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Effects of narrow-base walking and dual tasking on gait spatiotemporal characteristics in anterior cruciate ligament-injured adults compared to healthy adults

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Abstract

Purpose The present experiment was conducted to examine the hypothesis that challenging control through narrow-base walking and/or dual tasking affects ACL-injured adults more than healthy control adults.

Methods Twenty male ACL-injured adults and twenty healthy male adults walked on a treadmill at a comfortable speed under two base-of-support conditions, normal-base versus narrow-base, with and without a cognitive task. Gait patterns were assessed using mean and variability of step length and mean and variability of step velocity. Cognitive performance was assessed using the number of correct counts in a backward counting task.

Results Narrow-base walking resulted in a larger decrease in step length and a more pronounced increase in variability of step length and of step velocity in ACL-injured adults than in healthy adults. For most of the gait parameters and for backward counting performance, the dual-tasking effect was similar between the two groups.

Conclusions ACL-injured adults adopt a more conservative and more unstable gait pattern during narrow-base walking. This can be largely explained by deficits of postural control in ACL-injured adults, which impairs gait under more balance-demanding conditions. The observation that the dual-tasking effect did not differ between the groups may be explained by the fact that walking is an automatic process that involves minimal use of attentional resources, even after ACL injury. Clinicians should consider the need to include aspects of terrain complexity, such as walking on a narrow walkway, in gait assessment and training of patients with ACL injury.

Level of evidence III.

Keywords Gait · Anterior cruciate ligament · Balance · Attention · Kinematics

Introduction

While several studies have revealed alterations in gait patterns following ACL injury [2, 8, 10, 26], gait patterns in most of these studies have been assessed in normal, i.e. unconstrained, walking. However, walking in the real world requires the ability to modify the way one walks to negotiate task and environmental demands [3]. This ability may be impaired in individuals with ACL injury. Assessment of gait under demanding functional conditions might allow for identification of factors contributing to impaired walking adaptability in ACL-injured adults that are not detected under normal walking conditions. For instance, measurement of gait under conditions of narrow-base walking or walking while concurrently performing cognitive tasks could improve our understanding of the role of balance control and attentional demands, respectively, in functional walking performance after ACL injury.

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The ability to adjust one's gait in response to increased balance demands is crucial for safe walking. This ability can be evaluated using narrow-base walking [7, 12, 25] because it increases balance demands in the frontal plane. Decreased ability to walk within a narrow pathway has been shown in older adults [25], who walked with shorter step length, lower stride velocity and larger mediolateral centre of mass peak velocity and displacement in narrow-base condition compared to normal-base condition. In the present study, we focused on lateral balance demands, as walking is less passively stable in the mediolateral direction than in the fore-aft direction, requiring more active sensorimotor control [4]. This active control may be more challenging in individuals with ACL injury, as the ACL has been shown to play a major role in neuromuscular coordination of the lower extremities [2, 23] during walking.

Real-world walking also requires the ability to cope with varying attentional demands related to tasks other than walking. Attentional demands during walking are typically examined using a dual-task design [28] in which walking is performed simultaneously with a secondary cognitive task. A dual-task design relies on the theory of limited attention capacity, which assumes that if the combined resources needed for performing the primary and secondary task exceed the available attentional capacity, interference takes place which may affect performance on one or both tasks [28]. ~~Dual tasking~~ has been investigated on balance control during quiet stance in ACL-injured adults [18]. However, the effect of dual tasking on walking in ACL injury has not been clarified yet.

Despite the increased interest in assessing gait under demanding functional conditions, little is known about how ACL injury affects walking adaptability. This study provides specific performance results for persons with ACL injury when interacting with challenging terrain demands and cognitive dual tasking, as two major domains of walking adaptability [3]. In this experiment, we examined the effect of narrow-base walking and dual tasking on gait spatiotemporal characteristics in ACL-injured and healthy adults. Participants walked under two base-of-support (BOS) conditions, i.e. normal-base versus narrow-base, with and without dual tasking. Because of the reduced sensorimotor control in ACL-injured adults, we hypothesized that challenging control through narrow-base walking and/or dual tasking would affect ACL deficient adults more than healthy control adults.

Materials and methods

An a priori power analysis indicated that a total sample of 40 participants (20 per group) was required to detect an effect size equal to 0.58 (specified based on the study of Knoll et al. [13] comparing step length between male chronic ACL-injured adults and male healthy adults) using a mixed model ANOVA with alpha set to 0.05. A sample of male adults with complete ACL tear was recruited from orthopaedic and physiotherapy clinics. Most individuals had injured their ACL playing recreational soccer. ACL-injured adults were tested before starting their physiotherapy programme. Inclusion criteria consisted of age between 15 and 40 years, non-operated and non-acute ACL rupture with or without meniscal injury as diagnosed by clinical evaluation and confirmed by magnetic resonance imaging, and time since injury between 1 and 12 months. Exclusion criteria consisted of additional injury to the posterior cruciate ligament and collateral ligaments [10], injury to the contralateral leg [10], other musculoskeletal disorders except ACL injury, and pain or difficulty during walking [10]. The control group consisted of healthy male participants with no history of musculoskeletal injury in the lower leg, neck or back. Healthy participants were individually matched to injured participants with regard to age, body height, weight and years of education. For ACL-injured adults whose injury was on the dominant leg, the dominant leg of the matched healthy control was assessed. Similarly, ACL-injured adults whose injuries were located on the non-dominant leg were compared to the non-dominant leg performance of the healthy matched control.

The activity level of both groups was assessed using a Tegner activity rating scale with the scores varying between 0 (sick leave or disability pension) and 10 (participation in national and international elite competitive sports) [20]. The function and symptoms of participants with ACL injury was assessed using Knee injury and Osteoarthritis Outcome Score (KOOS) with subscale ~~scoring~~ ranging from 0 (extreme problems) to 100 (no problems) [24].

Experimental set-up

A motorized treadmill (Biometrix™, length = 1.5 m, width = 0.5 m) was used in the present study. Kinematics data were collected using a 7-camera motion capture system (Qualisys Inc., Sweden) at a sampling rate of 60 Hz. The 3-D residue of marker position tracking was lower than 1 mm in the measurement volume of about 1 m × 1.5 m × 2 m. Sphere-shaped retro-reflective markers, 10 mm in diameter, were attached to the 5th metatarsal base, heel and lateral malleolus of both legs.

To create the narrow-base condition, a narrow path was outlined by tape on the treadmill belt [12] (Fig. 1).

Experiment

The experiment began with determination of comfortable walking speed (CWS). The method described by Lamoth

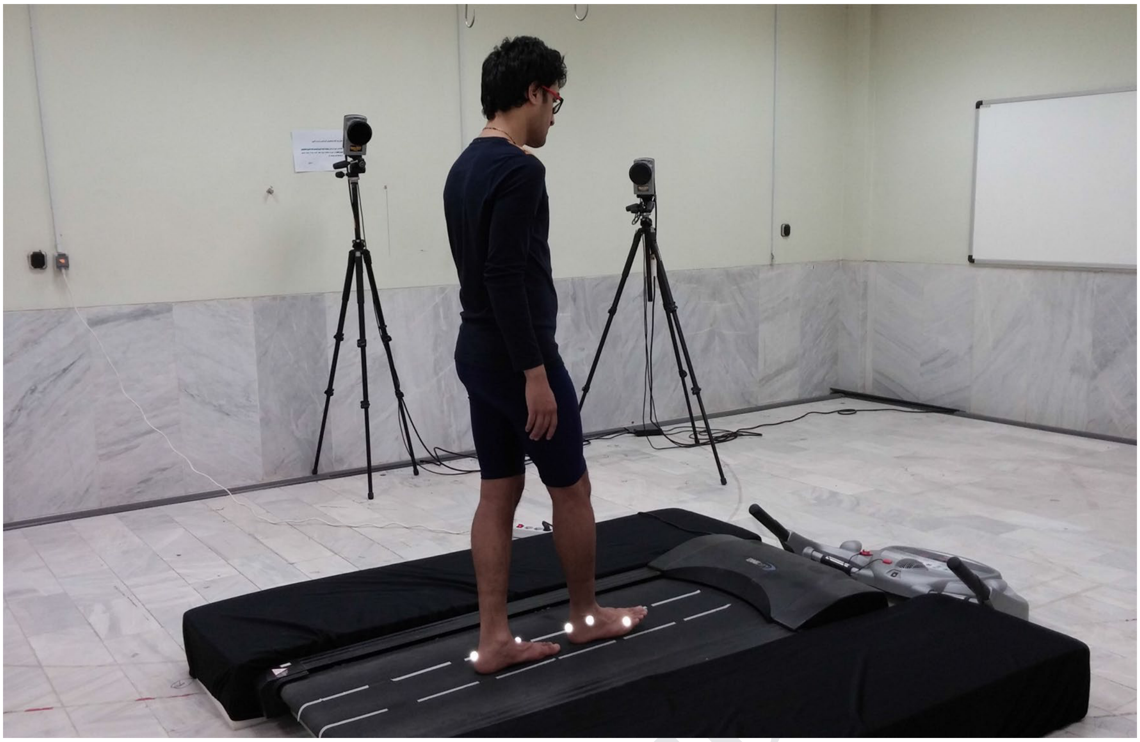

Fig. 1 Experimental set-up: walking within the narrow path traced using tape on the treadmill belt. The distance between the two lines is adjusted to 50 % of the distance between the participant's anterior superior iliac spines

et al. [14] was used to determine CWS. CWS was determined for each BOS condition and was subsequently applied to the corresponding experimental trials.

Participants walked barefoot under two BOS conditions and three cognitive loading conditions. For the BOS conditions, participants walked either with the preferred step width (normal-base condition) or with the narrower-than-preferred step width as imposed by a narrow path marked on the treadmill belt (narrow-base condition). The participants were instructed to place their feet within the marked path while walking. The width of the narrow path was limited to 50 % of the distance between the participant's anterior superior iliac spines [12]. The cognitive loading conditions involved walking without (single-task condition) and with (dual-task condition) a cognitive task. The cognitive task used in this study was verbal backward counting [1], starting from a random number between 500 and 600, with two difficulty levels: easy (backward counting in increments of 3) and difficult (backward counting in increments of 7). In dual-task conditions, participants were instructed to give equal priority to backward counting and walking tasks [12]. Dual-task conditions were performed with both normal- and narrow-base conditions, resulting in a total of six conditions. In addition, the experiment included a cognitive baseline condition, which involved measuring backward counting performance while sitting on a chair. The conditions were presented in a random order to minimize learning effects. Each trial lasted 2 min, and to minimize fatigue effects, each experimental condition was followed by a rest period of 5 min. The total session lasted approximately 2 h.

Data analysis

Gait spatiotemporal parameters were determined based on heel strikes (19). After the heel first contacted the treadmill, defined as the local minimum of the heel marker's vertical coordinate, and just before the belt of the treadmill carried the foot backward, a heel strike was scored. The threshold for backward foot transfer detection was adjusted for belt speed by measuring the belt displacement over 0.01 s at each speed. The gait variables were mean and variability of step length and mean and variability of step velocity. Coefficient of variation (CV) was used to describe variability of step length and step velocity. To determine step length, step time was multiplied by the treadmill speed and then was corrected for differences in the absolute heel coordinates of the corresponding heel strike. Step velocity was obtained by dividing step length by step time. High test–retest reliability has been reported for both spatial parameters (e.g. step length: ICC = 0.85) and temporal parameters (e.g. gait velocity: ICC = 0.76; step time: ICC = 0.71) and

Table 1 Demographic and functional characteristics of ACL-injured and healthy adults

	ACL-injured group ($n = 17$)	Healthy group ($n = 19$)	p value
	Mean (SD)	Mean (SD)	
Age (yr)	28.5 (7.1)	27.3 (6.6)	n.s.
Height (cm)	176.3 (4.3)	177.5 (5.0)	n.s.
Weight (kg)	75.2 (10.8)	74.7 (8.8)	n.s.
Time since injury (month)	3.8 (3.2)	N/A	~~N/A~~
Years of education (yr)	13.4 (1.8)	13.3 (1.8)	n.s.
Tegner scale[a] (before injury)	7.0 (0.9)	6.8 (1.2)	n.s.
KOOS[b]			
Pain	66.0 (12.3)	N/A	
Symptom	52.6 (8.4)	N/A	
Activity daily living	69.2 (11.0)	N/A	
Sport and recreation	23.5 (11.1)	N/A	
Quality of life	31.0 (13.2)	N/A	
CWS during normal-base walking (km/h)	4.5 (0.6)	5.1 (0.3)	<0.01
CWS during narrow-base walking (km/h)	3.4 (0.9)	4.4 (0.4)	<0.001

ACL anterior cruciate ligament, *CWS* comfortable walking speed, *N/A* not applicable

[a] Range of scores is from 0 to 10

[b] Range of scores is from 0 to 100

their variability measures (e.g. variability of gait velocity: ICC = 0.80) derived from three-dimensional motion capture systems [16]. In each walking trial, gait parameters were calculated for 30 successive gait cycles in the middle of the trial. Due to the lack of sufficient visible successive gait cycles in different conditions (mostly narrow-base walking), the data of 4 participants ($n = 1$ healthy adult and $n = 3$ ACL-injured adults) were excluded from further analysis. A custom-written MATLAB (2010a, MathWorks Inc.) program was used to process the motion data.

Cognitive performance was assessed by counting the number of correct subtractions in the backward counting task. The sum of correct responses was used as an overall cognitive score.

Ethics approval

This study was approved by the Local Ethics Committee at Ahvaz Jundishapur University of Medical Sciences (grant no pht-9014). Each participant gave signed informed consent to participate in this experiment.

Statistical analysis

Independent t tests were used to compare age, height, weight, years of education, activity level and CWS between the two groups. A paired t test was used to compare CWS between normal-base and narrow-base conditions. A separate 2 (group: ACL-injured vs. healthy adults) × 2 (leg: injured leg or matched leg ~~for~~ healthy adults vs. uninjured leg or matched leg of healthy adults) × 2 (BOS: normal-base vs. narrow-base) × 3 (cognitive loading: none vs. easy vs. difficult) mixed model of analysis of variances (ANOVA) was applied to each of the gait spatiotemporal variables. Cognitive performance was analysed using a 2 (group: ACL-injured vs. healthy) × 2 (cognitive loading: easy vs. difficult) × 3 (BOS: sitting vs. normal-base walking vs. narrow-base walking) mixed model ANOVA. Alpha was set at 0.05. Multiple comparisons were corrected for using the Bonferroni adjustment method. Effect size (partial eta squared) and observed power were reported using SPSS.

Results

Age, height, weight, years of education and activity level were similar for the two groups (Table 1). The CWS in normal-base and narrow-base conditions was significantly lower in ACL-injured adults compared to healthy adults. Furthermore, narrow-base walking resulted in lower CWS compared to normal-base walking in both ACL-injured ($p < 0.001$) and healthy adults ($p < 0.001$).

Walking performance

For ACL-injured adults, but not in healthy adults, a slightly lower mean step velocity was obtained with concurrent

Table 2 Mean (standard deviation) of gait spatiotemporal parameters in different base-of-support and cognitive loading conditions for both ACL-injured and healthy groups

	No cognitive task		Easy cognitive task		Difficult cognitive task	
	ACL-injured	Healthy	ACL-injured	Healthy	ACL-injured	Healthy
Injured/matched control leg	~~Normal BOS~~					
Mean step length (m)	0.66 (0.09)	0.70 (0.04)	0.66 (0.07)	0.70 (0.04)	0.66 (0.08)	0.70 (0.04)
Mean step velocity (m/s)	1.27 (0.17)	1.41 (0.09)	1.26 (0.18)	1.41 (0.10)	1.26 (0.18)	1.40 (0.10)
Variability of step length[b] (%)	2.6 (1.4)	1.9 (0.7)	2.1 (0.7)	1.6 (0.7)	1.8 (0.5)	1.5 (0.6)
Variability of step velocity[b] (%)	3.2 (1.1)	2.6 (0.8)	2.9 (0.7)	2.5 (0.6)	2.5 (0.6)	2.8 (1.4)
Uninjured/matched control leg	Normal BOS					
Mean step length (m)	0.65 (0.09)	0.70 (0.04)	0.65 (0.07)	0.71 (0.05)	0.65 (0.07)	0.71 (0.04)
Mean step velocity (m/s)	1.23 (0.18)	1.41 (0.08)	1.23 (0.18)	1.41 (0.08)	1.24 (0.17)	1.42 (0.08)
Variability of step length (%)	2.5 (1.2)	1.9 (0.5)	2.1 (1.1)	1.7 (0.5)	1.9 (1.0)	1.5 (0.5)
Variability of step velocity (%)	3.0 (0.9)	2.6 (0.5)	2.9 (1.1)	2.5 (0.5)	2.7 (0.7)	2.6 (0.7)
Injured/matched control leg	~~Narrow BOS~~					
Mean step length (m)	0.55 (0.09)	0.63 (0.05)	0.56 (0.09)	0.64 (0.05)	0.56 (0.09)	0.65 (0.05)
Mean step velocity (m/s)	0.95 (0.24)	1.22 (0.11)	0.96 (0.25)	1.22 (0.11)	0.96 (0.25)	1.22 (0.11)
Variability of step length (%)	3.3 (1.3)	2.3 (0.8)	3.3 (1.3)	1.9 (0.7)	3.0 (1.5)	1.9 (0.6)
Variability of step velocity (%)	4.2 (1.5)	3.1 (0.7)	4.2 (1.4)	2.8 (1.0)	3.7 (1.6)	2.5 (0.6)
Uninjured/matched control leg	Narrow BOS					
Mean step length (m)	0.55 (0.09)	0.64 (0.05)	0.55 (0.09)	0.65 (0.05)	0.55 (0.09)	0.66 (0.05)
Mean step velocity (m/s)	0.93 (0.25)	1.22 (0.10)	0.92 (0.24)	1.23 (0.10)	0.92 (0.24)	1.22 (0.10)
Variability of step length (%)	3.4 (1.7)	2.3 (0.8)	3.3 (1.8)	1.9 (0.8)	3.2 (1.5)	1.8 (0.5)
Variability of step velocity (%)	4.3 (2.0)	3.0 (0.8)	4.1 (1.9)	2.9 (1.2)	3.7 (1.4)	2.6 (0.8)

ACL anterior cruciate ligament, *BOS* base of support

[a] Variability measures were reported as coefficient of variation, i.e. standard deviation divided by mean × 100

performance of the easy ($p < 0.01$) and difficult backward counting tasks ($p < 0.01$) compared to the non-dual task in the narrow-base condition (significant interaction of group by BOS by cognitive loading, Tables 2, 3).

Narrow-base walking resulted in a substantial decrease in step length in ACL-injured adults ($p < 0.001$) compared to a minor decrease in healthy adults ($p < 0.001$, significant interaction of group by BOS, Tables 2, 3). Narrow-base walking was also associated with a more pronounced increase in variability of step length in ACL-injured ($p < 0.001$) than in healthy adults ($p = 0.03$). Larger variability of step velocity was found in the narrow-base condition compared to the normal-base condition in ACL-injured adults ($p < 0.01$), while in the healthy group the difference between the two BOS conditions was not significant.

The two legs were found to be different in ACL-injured adults with the injured leg displaying a slightly larger step length compared to the uninjured leg ($p = 0.01$), whereas no difference was observed between the two legs in healthy adults (significant interaction of group by leg, Tables 2, 3).

The main effect of cognitive loading was significant for all variables with the exception of step velocity. For step length, post hoc analysis showed no significant difference between the three cognitive loading conditions. Concurrent performance of the difficult backward counting task resulted in a lower variability of step length ($p < 0.01$) and variability of step velocity ($p = 0.02$) compared to the single-task condition.

Cognitive performance

The significant main effect of cognitive loading and BOS indicated larger cognitive scores in the easy backward counting task compared to the difficult backward counting task and in sitting compared to either normal-base ($p < 0.05$) or narrow-base ($p = 0.01$) conditions (Tables 4, 5). Other main effects or interactions were not significant.

Discussion

The most important finding of the present study was a larger effect of BOS on gait parameters in ACL-injured adults than in healthy adults. Whereas the difference between two BOS conditions was minor in healthy adults, narrow-base walking resulted in a substantially smaller

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AQ1 **Table 3** Summary of analysis of variance for gait spatiotemporal variables: *F* ratio (*p* value; partial eta squared; observed power) by variable

	Mean step length	Mean step velocity	Variability of step length	Variability of step velocity
Main effect				
Group	12.1 (**<0.01**; 0.26; 0.92)	20.1 (**<0.001**; 0.37; 0.99)	11.5 (**<0.01**; 0.25; 0.91)	9.7 (**<0.01**; 0.22; 0.86)
BOS	106.3 (**<0.001**; 0.76; 1.00)	145.4 (**<0.001**; 0.81; 1.00)	40.7 (**<0.001**; 0.55; 1.00)	28.1 (**<0.001**; 0.45; 1.00)
Cognitive loading	3.6 (**<0.05**; 0.10; 0.59)	0.5 (n.s.; 0.01; 0.12)	8.9 (**<0.001**; 0.21; 0.97)	4.9 (**<0.05**; 0.13; 0.79)
Leg	1.0 (n.s.; 0.03; 0.16)	1.9 (n.s.; 0.05; 0.27)	0.0 (n.s.; 0.00; 0.05)	0.0 (n.s.; 0.00; 0.05)
Interaction				
Group × BOS	7.2 (**<0.05**; 0.17; 0.74)	8.1 (**<0.01**; 0.19; 0.79)	10.5 (**<0.01**; 0.24; 0.88)	12.7 (**<0.01**; 0.27; 0.93)
Group × cognitive loading	1.8 (n.s.; 0.05; 0.33)	1.2 (n.s.; 0.03; 0.25)	0.1 (n.s.; 0.00; 0.07)	1.4 (n.s.; 0.04; 0.29)
Group × leg	8.5 (**<0.01**; 0.20; 0.81)	4.0 (n.s.; 0.10; 0.49)	0.2 (n.s.; 0.01; 0.07)	0.0 (n.s.; 0.00; 0.05)
BOS × cognitive loading	1.9 (n.s.; 0.05;0.38)	4.2 (**<0.05**; 0.11; 0.72)	0.6 (n.s.; 0.02; 0.14)	0.9 (n.s.; 0.03; 0.21)
BOS × leg	0.2 (n.s.; 0.01; 0.07)	0.1 (n.s.; 0.00; 0.06)	0.1 (n.s.; 0.00; 0.06)	0.0 (n.s.; 0.00; 0.05)
Cognitive loading × leg	1.2 (n.s.; 0.03; 0.24)	1.0 (n.s.; 0.03; 0.23)	0.4 (n.s.; 0.01; 0.10)	0.2 (n.s.; 0.01; 0.08)
Group × BOS × cognitive loading	0.1 (n.s.; 0.00; 0.06)	3.2 (**<0.05**; 0.09; 0.60)	1.8 (n.s.; 0.05; 0.36)	0.6 (n.s.; 0.02; 0.15)
Group × BOS × leg	0.4 (n.s.; 0.01; 0.10)	0.2 (n.s.; 0.01; 0.07)	0.5 (n.s.; 0.02; 0.11)	0.3 (n.s.; 0.01; 0.08)
Group × cognitive loading × leg	2.6 (n.s.; 0.07; 0.47)	1.1 (n.s.; 0.03; 0.23)	0.5 (n.s.; 0.01; 0.13)	0.5 (n.s.; 0.01; 0.13)
BOS × cognitive loading × leg	1.7 (n.s.; 0.05; 0.34)	2.8 (n.s.; 0.08; 0.53)	0.2 (n.s.; 0.01; 0.07)	0.1 (n.s.; 0.00; 0.07)
Group × BOS × cognitive loading × leg	0.7 (n.s.; 0.02; 0.17)	2.8 (n.s.; 0.08; 0.54)	0.0 (n.s.; 0.00; 0.05)	1.0 (n.s.; 0.03; 0.22)

BOS base of support

Table 4 Mean (standard deviation) of cognitive scores in different base-of-support and cognitive loading conditions for both ACL-injured and healthy adults

	Sitting		Normal BOS		Narrow BOS	
	ACL-injured	Healthy	ACL-injured	Healthy	ACL-injured	Healthy
Easy backward counting task	49.3 (21.7)	55.5 (24.1)	46.3 (21.0)	52.9 (19.8)	43.4 (17.9)	52.4 (18.6)
Difficult backward counting task	27.0 (13.2)	33.4 (14.5)	25.4 (12.9)	30.3 (12.5)	24.0 (13.5)	32.5 (14.4)

BOS base of support

Table 5 Summary of analysis of variance for cognitive scores: *F* ratio (*p* value; partial eta squared; observed power) by variable

	Cognitive score statistics
Main effect	
Group	1.6 (n.s.; 0.05; 0.24)
BOS	6.7 (**<0.01**; 0.16; 0.90)
Cognitive loading	180.1 (**<0.001**; 0.84; 1.00)
Interaction	
Group × BOS	1. 5 (n.s.; 0.04; 0.30)
Group × cognitive loading	0.1 (n.s.; 0.00; 0.06)
BOS × cognitive loading	1.0 (n.s.; 0.03; 0.22)
Group × BOS × cognitive loading	0.1 (n.s.; 0.00; 0.70)

BOS base of support

step length and higher variability of step length and variability of step velocity in ACL-injured adults. The reduced step length can be viewed as a conservative strategy [25] adopted by ACL-injured adults to adapt to challenging narrow-base walking. However, as indicated by the increased variability of step length and variability of step velocity, ACL-injured adults demonstrate more unstable gait [11] when walking in a narrow path.

This conservative and unstable gait pattern in ACL-injured adults in the more challenging narrow-base condition may be due to high balance requirements in this condition. Previously, it has been shown that ACL-injured adults have impaired balance in a single leg stance [5, 19]. Loss of proprioceptive inputs from the knee mechanoreceptors, which has been shown in ACL-injured adults [9, 22], results in lesser or possibly inaccurate sensory information and has been proposed as the main determinant of postural control deficits [9].

It is also possible that ACL-injured adults have modified their gait pattern to meet increased visuomotor demands associated with walking in a narrow path. As visuomotor processing of gait is attention-demanding [15], one would expect narrow-base walking to have a larger effect when combined with a cognitive task. However, in narrow-base walking, we did not find additional changes in most gait parameters when a cognitive task (backward counting) was added. Dual tasking had only a marginal effect on step velocity in the narrow-base condition in ACL-injured adults. This suggests that modification of gait in ACL-injured adults ~~while~~ narrow-base walking is not largely attributable to visuomotor demands associated with the task. Moreover, while an overall effect of cognitive loading was present for most gait variables, including in normal-base walking, these effects were similar in ACL-injured and healthy adults.

Similarly, for ACL-injured adults, dual tasking did not result in further deterioration of backward counting task performance even in the narrow-base condition. These findings can be explained by the fact that walking is a well-learned skill and therefore an automatic process with minimal demands on attentional resources. Apparently, this does not change much after ACL injury, despite impaired proprioceptive input. A similar explanation has been suggested for the lack of a more pronounced effect of dual tasking in ACL-injured adults on other highly practiced skills such as quiet standing [18]. It is likely that dual tasking in more challenging conditions, for example in terms of balance demands, combined or with more challenging cognitive tasks such as Stroop task, may better discriminate ACL-injured adults from healthy adults. For instance, a single leg stance on an unstable surface combined with performance of a cognitive task has resulted in greater deterioration of postural stability in adults with ACL reconstruction than in healthy adults [17].

The results of the present study can help clinicians to identify the most relevant domains of walking adaptability in assessment and treatment of ACL-injured adults. As walking disorders following ACL injury are not limited to impairments of stereotyped rhythmical gait patterns, therapists should consider the need to assess and retrain locomotor skills in more challenging circumstances. The scope of assessment and treatment should be broadened to include aspects of terrain complexity, such as walking on a narrow walkway. Greater demands for walking adaptability will be achieved if patients walk on a narrow walkway combined with cognitive dual tasking. However, further research is needed to substantiate the latter recommendation in clinical settings.

Some limitations of the present study need to be discussed. One of the main limitations of this study is the relatively low sample rate (60 samples/s) used. While this sample rate has been used previously in studies on gait variability [12, 25], it may have affected the magnitude of variability measures. However, this would most likely affect our conditions and groups in a similar fashion, such that it would not affect our conclusions. Moreover, the percentage variability in normal walking was quite comparable to other findings (2.3 % stride length variability) in healthy young adults when the sampling rate was doubled [27]. ~~Another limitation is our small sample size.~~ Finally, although gait in the present study was assessed under functional conditions of narrow-base walking and dual tasking, simulation of real-world walking using the present protocol is still limited due to ecological validity of treadmill walking [21]. As an alternative to treadmill walking with stationary gait analysis systems, overground walking can be examined in future research using mobile gait analysis systems (e.g. inertial sensor units [6]). This provides the ability to assess gait during daily life, for a longer duration and at a lower cost.

Conclusion

Narrow-base walking was associated with a more conservative and more unstable gait pattern in ACL-injured adults. Based on balance demands imposed by narrow-base walking, deficits in postural control in ACL-injured adults can largely explain their impaired performance. An additional cognitive task did not affect ACL-injured adults more than healthy adults. This may be related to the automatic process of a well-learned task such as walking.

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