The effects of dual-tasking on postural control in people with unilateral anterior cruciate ligament injury

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ABSTRACT

Several studies have investigated postural control in anterior cruciate ligament (ACL) deficient patients; yet the contribution of cognitive processing (attention) in the postural control of these patients is still unclear. A dual-task design was used to determine the effects of a concurrent digit span memory task on standing balance in a group of ACL patients \( n = 27 \) compared with a group of matched, healthy participants \( n = 27 \). In double limb stance, three levels of postural difficulty were studies on a force platform (rigid surface with eyes open, rigid surface with eyes closed, and foam surface with eyes closed). There were three cognitive conditions (no cognitive task, easy cognitive task and difficult cognitive task). For double limb stance, a mixed model analysis of variance showed that in the presence of a cognitive task, postural control was compromised yet there was no interaction between cognitive task difficulty and group (ACL or control). For single limb stance, the more difficult cognitive tasks were associated with lower standard deviations for velocity in the antero-posterior direction and the phase plane portraits. This cognitive task did not appear to compromise postural control in ACL injured patients to a greater extent than unimpaired people. Future studies should examine ACL patients with more severe disabilities and expose them to more demanding dynamic balance conditions to further explore dual-tasking effects.

1. Introduction

Injury to the anterior cruciate ligament (ACL) can compromise performance in sporting and recreational activities and have adverse effects on health and quality of life [1]. Adults with ACL injuries are known to have disturbed postural control on the injured leg [2,3]. A deficit in proprioception has been proposed as one factor associated with poor postural control in ACL deficient (ACLD) patients [2,3]. The role of higher cognitive processes in postural control remains unclear.

Recent research indicates that control of posture requires some degree of central attention, even in young healthy people without any central deficits [4,5]. The use of a dual-task paradigm enables investigation of the effects of cognitive tasks on balance [4,5]. According to the “limited capacity theory” of attention, if two tasks are performed together, they both compete for attention, which may affect the performance of one or both. The extent to which the performance on either task deteriorates indicates the level of interference between the two tasks [6]. Some researchers have reported that increasing the cognitive load during a challenging balancing task increases body sway [7,8]. Others reported decreased sway [9,10] or no change [11] in performance.

Decreases in cognitive performance have been demonstrated in some musculoskeletal conditions [12,13,14]. Swanik et al. [15] provided evidence that reduced cognitive processing ability is associated with subsequent ACL injury in challenging sports, possibly due to reduced neuromuscular control at the knee. Neurocognitive function was examined in 160 university athletes. Small yet statistically significant decreases in verbal memory, visual memory, processing speed, and reaction time were found in...
athletes who went on to have ACL tears. A potential factor that can affect the posture–cognition interaction in people with musculoskeletal injuries is the presence of pain. Pain may lead to changes in postural control as a result of the increased demand placed on attentional resources [16].

The aims of the present study were twofold: (1) to compare postural control between ACLD and healthy individuals and (2) to examine the interaction of postural and cognitive tasks between the two groups.

2. Material and methods

2.1. Participants

All participants signed an informed consent form which had been approved by the Ethics Committee at Tehran University of Medical Sciences before commencing the study (reference number 260-310). Twenty-seven male patients were investigated. They were recruited from the Department of Orthopedics at Moayeri Hospital and Milad Hospital, Tehran, Iran, via referral by an orthopedic surgeon. Inclusion criteria were: (1) non-operated, non-acute, complete ACL rupture with and without meniscal injury as confirmed by magnetic resonance imaging and clinical knee stability testing; (2) pain no more than grade two according to a Visual Analogue Scale at the time of assessment [17]. Since focused attention toward pain stimuli can temporarily reduce attentional capacity [16], it was considered as a factor that may confound the posture–cognition interaction; (3) absence of injuries involving the contra-lateral limb, neck or back [18] and (4) no history of ankle sprain on the ACLD side.

The Knee Injury and Osteoarthritis Outcome Score (KOOS) [19] was used to evaluate knee function in potentially stressful knee movements over the week prior to testing. The KOOS includes five subscales with a scoring range of 0–100. Higher scores represent mild knee problems (0 = severe disability, 100 = no disability). The Persian-version of KOOS is a reliable and valid outcome measure used for ACLD patients [19]. The Tegner activity scale [20] was used to comprehend the activity level of the two groups prior to injury. This scale is based on activity levels for sport (recreational or competitive, football, volleyball, etc.) and occupational activities involving light or heavy labor. It has 10 items with a scoring range of 0–10 for which higher scores represent higher levels of physical activity. The Tegner activity scale has acceptable psychometric properties for patients with knee injuries [20]. Most patients had injured their ACL during football.

The control group consisted of 27 male participants. They were recruited from uninjured teammates via invitation and through telephone contact. They were matched with the patients according to age, height, body mass index, activity level and sports background (Table 1). Patients and healthy participants completed a questionnaire prior to participation and were excluded if they had a history of musculoskeletal disorders including ACL injury [26]. The results showed that patients with musculoskeletal disorders including ACL injury [26]. The results showed that patients with musculoskeletal disorders including ACL injury [26].

2.2. Postural task

Although double limb stance (DLS) may be maintained by an ankle/hip strategy, altered characteristics demonstrated in the muscles of the ACL deficient leg [21] have the potential to affect balance in this position. Therefore, postural stability measurements were obtained in both DLS and single limb stance (SLS).

2.3. Cognitive task

A backward digit span task was selected as the cognitive task because it avoids potential alterations to postural sway demonstrated in cognitive tests using manual (button pressing) tasks [23] or visual focus [24]. The cognitive task required participants to hold a string of random digits in mind while rehearsing it in reverse order [16]. Difficulty was manipulated according to the length of the digit string relative to the individual’s maximum digit span. Maximum digit span was determined by administering a backward digit test of the Wechsler intelligence scale [16]. The maximum number of digits recalled plus one constituted the number of digits presented in the difficult cognitive task. The easy cognitive task presented half of the digits of the difficult task, rounded up when the number was odd.

2.4. Procedure

For DLS, three levels of postural difficulty (RO, RC, and FC) and three levels of cognitive difficulty (no-task, easy and difficult) were examined. For the condition where there was no cognitive task, participants were instructed to stand barefoot on the force plate. For the easy and difficult cognitive task conditions, participants were instructed to listen carefully to a random digit string repeated twice before beginning data collection. During the 30 s of data collection, participants were instructed to mentally rehearse the string of numbers in reverse order and to focus on accuracy with each repetition. Immediately after data collection, participants were requested to recall the reversed digits. Three different types of cognitive error were documented: intrusion (a wrong number), order error, or omission (a number missing) [23]. COP data were collected with a sampling frequency of 200 Hz.

Four levels of postural difficulty (sitting, RO, RC, and FC) and two levels of cognitive difficulty (easy and difficult) were combined in order to examine the effect of the postural task on cognitive performance.

In SLS, in the no-cognitive task condition, participants were instructed to stand one limb with open arms (30-degree abduction) for 20 s of data collection. The knee of the unsupported leg was in slight flexion [30].

In sum, each participant was exposed to 15 experimental conditions. Three trials with a rest period of 5 min between each condition were performed. All of the cognitive trials nested in each postural condition were fully randomized. The different postural conditions were also randomly presented.

To minimize learning effects, postural and cognitive tasks were explained to each participant before starting the measurements. Also, standing on the foam surface was practiced for a short period to reduce the task novelty. The whole experiment lasted approximately 120 min for each participant.

2.5. Data analysis

The dependent variables were postural sway and cognitive error. Anteroposterior (AP) and medio-lateral (ML) displacements of the COP were measured along the y-axis and x-axis of the force platform, respectively. COP signals were filtered using a zero-phase, sixth-order, Butterworth low-pass filter with a cut-off frequency of 10 Hz [26]. To examine postural performance, mean velocity, phase plane portrait, and standard deviation (SD) of velocity in AP and ML directions were calculated. A phase plane portrait, which is the square root of variances of velocity and displacement, was used to quantify the phase plane information and changes in stance stability [25]. The rationale for choosing multiple COP measures was their ability to measure different aspects of postural behavior. For instance, mean velocity and SD of velocity capture the dynamic aspects of postural control while phase plane portrait provides insight into static and dynamic aspects of postural control by including both velocity and amplitude in the analysis [25]. Also, a pilot study was performed by our research group to estimate the test-retest reliability of the above parameters in a group of patients with musculoskeletal disorders including ACL injury [26]. The results showed intra-class correlation coefficient ranges of 0.74–0.91, 0.68–0.82, 0.50–0.83 and 0.69–0.77 for mean total velocity, phase plane portrait, and SD of velocity in AP and ML directions, respectively, for different conditions of postural difficulty.

2.6. Statistical analysis

The average values of dependent variables for three trials of each experimental condition were used for statistical analysis. To examine postural performance in double stance conditions, separate 2 × 3 × 3 (two groups; three levels of postural difficulty; three levels of cognitive difficulty) mixed model of analysis of variance

Table 1: Demographic and functional characteristics of ACL-deficient and healthy groups.

<table>
<thead>
<tr>
<th></th>
<th>ACLD group (n=27)</th>
<th>Healthy group (n=27)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>(mean differences)</td>
</tr>
<tr>
<td>Demographic data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>26.74 (5.84)</td>
<td>26.29 (5.07)</td>
<td>0.76</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.77 (0.64)</td>
<td>1.79 (0.55)</td>
<td>0.16</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>23.69 (2.42)</td>
<td>22.84 (2.38)</td>
<td>0.20</td>
</tr>
<tr>
<td>Duration of injury (yr)</td>
<td>1.80 (2.23)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Tegner scalea</td>
<td>6.30 (0.77)</td>
<td>6.04 (0.85)</td>
<td>0.24</td>
</tr>
<tr>
<td>KOOSb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pain</td>
<td>67.14 (21.89)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Symptom</td>
<td>56.77 (11.84)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Activity daily</td>
<td>71.88 (22.38)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Sport and recreation</td>
<td>32.96 (27.57)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Quality of life</td>
<td>32.51 (24.20)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

ACLD: anterior cruciate ligament-deficient; N/A: not applicable.

a Range of scores is from 0–10.
b Range of scores is from 0–100.
(ANOVA) tests was used to determine main effects and interactions of these factors for each of the COP measures. For multiple comparisons, the Bonferroni adjustment method was used [27].

Separate $2 \times 2$ (two groups; two levels of cognitive difficulty) mixed model ANOVAs were used for SLS on the injured leg and non-injured leg (and their matched leg in the control group). A paired $t$-test was used to determine any significant difference between injured and non-injured legs.

Since the cognitive errors were not normally distributed, a log transformation was applied before doing the statistical analysis [27]. All cognitive errors were made in the difficult cognitive task conditions. Hence, for DLS conditions a $2 \times 4$ (two groups; four levels of postural difficulty) mixed model of ANOVA was used to detect possible main effects and interactions on the transformed errors of the difficult cognitive task conditions. For SLS conditions, an independent $t$-test was used to determine any cognitive error difference between the two groups.

### 3. Results

#### 3.1. Postural performance for double stance conditions

Table 2 shows the mean and SD of COP measures in different conditions of postural and cognitive difficulty for both groups. A summary of ANOVA results for the four measures of postural performance is shown in Table 3.

The main effects of group, postural difficulty and cognitive difficulty were statistically significant for all parameters. Interaction of postural by cognitive difficulty was significant for all dependent variables. Repeated-measures ANOVA revealed that the interaction of postural by cognitive difficulty was significant for all parameters. Interactions of group by postural difficulty, group by cognitive difficulty and group by postural by cognitive difficulty were not significant for any of the dependent variables with the exception of the SD of velocity in the AP direction for which group by postural difficulty interaction was significant ($F_{2,104} = 3.70, p = 0.03$) (Fig. 1). The independent $t$-test showed significant differences in the two groups in RC and FC conditions ($p < 0.01$) but not in the RO condition ($p = 0.15$).

Also, to determine whether a trade-off occurred between postural and cognitive performances, we re-analyzed all data after eliminating trials in which cognitive errors were made [28]. The analyses showed that the overall pattern of results did not change.

#### 3.2. Cognitive performance for double stance conditions

All cognitive errors were made in the difficult cognitive task conditions. The number of errors performed in sitting, RO, RC, and FC conditions was 34, 47, 48, and 51 for the ACLD group and 7, 23, 24, and 36 for the healthy group, respectively.

The main effect of group was statistically significant ($F_{1,52} = 5.49, p = 0.02$) meaning that cognitive errors of patients in all conditions of postural difficulty ($F_{2,106} = 24.67, p < 0.01$ in RO; $F_{2,106} = 11.25, p < 0.01$ in RC; and $F_{2,106} = 37.60, p < 0.01$ in FC). Multiple comparisons showed that mean velocity decreased with an increase in the level of cognitive difficulty. The same pattern of results was obtained for other parameters.

### Table 2

Mean and standard deviation of COP parameters in different conditions of postural and cognitive difficulty for both ACLD and healthy groups in double limb stance.

<table>
<thead>
<tr>
<th>Levels of postural difficulty</th>
<th>Levels of cognitive difficulty</th>
<th>No task</th>
<th>Easy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACLD</td>
<td>Healthy</td>
<td>ACLD</td>
</tr>
<tr>
<td>Rigid surface—eyes open</td>
<td>Mean velocity</td>
<td>1.50(0.23)</td>
<td>1.37(0.11)</td>
</tr>
<tr>
<td></td>
<td>Phase plane</td>
<td>2.21(0.34)</td>
<td>2.02(0.30)</td>
</tr>
<tr>
<td></td>
<td>SD of velocity (AP)</td>
<td>1.39(0.24)</td>
<td>1.35(0.31)</td>
</tr>
<tr>
<td></td>
<td>SD of velocity (ML)</td>
<td>1.51(0.26)</td>
<td>1.32(0.15)</td>
</tr>
<tr>
<td>Rigid surface—eyes closed</td>
<td>Mean velocity</td>
<td>2.25(0.54)</td>
<td>1.95(0.31)</td>
</tr>
<tr>
<td></td>
<td>Phase plane</td>
<td>3.32(0.79)</td>
<td>2.80(0.41)</td>
</tr>
<tr>
<td></td>
<td>SD of velocity (AP)</td>
<td>2.02(0.42)</td>
<td>1.69(0.28)</td>
</tr>
<tr>
<td></td>
<td>SD of velocity (ML)</td>
<td>2.38(0.68)</td>
<td>2.01(0.35)</td>
</tr>
<tr>
<td>Foam surface—eyes closed</td>
<td>Mean velocity</td>
<td>4.02(0.66)</td>
<td>3.71(0.46)</td>
</tr>
<tr>
<td></td>
<td>Phase plane</td>
<td>5.82(0.86)</td>
<td>5.35(0.70)</td>
</tr>
<tr>
<td></td>
<td>SD of velocity (AP)</td>
<td>3.73(0.56)</td>
<td>3.29(0.57)</td>
</tr>
<tr>
<td></td>
<td>SD of velocity (ML)</td>
<td>3.97(0.68)</td>
<td>3.78(0.60)</td>
</tr>
</tbody>
</table>

COP: center of pressure; ACLD: anterior cruciate ligament deficient; SD: standard deviation; AP: anteroposterior; ML: mediolateral.

Unit of mean velocity and SD of velocity is cm/s.

Phase plane is in an arbitrary unit.

### Table 3

Summary of analysis of variance for four measures of postural performance in double limb stance: $F$-ratios and $p$-values by variable.

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Mean velocity</th>
<th>Phase plane portrait</th>
<th>SD of velocity (AP)</th>
<th>SD of velocity (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F$ ratio</td>
<td>$p$ value</td>
<td>$F$ ratio</td>
<td>$p$ value</td>
</tr>
<tr>
<td>Main effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>6.40</td>
<td>0.04</td>
<td>7.43</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Postural difficulty</td>
<td>796.55</td>
<td>-0.01</td>
<td>959.62</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cognitive difficulty</td>
<td>47.55</td>
<td>-0.01</td>
<td>83.59</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Interaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group $\times$ postural difficulty</td>
<td>2.06</td>
<td>0.14</td>
<td>2.48</td>
<td>0.09</td>
</tr>
<tr>
<td>Group $\times$ cognitive difficulty</td>
<td>1.50</td>
<td>0.22</td>
<td>1.43</td>
<td>0.24</td>
</tr>
<tr>
<td>Postural $\times$ cognitive difficulty</td>
<td>14.74</td>
<td>-0.01</td>
<td>15.19</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Group $\times$ postural $\times$ cognitive difficulty</td>
<td>0.34</td>
<td>0.83</td>
<td>0.97</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Significant $p$-values are in bold.

SD: standard deviation; AP: anteroposterior; ML: mediolateral.
were significantly greater than healthy individuals. The main effect of postural difficulty was also statistically significant ($F_{3,156} = 4.41, p < 0.01$).

Multiple comparisons showed a significant cognitive error increment from sitting to RO, RC, and FC conditions ($p < 0.05$) but there was no significant difference between RO and RC and also between RC and FC conditions ($p > 0.05$). There was no significant interaction between group and postural difficulty ($F_{3,156} = 0.76, p = 0.50$).

### 3.3. Postural performance for single stance conditions

A summary of ANOVA results for different measures of postural performance is shown in Table 4. The only significant result was for the main effect of cognitive difficulty. For the more difficult cognitive task condition, lower levels of SD of velocity in AP and phase plane portrait were observed. Also, the results of the t-test showed that there was no significant difference between injured and non-injured legs in the ACLD group ($p > 0.05$).

### 3.4. Cognitive performance for single stance conditions

The number of errors created when standing on the injured and non-injured legs (or their matched limb in the control group) was 51 and 42 for the ACLD group and 19 and 24 for the healthy group, respectively. The results of cognitive performance showed that cognitive errors of patients were significantly greater than healthy participants ($p < 0.05$).

### 4. Discussion

The results showed greater postural sway in ACLD patients than healthy participants for all DLS conditions. The only exception was for the SD of velocity in the AP direction, where there was a significant difference between the two groups when standing with eyes closed, yet not with eyes open. Loss of visual input may have prevented compensation for the loss of peripheral information provided by damaged ACL and left the central processing system without sufficient information to maintain postural stability. Increased postural sway in patients may be explained by loss of proprioceptive inputs from the impaired ligament [2,29,30].

These findings are inconsistent with Lysholm [2] and O’Connell [31] who found no sway differences between ACLD and control groups. They employed a less challenging postural condition by placing the feet further apart rather than together. In contrast, Okuda et al. [3] also found no difference in postural sway between the two groups when placing the feet together. When DLS was challenged more by allowing the force platform to move (sway referenced), Lysholm et al. [2] found a greater body sway in the ACLD group. In the same study, no difference in postural sway was observed between the two groups during DLS on a fixed force platform.

There are several possible explanations for why there was no significant difference between ACLD and healthy groups in SLS. First, the position of the unsupported leg in the current study may have been less comfortable than for Lysholm, Guaffin and Zattestrom who found greater postural sway in the ACLD group [2,29,30]. In support of this possibility, O’Connell et al. found differences in balance during stance on a straight leg with the other leg in slight knee flexion. The only significant differences between the two groups were seen for balance board testing and not on a postural sway meter apparatus [31]. Also, Okuda et al. used a similar position and reported no balance difference between the two groups in the open eyes condition [3]. Second, the postural parameters used in the present experiment may not be comparable with other studies.

For example, Lysholm and Guaffin used the “equilibrium score” and “sway area” to quantify the balance differences on a stable force platform. However, the researchers did not report the reliability of these measures. The possible relationship between low cognitive scores in the ACLD group and increased sway in a relatively easy position of DLS...
warrants some discussion. One explanation for the sway difference between groups may relate to cognition. Swainik et al. [15] reported significantly greater pre-season cognitive errors in subjects who subsequently went on to sustain an ACL injury. It is interesting to speculate on whether reduced cognitive ability may have been associated with the occurrence of the ACL injury.

There are several possible explanations for why the dual-tasking effect was not different between the two groups. First, because quiet standing is a well-learned skill, it may require little attention for both ACLD and healthy participants. In other words, performing a more dynamic balance task may better discriminate the dual-tasking effect [10]. Second, the dual-tasking effect on the performance of “standing” as a large scale motor synergy would be masked with compensation provided by smaller scale synergies [32]. Third, while an association has been hypothesized between sensorimotor and cognitive abilities [33], it is probable that the cognitive abilities of the patients who participated in this study may not have been affected enough due to their low level of disability (i.e. score of 71.88 ± 22.38 on activity daily living subscale of KOOS) to show a different pattern of dual-tasking amongst groups. Therefore, selecting more impaired ACLD patients could help to better understand the effects of dual-tasking on postural control.

In conclusion, the findings confirm the effect of a concurrent digit span memory task on standing balance in ACLD patients but the response to cognitive loading was not significantly different between the two groups. Future studies should examine ACL patients with more severe disabilities and expose them to more challenging dynamic balance conditions to further explore dual-tasking effects.

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Conflict of interest statement

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