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Gait speed is more challenging than cognitive load on the stride-to-stride variability in individuals with anterior cruciate ligament deficiency

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ABSTRACT

Background: Several investigations have studied gait variability of individuals with anterior cruciate ligament (ACL) deficiency; however, the effect of dual-tasking on the gait variability of these individuals remained unclear. The aim of the present study was to determine the effect of gait speed and dual-tasking on knee flexion–extension variability in subjects with and without ACL deficiency.
Methods: The knee flexion–extension Lyapunov exponent (LyE) was measured in 22 ACL-deficient (Mean±SD) (25.95 ± 4.69 years) and 22 healthy subjects (24.18 ± 3.32 years). They walked at three levels of gait speed in isolation or concurrently with a cognitive task.
Results: Repeated-measure analyses of variance (ANOVAs) demonstrated that the interaction of group by gait speed was statistically significant. As the gait speed increased from low to high, the knee flexion–extension LyE significantly decreased for the subjects with ACL deficiency (effect size: 0.57, $P = 0.01$). The interaction of group by cognitive load was not statistically significant ($P = 0.07$). In addition, the ACL-deficient subjects had statistically slower reaction times than healthy subjects during the dual-task compared with the single-task condition.
Conclusions: The ACL-deficient and healthy individuals had a tendency to maintain safe gait. It seems that the ACL-deficient subjects sacrificed the cognitive task more than the healthy individuals to pay more attention toward gait. Additionally, it seems that the gait speed was more challenging than cognitive load on the stride-to-stride variability in the individuals with ACL deficiency.

1. Introduction

Anterior cruciate ligament (ACL) deficiency is one of the most common knee injuries. Anterior cruciate ligament deficiency is correlated with knee instability, functional limitation, muscle weakness, and an increased incidence of premature osteoarthritis [1]. In the United States, the annual incidence of ACL tear is 68.6/100,000 person-years [2]. Several authors have observed altered knee joint kinematics or kinetics in the gait patterns of people who have sustained significant ACL deficiencies [3–5]. In ACL

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deficiency, neuromuscular functions are changed due to pain, instability, fear, damaged mechanoreceptors, and diminished somatosensory information [6].

Previous findings have shown that motor coordination patterns may change during gait in ACL-deficient individuals, which could be associated with the decreased capacity to obtain sensory information. The gait changes observed in ACL-deficient subjects are mainly considered to be more knee extension during stance phase and less knee flexion during swing phase [7]. Stride-to-stride gait variability in the subjects with ACL deficient have been examined in previous studies [1,8]. It has been suggested that stride-to-stride gait variability likely reflects balance control during walking, and consistency of the stepping pattern [9]. These findings have revealed that ACL-deficient subjects demonstrate significantly less variable walking patterns than healthy individuals [8,10,11]. Decreased gait variability reflects a decline in the system's complexity, and this is one possible explanation for reduced executive function and ongoing functional instability (e.g., the ability to cope) [1]. This could imply that an ACL-deficient knee is more susceptible to injury [1,8], which may be related to impaired motor programming. The Lyapunov exponent (LyE) is a measure that estimates the fundamental structure of variability during movement, and it is mainly effective for movement data with inherent periodicity [12]. The LyE is a nonlinear measure that has been evaluated in treadmill walking and normal over ground walking, with and without performing dual tasks [13,14].

It is well established that walking requires some degree of central attention, even in healthy young adults without any central deficits [15]. The dual-task paradigm facilitates study of the effects of cognitive load on gait properties. Results have demonstrated that there is a high correlation between cognitive function and gait variability [14]. Cognitive loading provides a proper experimental set-up to challenge motor performance, such as gait variability, even in healthy young adults. Under motor cognitive dual-tasking, the healthy individuals choose strategies such as increased stride-to-stride gait variability and decreased gait speed [15]. A literature search revealed that decreased gait speed, extreme values of stride-to-stride gait variability, and central nervous system structural changes are independent and effective factors that are mostly related to gait instability and risk of falling. However, walking performance on complex locomotor tasks (e.g., walking with different speeds) and dual-tasking has been associated with gait variability, which is a potential pathway linking fall risk [16,17]. Understanding the role of dual-tasking and gait speed on gait variability could present insights into enhancing treatment efficacy. Previous studies have demonstrated that intervention may restore gait variability, which could be effective in minimizing the risk of falling [18]. However, using higher gait speeds as well as dual-tasking in ACL-deficient patients might present a suitable therapy to affect gait variability.

Some studies have examined the effect of cognitive load on the gait kinematics of ACL-deficient subjects. The results of these studies have shown that the cognitive task did not appear to compromise the gait kinematics in the ACL-deficient subjects more than the healthy controls [19,20]. There are three possible reasons as to why the dual-tasking effect was no different between the subjects with and without ACL deficiency. First, in the conducted studies, the knee joint kinematics were not considered — only spatiotemporal characteristics were measured. In other words, the effect of dual-tasking on the performance of spatiotemporal characteristics as a large-scale motor synergy would be masked with the compensation provided by smaller scale synergies such as knee kinematics [21]. Second, in these studies, the cognitive task performance only focused on error rates. The two main variables of such cognitive tasks are error rates (ERs) and reaction times (RTs). In other words, the effect of motor task difficulty on cognitive performance as an error rate would be masked with a delay in reaction time. Therefore, simultaneous assessment of reaction time and error rate could provide more comprehensive information regarding cognitive performance while performing dual tasks in these individuals. Third, the studies showed that gait difficulty could affect cognitive–motor interference [22]; thus, the ACL-deficient subjects should be exposed to more challenging conditions. Performing a more difficult motor task may better discriminate the dual-tasking effect. Increasing walking speed can challenge the movement control system [23]; therefore, walking speed would alter the allocation of attention during locomotion [22].

There are various studies that have examined stride-to-stride variability in subjects with ACL deficiency [1,8,11]. It is believed that there is no available information regarding the simultaneous effect of gait speed and cognitive load on stride-to-stride variability in subjects with ACL deficiency. Therefore, the main objective of the present study was to investigate the effect of simultaneous walking speed and cognitive load on the stride-to-stride variability in individuals with and without ACL deficiency.

2. Materials and methods

2.1. Participants

In the present study, 22 healthy males and 22 males with ACL deficiency, diagnosed by an orthopedic surgeon using magnetic resonance imaging, participated in the study (Table 1). All ACL-deficient participants had unilateral, non-acute and complete ACL tears with and without meniscus injury, and at least one giving-way episode since the time of injury, which was identified through asking a question. In addition, the ACL-deficient group was not classified into coping or non-coping subgroups. The subjects with ACL deficiency were recruited from Akhtar hospital via telephone contact. The control group volunteered from students through telephone contact and announcements. The mean time from injury to testing day was 26.33 months (standard deviation (SD) 22.5, range: six to 108 months). The symptoms and function of the involved knee joint were estimated using the Knee injury and Osteoarthritis Outcome Score (KOOS) questionnaire (mean 72.21, SD 13.45) [24]. The healthy group was matched with the ACL-deficient subjects according to age, height, weight, and sports activity level before injury. The level of sports activity for the two groups was measured by the Persian version of the TEGNER Activity Level Scale [25].

Exclusion criteria in both groups were: (1) a history of any injury; (2) fracture or osteoarthritis in lower limb joints; (3) a history of severe low back pain in the past six months; (4) use of any drug that could affect an individual's ability to perform

Table 1
Mean and standard deviation (SD) of demographic properties in the individuals with and without ACL deficiency.

Variables	ACLD group (n = 22)		Healthy group (n = 22)		*P*
	Mean	SD	Mean	SD	
Age (years)	25.95	4.69	24.18	3.32	0.15
Height (cm)	179.23	5.93	178.09	5.24	0.51
Weight (kg)	83.00	13.70	77.73	24.04	0.12
Gait speed	3.52	0.48	3.41	0.50	0.47
Sport activity level (TEGNER questionnaire)[a]	8.09	1.63	7.18	1.76	0.08
KOOS questionnaire[b]	72.21	13.45	N/A	N/A	N/A

P-values are related to the result of independent *t*-test.
ACLD, anterior cruciate ligament deficiency; N/A, not applicable.
[a] Range of score is 0–10.
[b] Range of score is 0–100.

physical activity and respond to cognitive tasks; (5) a history of visual impairment; (6) a history of neurological impairment; (7) vestibular deficit; (8) hearing problems; and (9) cognitive impairment. The test trial was repeated if feeling pain in the knee, which was obtained using a visual analog scale, was ≥3. Pain may cause changes in motor–cognition interaction [26], as well as gait variability [27] in people with musculoskeletal problems [28]. After briefing about the research protocol, which complied with the principles of the Declaration of Helsinki, the participants were asked to sign an informed consent form. The study was approved by the Ethical Committee of the University of Social Welfare and Rehabilitation Sciences.

2.2. Procedure

Walking on the treadmill (Stingray, M8000i, made in Taiwan) was performed at three walking speed levels (self-selected, high and low speed) and two levels of cognitive task difficulty (with and without cognitive load) [11]. All subjects walked on the treadmill with their own shoes throughout the study. Prior to any data collection, all participants were given six minutes to warm up and familiarize themselves with the treadmill at their self-selected speed [29]. They were also given four minutes to get familiar with the auditory Stroop test. The self-selected speed was identified by starting at a low speed followed by subsequent slow speed-up and speed-down of the treadmill until the participant stated that the walking speed was upper/lower than the self-selected speed. This process was repeated three times, and the mean of three 'upper than self-selected' and three 'lower than self-selected' speeds was calculated as the self-selected speed [30]. It should be noted that during the process of determining self-selected speed, the subjects were blind to their walking speed. After calculating the high speed (20% higher than the self-selected speed), the low speed (20% lower than the self-selected speed) was calculated. Performing cognitive tasks and recording kinematic measures were performed simultaneously.

The Vicon Motion System (Vicon Motion System Ltd.®, Oxford, UK) with five cameras was used for gait analysis. The sampling frequency was set at 100 Hz. Marker placement was performed on the 15 bony landmarks of the lower extremities and pelvis (based on Helen Hayes' method). These landmarks include: both anterior superior iliac spines, mid-thigh lateral femoral epicondyles, mid tibias, lateral malleolus, outsole of the shoes approximately at the second metatarsal heads, heels, and sacrum (the midpoint between the two posterior superior iliac spines) [1,8,11]. The tests were conducted at 95-second and three-minute intervals. This three-minute interval was considered to reduce the effect of fatigue and prevent its likely outcome on the test. Using the Davis algorithms [31], the three dimensional angular displacement of the knee joint was calculated. The knee kinematic during gait was not filtered before the analysis. In this way, a more precise image of the variations within the system was obtained [8]. The present study only measured sagittal angular knee displacement. Data from the other planes collected via skin markers are associated with increased error [32]. Matching the leg of the control group was performed by the dominant limb. For example, if the individual's dominant limb in the anterior cruciate ligament deficiency (ACLD) group was the involved limb, the dominant leg of the matched one was analyzed as the control. The foot used to kick the ball was considered as the dominant limb.

The LyE was measured using Chaos Data Analyzer (CDA) software (professional version 2.1). This software was developed by Julien C Sprott from the Physics Department of Wisconsin University, Madison, United States. The LyE quantifies the separation rate of infinitesimally close trajectories. The LyE for sagittal angular knee displacement time series was calculated using the algorithm presented by Wolf et al. [33] The LyE is zero for periodic data where there is no divergence in the trajectories. In the other words, the trajectories overlap rather than diverge in the phase space. Five embedded dimensions were found for the present calculation [12]. The LyE is relatively large for random noise when trajectories in the phase space have large divergence.

For measuring the cognitive performance, the auditory Stroop test was used. The auditory Stroop test can measure both reaction time and error rate as cognitive performance simultaneously. This assignment was also used in the other studies to examine the simultaneous effects of the motor task difficulty on the cognitive performance [34–36]. The auditory Stroop test is a modification of the Stroop test that has been described as a judgment of the tone of the stimulus word [36]. The subjects responded vocally while they were questioned with the words 'low' and 'high'. Hence, the participants had to respond to the stimulus

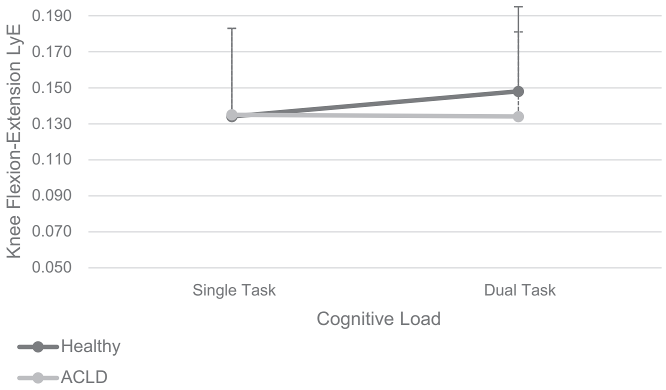

Figure 1. The interaction of groups (healthy and ACL-deficient subjects) and cognitive load (single-task and dual-task conditions) on knee flexion–extension Lyapunov exponent during walking. ACLD, anterior cruciate ligament deficiency; LyE, Lyapunov exponent.

based on the sound tonicity, not the words. For example, when the word 'low' was played with high pitch, the subject should report it after detection of the played word in the shortest possible time. In the present example, the correct answer is 'high'. In each test, the subjects responded 28–30 times to the desired questions. The reaction time was calculated as the average of all required times for the subjects to respond to the stimuli. The ERs were calculated using this formula: the number of the incorrect responses divided by the total number of stimuli. It should be noted that the stimuli were presented in random order. The cognitive test was run by a custom made MATLAB program (MATLAB R2012 a, Mathwork, Inc.). For playing and recording the sound, a wireless handset microphone was used (LEM-NP 101, Taiwan).

2.3. Statistical analysis

The background variables of the two groups were compared using a series of independent *t*-tests. Furthermore, a three-way ($2 \times 3 \times 2$) (two groups; three levels of gait speed; two levels of cognitive task) analysis of variances (ANOVA) with repeated measures was employed to evaluate the main and interaction effects of the group by walking speed by cognitive load on the dependent variable (knee flexion–extension LyE). A two-way (2×4) (two groups; four levels of motor task difficulty) ANOVA with repeated measures was used to evaluate the main effect and the interaction of the group by walking speed on the dependent variables (reaction times and error rates). Post-hoc analysis was conducted using Bonferroni correction method. The alpha level was set five percent for all tests.

3. Results

There was no significant level of difference between the ACL-deficient and healthy subjects in terms of age, height, weight, and sports activity level ($P > 0.05$).

The interaction of the group by cognitive load was close to a marginally significant level ($P = 0.07$) for the knee flexion–extension LyE. In healthy individuals, the knee flexion–extension LyE increased (statistically not significant) as the cognitive load was imposed on walking (effect size (ES): 0.34). But for the ACL-deficient subjects, the knee flexion–extension LyE was not altered once the cognitive load was added to the walking task (ES: 0.02) (Figure 1). In other words, the knee flexion–extension variability became more random for the healthy individuals and remained consistent for the ACL-deficient subjects due to the cognitive load.

The interaction of the group by gait speed was statistically significant for the knee flexion–extension LyE ($P = 0.01$) (Table 2). As the gait speed increased from the 'self-selected' to 'high' speed, the knee flexion–extension LyE did not change significantly in

Table 2
Mean and standard deviation (SD) of the LyE parameters during walking in the individuals with and without ACL deficiency.

Dependent variables	Gait velocity	Single task		Dual task	
		ACLD Mean (SD)	Healthy Mean (SD)	ACLD Mean (SD)	Healthy Mean (SD)
Hip flexion–extension LyE	High	0.106 (0.024)	0.115 (0.041)	0.106 (0.030)	0.120 (1.10)
	Self-selected	0.111 (0.024)	0.108 (0.035)	0.116 (0.024)	0.116 (50.51)
	Low	0.113 (0.026)	0.115 (0.024)	0.104 (0.027)	0.106 (0.027)
Knee flexion–extension LyE	High	0.123 (0.046)	0.139 (0.054)	0.125 (0.053)	0.150 (0.071)
	Self-selected	0.133 (0.048)	0.121 (0.039)	0.136 (0.053)	0.161 (0.089)
	Low	0.148 (0.049)	0.141 (0.054)	0.134 (0.042)	0.134 (0.053)

ACLD, anterior cruciate ligament deficiency; LyE, Lyapunov exponent.

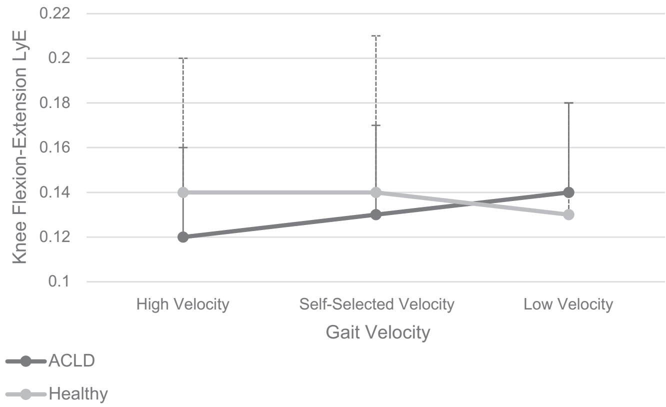

Figure 2. The significant interaction of groups (healthy and ACL-deficient subjects) and gait velocity (high, self-selected and low) on knee flexion–extension Lyapunov exponent during walking. ACLD, anterior cruciate ligament deficiency; LyE, Lyapunov exponent.

the healthy subjects (ES: 0.09). As the gait speed increased from the 'low' to 'high' speed, the knee flexion–extension LyE did not change in the healthy subjects (ES: 0.18). As the gait speed increased from the 'self-selected' to 'high' speed, the knee flexion–extension LyE significantly decreased in the subjects with ACL deficiency (ES: 0.57). As gait speed increased from the 'low' to 'high' speed, the knee flexion–extension LyE remarkably reduced in the subjects with ACL deficiency (ES: 1.27) (Figure 2). In the other words, LyE did not change with increasing gait speed in the healthy individuals, but decreased with rising gait speed in the ACL-deficient participants.

The interaction of the group by motor task difficulty was not statistically significant for the average reaction time and error rate. The main effects of the group were statistically significant for the average reaction time (Table 3). The average reaction times were significantly longer in the ACL-deficient subjects during the dual-task conditions as compared with those of healthy individuals (high speed (ES: 0.67), 'self-selected' (ES: 0.67) and 'low' speeds (ES: 0.80)) (Table 4). There was no statistical difference in the average reaction time in both groups during sitting position (single task) (ES: 0.56). In other words, the reaction time increased in dual-tasking conditions for the individuals with ACL deficiency as compared with the healthy controls (Table 5).

4. Discussion

The results of the present study indicate that the ACL-deficient knee had lower knee flexion–extension LyE when walking velocity was increased to 'high' speed. In addition, the results demonstrate that the dual-tasking effect was no different between the ACL-deficient and healthy subjects. Moreover, the results suggest that although there was no statistical difference in the cognitive performance in sitting position, the reaction time during dual-task conditions was higher in the subjects with ACL deficiency compared to the healthy controls, regardless of gait speed (Figure 3).

The present results suggest that the ACL-deficient subjects had more deterministic patterns during the 'self-selected' speed; however, this was not statistically significant. This pattern is in agreement with results from investigations demonstrating that ACL-deficient patients had less variable walking patterns than healthy controls [1,11,12]. Decreased variability could suggest declined functional responsiveness to the environmental changes for the ACL-deficient knee. In addition, Stergiou et al. examined the effect of walking speed on knee flexion–extension LyE in ACL-deficient individuals. Their results revealed that knee flexion–extension LyE decreased once the walking speed increased (not significant, *P*-value was not reported) [11]. In the present

Table 3
Results of three-way ANOVAs for LyE measures during walking: F ratios and *P*-values by variable.

Independent variables	Hip flexion–extension LyE		Knee flexion–extension LyE	
	F	*P*	F	*P*
Main effect				
Group	0.02	0.89	0.22	0.64
Gait velocity	0.34	0.71	0.46	0.63
Cognitive load	0.01	0.94	0.40	0.84
Interaction				
Group × gait velocity	1.34	0.36	4.73	**0.01**
Group × cognitive load	0.78	0.38	3.60	**0.07**[a]
Gait velocity × cognitive load	4.02	**0.02**	2.59	0.10
Group × gait velocity × cognitive load	0.20	0.82	1.42	0.25

$P \le 0.05$ are in bold.
LyE, Lyapunov exponent.
[a] Close to a marginally significant level.

Table 4
Results of two-way ANOVA for average reaction time and error ratio during walking: F ratios and *P*-values by variable.

Independent variables	Reaction time		Error ratio	
	F	*P*	F	*P*
Main effect				
Postural difficulty	0.02	0.89	0.86	0.47
Group	6.11	**0.02**	2.08	0.16
Interaction				
Postural difficulty × group	0.08	0.78	0.90	0.44

$P \leq 0.05$ is in bold.

study, the interaction of walking speed by group was statistically significant. Comparing the effect sizes reveals that there are similar values between these two mentioned studies. For example, the effect size of the knee flexion–extension LyE between the 'high' and 'low' walking speed in the present study and the previous one [11] was 0.57 and 0.64, respectively. The difference in the *P*-value reported in the previous study might be as a result of inadequate sample size (10 subjects with ACL deficiency).

Negahban et al. investigated the effect of postural task difficulty on the nonlinear pattern of postural sway for ACL-deficient subjects [37]. They observed that the nonlinear pattern of postural sway demonstrated a more predictable pattern as the postural task difficulty increased. They concluded that regularity of center of pressure (COP) time series may reduce the ability of the ACL-deficient knee to adapt to various changes, leading to future injury and pathology [37]. This conclusion is in agreement with the results of the present study. The healthy individuals did not have significant changes in knee flexion–extension LyE at different walking speeds. The subjects with ACL deficiency preferred to change their strategy in a way that the knee flexion–extension LyE decreased, especially at higher speeds.

The results of the current study did not support the original hypothesis. Simultaneous exposure of cognitive and walking tasks revealed similar gait performance for both groups. The results of this study are in the agreement with the study conducted by Negahban et al. They also did not observe significant interaction of group by cognitive load [3]. Importantly, the present study is also in agreement with a study conducted by Mazaheri et al., who investigated the effect of dual-tasking on the variability of step length and step velocity in individuals with ACL deficiency. Similarly, the results indicated that the variability of spatiotemporal characteristics in both groups was identical during dual-task conditions [19]. They could be related for several reasons. First, they might be related due to complexity of motor tasks. It seems that gait in ACL-deficient individuals is a well-learned and less attention-demand skill [38] because they have been doing it for many hours per day for their whole life. In the other words, walking on a treadmill is not sufficient for differentiation, and a more complex motor task is needed. Similar to these findings, Hoffman et al. reported that there were no differences in postural static tests between patients undergoing ACL reconstruction and a healthy group. However, in dynamic postural conditions, there was a significant difference in the rate of postural fluctuations between the two mentioned groups [39]. As shown in Figure 1, the knee flexion–extension LyE increased during dual-tasking in healthy subjects (ES: 0.34), but it was not changed in ACL-deficient subjects (ES: 0.02). Second, it might be associated with the error compensation mechanism. The error compensation is a task-specific approach, in a way that once an error occurs in a system with an impact on the final output, the other components (synergies) modify their roles to compensate the effect of the error on the overall performance of the system [21]. In agreement with this hypothesis, Lindstrom et al. showed that despite changes in muscle performance, kinematic changes were not observed in subjects with chronic ACL rupture [40]. Similarly, Fraizer et al., in their literature review, indicated that muscle performance increased during dual-tasking. They concluded that poor balance in individuals would be compensated by increasing muscle activity while performing a dual task [41]. To have proper judgment about the system's behavior during dual-task performances, it is important to have all the elements of the system, including muscle and brain activities.

The results of this study revealed that the interaction of the group by motor task difficulty was not statistically significant for the reaction time and error rate. Similarly, post-hoc analysis revealed that the reaction time in the subjects with ACL deficiency during dual-task conditions (walking with cognitive load) was higher than healthy subjects. There was no between-group difference during a single task condition (sitting position). Both groups in the present study comprised young adults. Briefly, it demonstrated that the young adults understood the complexity of the multiple task performance, and purposely shifted their attention toward accomplishing one part of the more complex task at the expense of some other tasks. One possible way of

Table 5
Results of independent *t*-tests for average reaction time in four levels of postural task difficulty in the individuals with and without ACL deficiency.

Variable	Motor task conditions	ACLD		Healthy		*t*	*P*
		Mean	SD	Mean	SD		
Reaction time (seconds)	Walking with high velocity	0.67	0.13	0.59	0.11	−2.28	**0.03**
	Walking with self-selected velocity	0.67	0.11	0.59	0.13	−2.07	**0.04**
	Walking with low velocity	0.70	0.13	0.60	0.12	−2.21	**0.03**
	Sitting position	0.66	0.15	0.59	0.10	−1.69	0.10

$P \leq 0.05$ are in bold.
ACLD, anterior cruciate ligament deficiency; SD, standard deviation.

Figure 3. The interaction of groups (healthy and ACL-deficient patients) and postural task difficulty (walking with high, self-selected and low velocity, and sitting) on average reaction time. ACLD, anterior cruciate ligament deficiency.

preventing falling was to decrease the complexity of more complex tasks (gait) through decreasing gait speed [42]. Another strategy for fall prevention is to change the priority from the cognitive task to the gait through diminishing the cognitive performance. This strategy is usually employed for young adults. In the present study, since the treadmill did not allow for decreasing gait speed, the ACL-deficient and healthy participants could possibly have sacrificed the cognitive task to pay more attention toward gait. Since the participants were more inclined toward not falling rather than proving a rapid response to an unrewarding cognitive task, a bias toward fall prevention might have been created. The young ACL-deficient and healthy participants had the ability to maintain a posture-first strategy when the focus of their attentions was directed toward the cognitive tasks [43].

The current results support the idea that ACL-deficient subjects do not have the cognitive capacity to handle dual-task conditions without altering cognitive performance. This might be related to the fact that patients suffering from pain walk with less automaticity [44]. These findings are supported by several studies [35,43,45]. These treatments and their roles on walking performance have not been investigated, thus this could be an attractive research topic for future studies.

This study had several limitations. One was that the participants walked on a treadmill instead of walking on the ground. Terrier found that walking on a treadmill could induce high gait stability and decrease a correlation pattern in stride intervals, but might not change variability of kinematic measurements for healthy individuals [46]. It was necessary to use a treadmill in this study to maintain a constant walking speed during walking for a long period of time. Thus, the obtained results cannot be generalized to over-ground walking. Additionally, another limitation was the effect of shoe type on gait variability. Therefore, the effect of different shoe types on gait kinematics should be investigated. Furthermore, only evaluation of the kinematic parameters in male subjects was investigated, and evaluation of lower limb muscle performance was not addressed.

It is suggested that future research considers the knee muscle activity patterns during dual-task conditions in subjects with ACL deficiency. Also, future studies should be conducted to examine the dual-tasking effect on gait kinematics of women suffering from ACL deficiency [47]. As depicted in Figure 1, more difficult motor and cognitive tasks challenge the stride-to-stride gait variability (although not significantly). Thus, use of more difficult motor and cognitive tasks may better differentiate ACL-deficient and healthy individuals during dual-task constraints. Collecting surrogate measures for cortical activity during walking demonstrated that complex tasks (gait under challenging conditions including dual-tasking and gait speed) seem to influence the prefrontal brain activity in young individuals [15]. Based on these results, ACL-deficient subjects have less variable knee kinematics under challenging conditions, including faster gait speed and higher dual-tasking, as compared to healthy individuals (although there were no significant differences in dual-tasking). Kruz et al. demonstrated that gait variability was partially correlated with sensorimotor cortical activation, as measured by Functional Near-Infrared Spectroscopy (fNIRS) [48]. It is suggested that the brain activity of ACL-deficient subjects be investigated during complex motor tasks such as dual-task/high speed walking in future studies.

5. Conclusion

The result of the present study demonstrated that ACL deficiency might be one factor that modulates the motor–cognition interaction. Performing both motor and cognitive tasks simultaneously in ACL-deficient subjects might result in shifting more attention toward the motor task. This causes the cognitive task to be sacrificed. Additionally, it seems that gait speed is more challenging than cognitive load on stride-to-stride variability for the individuals with ACL deficiency. The present study provides evidences that more difficult motor and cognitive tasks probably differentiate the ACL-deficient subjects from healthy individuals during dual-tasking. The results suggest that physiotherapists and clinicians could focus on cognitive load as well as high-speed walking to challenge the knee during rehabilitation of ACL-deficient patients.

Conflicts of interest

None.

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