuals with ACL reconstruction demonstrated alterations in COP measures during stair use. We observed no differences in COP measures between the ACLR leg, non-ACLR leg, and healthy control leg during stair ascent. However, there were alterations in some COP measures observed in the ACLR leg during stair descent. We found that COP excursion in the medial-lateral direction was greater in the ACLR leg compared to the non-ACLR leg during stair descent. We also observed lower medial-lateral TTB and medial-lateral TTB percentage in the ACLR leg compared to the non-ACLR leg. Taken together, this study provides preliminary evidence that alterations in dynamic postural control are present in the ACLR limb compared to the non-ACLR limb during stair descent, a challenging, but common activity of daily living.

Contrary to our hypothesis, we found no evidence to indicate that postural control as assessed by COP measures is altered in people with ACLR limb during stair ascent. Failure to observe alterations in postural control during stair ascent might suggest that any ACL tissue sensory deficits caused by injury have been compensated developing extra-articular sensation and control of the knee joint through the mechanoreceptors and sensory nerve fibres in peri-articular tissue [1]. Alternatively, our findings may indirectly suggest that demands of stair ascent on dynamic postural control may not be sufficiently challenging enough to reveal impairments in people following ACLR. Direct comparison of our findings is precluded as no other research to our knowledge has assessed postural control in those with ACLR during stair ascent. Although stair ascent is considered a key indicator of functional independence [21], falls are almost three times more frequent during stair descent compared to stair ascent [22]. The increased risk of falls during stair descent is consistent with previous research demonstrating that stair descent is more challenging that stair ascent from a dynamic stability perspective [23]. It should also be acknowledged that we assessed the first step of stair ascent due to the configuration of our force platforms to detect single-leg stance. The second step of stair ascent may be considered more challenging than the first as participants gain momentum, and possibly more sensitive to detect alterations in postural control.

Our hypothesis that postural control would be altered post-ACLR during stair descent was partially supported. Specifically, greater ML COP excursion was found in the ACLR leg compared to the non-ACLR leg during stair descent. This finding is somewhat similar to previous research evaluating COP excursion, albeit during a single-leg balance task [10]. Consistent with the implication of COP excursion, ML TTB was shorter in the ACLR leg compared to the non-ACLR leg. This indicates that the ACLR leg demonstrates greater postural instability as the COP is closer in time to reaching the ML boundary of the base of support. Collectively, these findings may suggest compromised ACL sensory infrastructure and/or may reflect an inability to compensate with sensory information from other sources. Notably, the small to large effect sizes (0.38-0.80) could have clinical implications. We speculate that given the repetitive nature at the knee joint during stair descent, our observations warrant further investigate to determine the clinical relevance.

Knee muscle weakness is often reported in people following ACLR [2], and knee muscle weakness has previously been related to dynamic balance in people with knee osteoarthritis [24]. Thus, it is feasible that alterations in measures of medial-lateral postural control during stair descent may be in part attributed to knee muscle weakness. However, we previously reported knee muscle strength in this study sample and found no statistical differences in knee extensor strength or knee flexor strength between the ACLR limb and non-ACLR limb [25]. Perhaps a more sensitive measure than maximal knee muscle strength to better understand alterations in dynamic postural control is task-specific knee muscle activation. We have previously demonstrated lower muscle activation in the rectus femoris of the ACLR limb compared to controls during stair descent [26], which although functions largely in the sagittal plane may reflect alterations related to postural control in the frontal plane during stair descent. Overall, it appears that factors other than maximal knee muscle strength and task-specific muscle activation play a role in reduce medial-lateral postural control during stair descent. Proprioception alterations are also often found in people post-ACLR [27] and may in part be attributable. Further investigation is necessary to understand the mechanisms underpinning alterations in dynamic postural control.

The main strength of our study is a novel approach use of dynamic TTB in addition to assessing COP excursion and velocity during the dynamic task of stair ambulation. There are limitations to this study. First, as this is a cross-sectional study, we cannot determine if COP measures were altered before or following ACLR. Furthermore, the clinical implications of the observed alterations in COP measures within the ACLR leg remain unknown. Second, as exploratory study, we did not correct for the multiple statistics performed, which increases the risk of type 1 error. Third, we did not document information regarding pre- or post-surgery rehabilitation, which could influence COP measures. Fourth, the time elapsed from ACLR surgery was quite variable, ranging from 2-18 years. Fifth, we did not include tests that quantify sensory and/or proprioception deficits, thus our suggestion that alterations in sensory function are an underpinning mechanism for COP alternations remains speculative. Lastly, we not document specific meniscal damage details in participants with ACL injury, which given menisci tissue include mechanoreceptors including Ruffini endings, Pacinian corpuscles and Golgi tendon organs [28] could influence our findings. However, interestingly previous research suggests meniscal damage has minimal effect on postural stability in those with ACL injury [29].

In summary, this study provided preliminary evidence that dynamic postural control, as determined by COP variables during stair descent, are altered when compared to the non-ACLR leg. However, there were no differences in dynamic postural control between ACLR participants and healthy controls as assessed in this study. Further research is needed to better understand the clinical implications of side-to-side differences in postural control following ACLR leg during dynamic everyday tasks. With such knowledge, COP measures may be a prudent modifiable target for rehabilitation programs.

Conflict of interest: None of the authors have any conflicts of interest to declare.

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Table 1 Participant characteristics. Average values are shown with standard deviations, with the exception of female/male ratio.

	ACLR group (n = 17)	Controls (n = 16)
Age, yr	25 (6)	26 (4)
Females, n (%)	11 (65%)	10 (63%)
Height, m	1.73 (0.14)	1.70 (0.12)
Mass, kg	75.2 (16.6)	68.0 (12.1)
BMI, kg/m^2	24.7 (2.7)	23.7 (4.1)
Tegner Score	7 (2)	6 (1)

BMI: body mass index

Table 2 Centre of pressure measures comparing the ACL reconstructed leg, non-injured leg, and healthy control leg during stair ascent and descent. Average values with standard deviations are shown.

	Stair Ascent			Stair Descent		
	ACLR leg (n=17)	Non-ACLR leg (n=17)	Control (n=16)	ACLR leg (n=17)	Non-ACLR leg (n=17)	Control (n=16)
Single stance time (ms)	458 (40)	464 (31)	447 (43)	424 (59)	424 (50)	445 (35)
AP COP excursion (cm)	14.43 (4.50)	15.48 (4.48)	15.81 (4.48)	12.03 (3.18)	12.56 (3.58)	12.57 (2.84)
ML COP excursion (cm)	4.01 (1.55)	3.24 (1.24)	3.31 (1.02)	6.47 (3.36)	**5.40 (2.38)[a]**	5.44 (1.69)
AP COP velocity (cm/s)	22.92 (5.08)	24.54 (4.89)	26.31 (5.97)	32.93 (8.38)	34.85 (10.82)	33.65 (8.25)
ML COP velocity (cm/s)	8.03 (1.89)	7.04 (1.43)	7.66 (2.27)	16.31 (8.63)	13.13 (5.32)	13.06 (4.51)
AP TTB acceleration (ms)	207 (21)	208 (19)	202 (20)	169 (26)	164 (29)	176 (18)
ML TTB acceleration (ms)	217 (17)	222 (16)	216 (19)	181 (27)	**194 (26)[a]**	197 (19)
AP TTB percentage (%)	90.6 (5.7)	89.6 (7.3)	90.7 (6.6)	79.7 (6.1)	77.0 (7.1)	79.4 (7.1)
ML TTB percentage (%)	95.1 (3.3)	95.7 (4.6)	97.0 (3.0)	85.5 (8.2)	**91.3 (6.2)[a]**	88.7 (6.7)

[a] indicates significantly different compared to ACL leg ($p<0.05$); AP: anterior-posterior; ML: medial-lateral; COP: centre of pressure; TTB: time-to-boundary