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Impact of Balance Training When Incorporating Cognitive Tasks/External Focus of Attention, On Postural Control in Subjects Following Anterior Cruciate Ligament Reconstruction: A Randomized Controlled Trial

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Abstract

Introduction: The current investigation assessed effects of balance exercises both incorporating and excluding cognitive tasks (CTs) and external focus of attention (EFA) on postural control in athletes who have undergone anterior cruciate ligament reconstruction (ACLR).

Methods: A total of 48 athletes post-ACLR were randomly assigned to one of the three groups: traditional balance training (BT), balance training with external focus of attention (BTF), and balance training with cognitive demands (BTC). Postural control was evaluated by a force platform before and after an 8-week intervention, during which participants engaged in balance exercises four times a week. The interventions included standard balance exercises, balance exercises with EFA, and balance exercises incorporating CTs. Assessments included sway amplitude, average sway velocity, and standard deviation of sway velocity in both anteroposterior (AP) and mediolateral (ML) directions during single-leg quiet standing. Additionally, the time taken to regain stability following mechanical perturbation was measured.

Results: The results indicated a remarkable reduction in the sway amplitude especially in ML direction for intervention groups. Also, standard deviation of sway velocity was significantly reduced in intervention groups when comparing to the control group. In general, time to return to stability after mechanical perturbation did not changed in any group. It just increased in BT group post intervention.

Conclusion: incorporating cognitive load and external focus of attention in the conventional balance training of athletes post ACLR surgery reduced sway amplitude and postural control cost, but had no significant effect on time to return to stability after applying mechanical perturbation.
Keywords: Anterior cruciate ligament reconstruction, postural control, balance exercises, focus of attention, cognitive task.

Introduction

The injury of the anterior cruciate ligament (ACL) in the knee is among the most prevalent and debilitating sports injuries, resulting in severe consequences for sports participation and long-term mobility issues (1). A key indicator of treatment success is the ability to return to high-level athletic activity (2). Rehabilitation is a crucial component of the treatment process. The high risk of re-injury and the low rates of athletes returning to their pre-injury levels of activity following anterior cruciate ligament reconstruction (ACLR) suggest that current practices do not adequately address all relevant aspects of recovery. Approximately 80% of patients who undergo ACL reconstruction engage in some form of sports activities, yet only 65% return to their pre-injury level, and just 55% resume competitive-level sports (3). Additionally, 55% of individuals fail to return to their pre-injury level of sports activity after ACL reconstruction, with a higher risk of re-injury for those who do succeed in returning to that level (4). Studies examining the return to sport post-ACL reconstruction indicate the presence of cognitive dysfunctions and abnormal cognitive-motor interference, even after patients have completed their rehabilitation programs (5).

Recent research has identified deficits in neurocognitive functions among male athletes post- ACLR), as noted in a study by Kiani. This study further indicated that even athletes who successfully meet standard return-to-sport criteria may still exhibit deficiencies in various cognitive domains, including sustained attention, working memory, and cognitive flexibility. These results underscore the importance of incorporating neurocognitive training into rehabilitation protocols following ACLR (6). Additionally, balance impairments and inadequate postural control are significant risk factors for re-injury in both the operated and contralateral knees (4-6).

An established approach from motor learning research, known as external focus of attention (EFA), may improve postural control by minimizing the demand on neurocognitive resources (7). Therefore, the objective of this study was to evaluate the effectiveness of integrating cognitive demands or EFA into conventional balance training to enhance balance control during steady single-leg stance, particularly when faced with trunk-level external perturbations. We hypothesized that the incorporation of cognitive demands and EFA would lead to greater improvements in postural balance compared to a traditional balance training program.

Materials and Methods

Design

This randomized controlled trial employed a double-blind, parallel-group design, adhering to the SPIRIT (Standard Protocol Items: Recommendations for Interventional Trials) guidelines (Protocol). The study took place at sports physiotherapy clinics in Khuzestan, Iran, from December 2021 to December 2022. All assessments were conducted at the Rehabilitation Research Center affiliated with Ahvaz Jundishapur University of Medical Sciences in Ahvaz, Iran. Ethical approval was granted by the local ethics committee (code: IR.AJUMS.REC.1400.335), and the trial was registered with the Iranian Registry of Clinical Trials (registration ID: IRCT20211004052666N1). Participants provided written informed consent following a thorough explanation of the study procedures.

Participants

The study enrolled individuals who had undergone ACLR surgery at least six months prior (8), aged between 18 and 47 years (9). Inclusion criteria included a history of diabetes (9), the use of medications impacting balance or cognition (8), musculoskeletal issues in the back or neck (9), prior traumatic injuries or surgeries expect for the ACLR in the operation side (8), recent neck or back pain (9), and those who had achieved full knee range of motion without receiving any other treatments in the previous six weeks (10). Individuals were excluded if they had experienced a posterior cruciate ligament rupture (11), surgery or injury to the contralateral lower limb (11), any surgical or traumatic issues with the ankle or hip joints (11), instability complaints (11), neurological or vestibular disorders, or uncorrected visual impairments (12). Joint effusion, pain, and the ability to achieve full active range of motion in the operated knee were also considered for exclusion (13). The Tegner activity rating scale (14) was utilized to assess participants' activity levels, while the Knee Injury and Osteoarthritis Outcome Score (KOOS) was used for evaluating disability, where scores range from 0 to 100, with higher scores indicating lesser disability (15). Additionally, demographic information including gender, age, height, weight, and comorbidities was collected. Prior to participation, all subjects signed an informed consent form, allowing them to review the study protocol and ask any questions they had.

Randomization

After the initial evaluation, participants were randomly assigned to one of three groups using computer-generated random numbers organized in stratified permuted blocks with sizes of 4 and 6: (i) Routine Balance Training (BT), (ii) Balance Training with External Focus of Attention (BTF), or (iii) Balance Training with Cognitive Tasks (BTC). All assessments were performed by a physiotherapist who was blinded to the group allocations, and participants were also kept unaware of their respective treatment groups.

Intervention

All participants underwent an 8-week training program, consisting of four sessions per week, under the guidance of a physiotherapist who remained blinded to the assessment outcomes. Detailed descriptions of the training program for each group could be found in the published protocol for this study.

Outcome measures

Each participant underwent two assessments: one at baseline and another after the 8-week intervention. Demographic information was also collected during the baseline assessment. Evaluations were performed by a trained physiotherapist, who remained blinded to group allocation throughout the study. To minimize fatigue effects, pre- and post-intervention tests were administered in a random order, with participants allowed sufficient rest (2–5 minutes) between tests.

Postural control and overall stability were evaluated both before and after the intervention. Postural control was assessed through center of pressure (COP) measures collected during 30 seconds of single-leg standing on both firm and foam surfaces, using a force platform (Kistler 9286BA, Kistler, Switzerland). The participants' ability to maintain single-leg balance was challenged with mechanical perturbations administered through a force-controlled pulling system. Key steady-state COP metrics included sway in the anterior-posterior (AP) and medio-lateral (ML) directions, mean total velocity, and standard deviation of sway velocity in both AP and ML directions. Additionally, the time taken to regain stability following mechanical perturbations was measured pre- and post-intervention.

Due to participant logistical constraints, particularly professional athletes who could not return for a one-month follow-up, some measures were not analyzed or reported. A force plate (Kistler 40×60, 9286BA, Kistler, Switzerland) recorded COP positions at a sampling frequency of 100 Hz. A Thera Band green sponge was positioned on the force plate to decrease proprioceptive feedback during the "foam" conditions.

The steady-state single-leg postural control assessment included four test conditions—two on each leg on both firm and foam surfaces. Participants were instructed to stand on one leg with straight knees while the contralateral knee was semi-flexed and arms positioned on the chest. Mechanical perturbations were introduced during all four standing conditions. Each test was conducted in triplicate, and the mean values were subsequently utilized for statistical analyses.

The raw data was processed using a zero-lag, fourth-order Butterworth digital filter, set with a cutoff frequency of 10 Hz. All calculations were performed offline using custom scripts in MATLAB (R2018b, MathWorks, United States). The time to stability was defined as the duration from the application of mechanical perturbation to the moment that COP displacement velocity returned to the mean ±2×SD bounds of the average steady-state values. An automated detection algorithm, supplemented by visual confirmation feedback, ensured accurate detection of this parameter.

Statistical Analysis

Data were evaluated utilizing IBM SPSS Statistics Software version 24 for Windows (SPSS Inc., Chicago, IL). a significance value set at $p < 0.05$. The normality of variables was assessed through the Shapiro-Wilk test, and when necessary, normalization was achieved via logarithmic transformation. An intention-to-treat analysis, employing the last observation carried forward method, accounted for the twelve participants who withdrew from the intervention (5 from the control group, 4 from the cognitive focus group, and 3 from the external focus group). To compare the clinical and demographic variables of across groups at baseline, independent sample t-tests, Mann–Whitney U tests, or Chi-Squared tests were applied. Additionally, one-way analysis of variance (ANOVA) and repeated measures ANOVA were conducted to assess outcomes among the intervention and control groups.

Sample Size

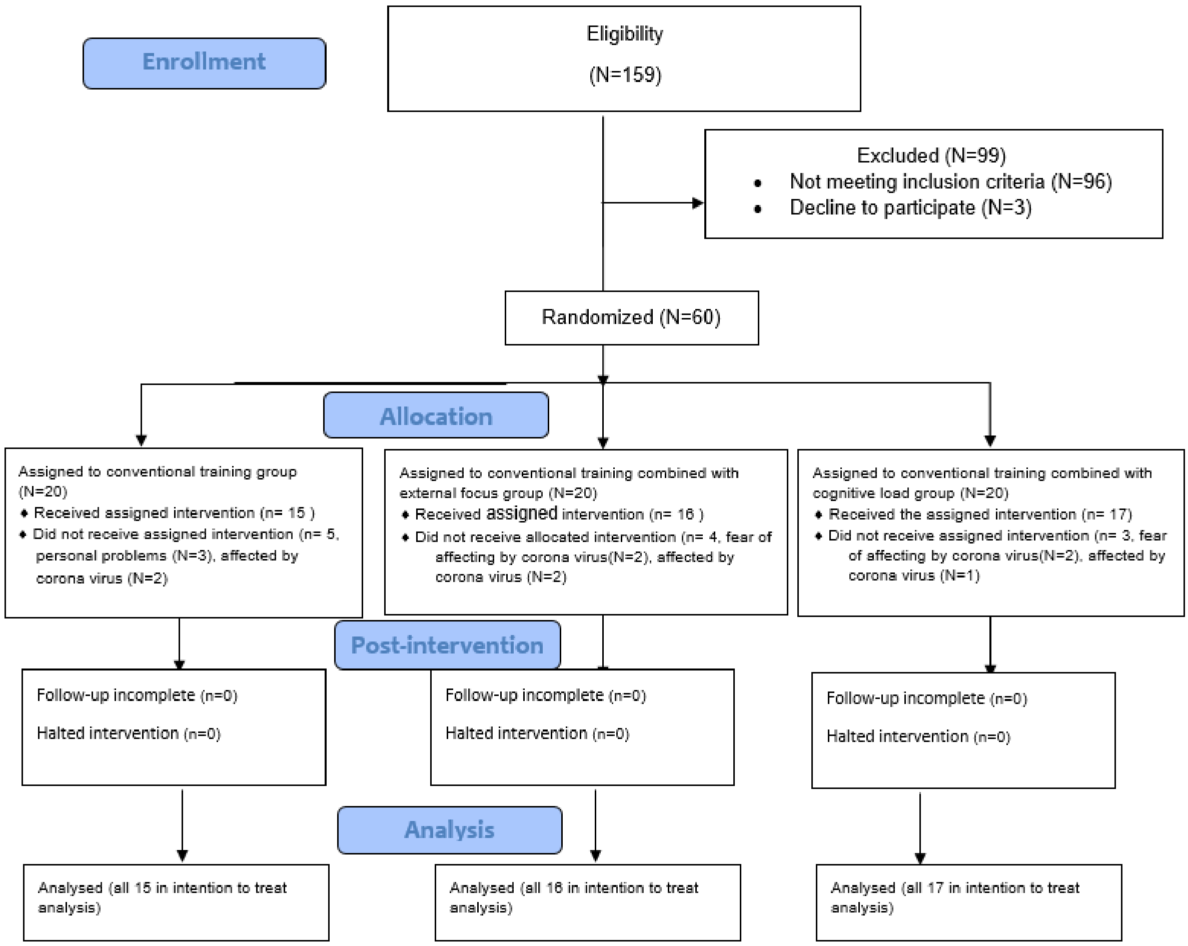
Using a significance level of 0.05, an effect size of 0.8, and desired power of 80%, the necessary sample size was calculated to be 20 subjects per group using G-power software, version 3.1.10.

Using a P value of 0.05, an effect size of 0.8, and a desired power of 80%, the required sample size was determined to be 20 participants per group through GPower software, version 3.1.10.

Results

As depicted in Figure 1, the CONSORT flow diagram outlines the study's design. A total of 60 participants underwent ACLR reconstruction were randomized into three groups: traditional balance training (BT), traditional balance training with cognitive demands (BTC), and traditional balance training with external focus of attention (BTF).

Discontinuations included five participants from the BT group (3 due to personal reasons and 2 linked to concerns about the coronavirus), four from the BTF group (2 due to fear of exposure and 2 affected by the virus), and three from the BTC group (2 due to fear and 1 affected by the virus). Ultimately, 48 individuals successfully completed the intervention, and no adverse effects were reported across any of the groups.



No significant statistical differences were found in demographic and clinical variables among individuals of both groups at baseline (Table 1). Furthermore, no adverse events were recorded in any of the groups following the interventions.

Table 1. Demographic and clinical characteristics of exergaming and control groups (n = 45)

	Conventional training group (n=18) Mean±SD	conventional training combined with external focus group (n=16) Mean±SD	conventional training combined with cognitive load group (n=17) Mean±SD	P-value
Demographic data				
Age (years)	26.30±3.85	25.90±4.76	25.89±4.32	0.76
Height (m)	1.97±0.80	1.80±0.45	1.87±0.50	0.74
Weight (kg)	72.46±9.59	74.94±10.87	70.64±9.95	0.49
BMI (kg/m^2)	24.15±3.24	23.37±3.92	24.65±3.44	0.53
Activity level (Tegner sclae)	8.20±0.55	8.40±0.30	8.90±0.15	0.66
Education (years)	13±1.77	12±1.67	13.66±1.77	0.61
Duration after reconstruction surgery (months)	12±3.95	13±4.26	13±6.40	0.58
KOOS questionnaire				
Pain	99.20±0.77	98.20±0.55	99.20±0.15	0.78
Symptoms	98.20±0.27	97.20±0.43	98.40±0.34	0.56
ADL	97.80±0.17	98.50±0.47	97.80±0.23	0.65
Sport/rec	99.80±0.67	98.20±0.29	99.84±0.24	0.51
QOL	98.80±0.28	97.50±0.57	97.90±0.58	0.54

SD: standard deviation; BMI: body mass index; KOOS: Knee Injury and Osteoarthritis Outcome Score; ADL: activities of daily living; QOL: quality of life

AP Sway - Non-Operated Side on Firm Surface: The findings from the repeated measures analysis of variance indicated a significant difference in anterior-posterior (AP) sway while standing on a firm surface with the non-operated leg across different time points (Ftime = 9.00, P < 0.01). There was no significant interaction between the intervention (group) and time (Finteraction = 2.65, P > 0.05). Notably, AP sway was significantly decreased post-intervention in the BTF group (F = 2.868, P < 0.05); however, no significant differences were observed between pre- and post-intervention measurements in the BT and BTC groups. Additionally, the analysis of variance revealed no statistically significant differences between the groups at either pre- or post-intervention stages.

AP Sway-Operated Side on Firm Surface: Results from the repeated measures analysis of variance demonstrated a significant variation in AP sway when standing with the operated leg on a firm surface across different time points (Ftime = 6.56, p < 0.05). No significant interaction was found between the intervention (group) and time (Finteraction = 1.14, p > 0.05). AP sway significantly decreased post-intervention in the BTC group (F = 3.316, P < 0.01), while no significant differences were noted between pre- and post-intervention in the BT and BTF groups. Furthermore, the analysis of variance indicated no significant differences between the groups at either pre-or post-intervention stages.

AP Sway - Non-Operated Side on Foam Surface: The findings from the repeated measures analysis of variance revealed no significant difference in AP sway while standing with the non-operated leg on a foam surface across time points (Ftime = 2.16, $p > 0.05$) or between groups (Fbetween = 1.10, $p > 0.05$). A significant interaction between the intervention (group) and time was detected (Finteraction = 3.92, $p < 0.05$). Post-intervention, AP sway significantly reduced in the BTC group ($F = 3.979$, $p < 0.01$), while no significant differences were observed between pre- and post-intervention for the BT and BTF groups. Analysis of variance indicated no significant differences between groups prior to the intervention; however, post-intervention AP sway was significantly higher in the BT group when compared to the BTF and BTC groups.

AP Sway - Operated Side on Foam Surface: The repeated measures analysis of variance results showed no significant differences in AP sway when standing with the operated leg on foam surface across time points (Ftime = 2.41, $p > 0.05$) or between groups (Fbetween = 0.037, $p > 0.05$). A significant interaction between intervention (group) and time was identified (Finteraction = 3.23, $p < 0.05$). Post-intervention, AP sway decreased significantly in the BTF ($F = 2.389$, $p < 0.05$) and BTC ($F = 3.297$, $p < 0.01$) groups, although no significant differences were evident in the BT group between pre- and post-intervention measurements. The analysis of variance showed no significant differences between intervention and control at either pre- or post-intervention stages.

ML Sway - Non-Operated Side on Firm Surface: The findings from the repeated measures analysis of variance indicated a significant difference in mediolateral (ML) sway when standing on a firm surface with the non-operated leg across different time points (Ftime = 6.6, $p < 0.05$). A significant interaction between the intervention (group) and time was observed (Finteraction = 4.83, $p < 0.05$). Notably, ML sway significantly decreased post-intervention in the BTC group ($F = 3.698$, $p < 0.01$), whereas no significant differences were recorded between pre- and post-intervention in the BT and BTF groups. Furthermore, the analysis of variance revealed no significant differences between groups prior to the intervention; however, post-intervention ML sway while standing with the non-operated leg on a firm surface was greater in the BT group compared to both the BTF and BTC groups.

ML Sway - Operated Side on Firm Surface: Data from the repeated measures analysis demonstrated a statistically significant difference in ML sway when standing on a firm surface with the operated leg across time points (Ftime = 8.86, $p < 0.01$). No significant interaction was found between the intervention (group) and time (Finteraction = 2.98, $p > 0.05$). ML sway was significantly reduced post-intervention in both the BTF ($F = 3.531$, $p < 0.05$) and BTC ($F = 3.288$, $p < 0.01$) groups, while no significant differences were evident between pre- and post-intervention in the BT group. The analysis of variance revealed no significant differences between groups before the intervention; post-intervention, ML sway while standing with the operated leg on a firm surface was higher in the BT group compared to both the BTF and BTC groups.

ML Sway - Non-Operated Side on Foam Surface: The analysis indicated a significant difference in ML sway when standing with the non-operated leg on a foam surface across time points (Ftime = 9.67, $p < 0.01$). A significant interaction between the intervention (group) and time was also identified (Finteraction = 4.66, $p < 0.05$). Post-intervention, ML sway significantly decreased in both the BTF ($F = 2.898$, $p < 0.05$) and BTC ($F = 2.533$, $p < 0.05$) groups, while no significant differences were found between pre- and post-intervention in the BT group. Analysis of variance revealed no significant differences between groups at baseline; however, post-intervention, ML sway while standing with the non-operated leg on a foam surface was elevated in the BT group compared to both the BTF and BTC groups.

ML Sway - Operated Side on Foam Surface: The analysis through repeated measures revealed a significant difference in mediolateral (ML) sway when participants stood on a foam surface with the operated leg at different time points (Ftime = 6.93, $p < 0.05$). A notable interaction between the intervention groups and time was also detected (Finteraction = 4.40, $p < 0.05$). Post-intervention, there was a considerable reduction in ML sway for the non-operated leg within the BTF ($F = 3.028$, $p < 0.05$) and BTC ($F = 3.692$, $p < 0.01$) groups; however, no significant changes were found in the BT group. The analysis indicated no significant differences among groups before the intervention, although post-intervention, ML sway for the non-operated leg was greater in the BT group compared to both the BTF and BTC groups.

Mean Total Velocity - Non-Operated Side on Firm Surface: The repeated measures analysis of variance indicated significant differences in mean total velocity while standing with the non-operated leg on a firm surface across different time points ($F_{time} = 13.84$, $p < 0.01$) and among groups ($F_{between} = 4.13$, $p < 0.05$). There was no significant interaction between the intervention groups and time ($F_{interaction} = 1.58$, $p > 0.05$). The mean total velocity significantly decreased post-intervention in the BTF group ($F = 3.588$, $p < 0.01$), but no significant differences were noted between pre- and post-intervention in the BT group. The analysis of variance found no significant differences between groups post-intervention; however, prior to the intervention, the mean total velocity while standing with the non-operated leg was lower in the BTC group compared to both BT and BTF groups.

Mean Total Velocity - Operated Side on Firm Surface: The findings from the repeated measures demonstrated significant differences in mean total velocity while standing with the operated leg on a firm surface across different time points ($F_{time} = 28.36$, $p < 0.01$) and groups ($F_{between} = 3.46$, $p < 0.05$). There was no noteworthy interaction detected between the intervention groups and time ($F_{interaction} = 1.58$, $p > 0.05$). Post-intervention, mean total velocity notably decreased in the BTF ($F = 3.916$, $p < 0.01$) and BTC ($F = 3.264$, $p < 0.01$) groups, whereas no significant changes were observed in the BT group. The analysis of variance revealed no significant differences between groups prior to the intervention, but post-intervention, the mean total velocity for the non-operated leg was greater in the BT group compared to the BTC group.

Mean Total Velocity - Non-Operated Side on Foam Surface: The results revealed significant differences in mean total velocity while standing on a foam surface with the non-operated leg, both across time points ($F_{time} = 25.46$, $p < 0.01$) and among groups ($F_{between} = 6.41$, $p < 0.01$). No significant interaction between the intervention groups and time was observed ($F_{interaction} = 2.49$, $p > 0.05$). Post-intervention, mean total velocity significantly decreased in both the BTF ($F = 3.776$, $p < 0.01$) and BTC ($F = 3.036$, $p < 0.05$) groups; however, the BT group showed no significant differences between pre- and post-intervention measurements. Additionally, analysis indicated that the mean total velocity for the non-operated leg was significantly lower in the BTC group compared to both the BT and BTF groups. Following the intervention, values in the BTC and BTF groups were both lower than those in the BT group.

Mean Total Velocity - Operated Side on Foam Surface: The findings demonstrated significant differences in mean total velocity while standing with the operated leg on a foam surface, both at different time points ($F_{time} = 21.59$, $p < 0.01$) and across groups ($F_{between} = 4.41$, $p < 0.05$). There was no noteworthy interaction detected between the intervention groups and time ($F_{interaction} = 2.22$, $p > 0.05$). Following intervention, mean total velocity was significantly reduced in both the BTF ($F = 3.584$, $p < 0.01$) and BTC ($F = 3.3656$, $p < 0.01$) groups, while no significant differences were observed in the BT group between pre- and post-intervention. The analysis indicated no significant differences among groups prior to the intervention, although post-intervention, both BTC and BTF groups exhibited lower mean total velocity compared to the BT group.

Standard Deviation of AP Sway Velocity - Non-Operated Side on Firm Surface: Findings from the repeated measures analysis of variance indicated significant differences in the standard deviation of anterior-posterior (AP) sway velocity while standing with the non-operated leg on a firm surface, both across time points ($F_{time} = 11.22$, $p < 0.01$) and between groups ($F_{between} = 3.34$, $p < 0.05$). No significant interaction was detected between intervention groups and time ($F_{interaction} = 1.20$, $p > 0.05$). There was a significant reduction in the standard deviation of AP sway velocity post-intervention in the BTC group ($F = 3.041$, $p < 0.01$), while the BT and BTF groups showed no significant differences between pre- and post-intervention assessments. Moreover, analysis revealed no significant differences among groups before the intervention; however, post-intervention, the standard deviation of AP sway velocity while standing with the non-operated leg was lower in the BTC group compared to the BT group.

Standard Deviation of AP Sway Velocity - Operated Side on Firm Surface: The results indicated significant differences in the standard deviation of AP sway velocity while standing with the operated leg on a firm surface across time points ($F_{time} = 27.50$, $p < 0.001$). No significant interaction was found between the intervention groups and time ($F_{interaction} = 0.7$, $p > 0.05$). Post-intervention, there was a significant reduction in the standard deviation of AP sway velocity for both the BTF ($F = 3.628$, $p < 0.01$) and BTC ($F = 3.736$, $p < 0.01$) groups, while the BT group showed no significant differences in pre- and post-intervention measurements. The analysis revealed no significant differences between groups prior to the intervention; however, post-intervention, the standard deviation of AP sway velocity while standing with the operated leg was lower in the BTC group compared to the BT group.

Standard Deviation of AP Sway Velocity - Non-Operated Side on Foam Surface: The repeated measures analysis of variance revealed significant differences in the standard deviation of anterior-posterior (AP) sway velocity while standing on a foam surface with the non-operated leg, both between groups (Fbetween = 4.64, $p < 0.05$). A significant interaction between the intervention groups and time was also revealed (Finteraction = 4.19, $p < 0.05$). Post-intervention, there was a significant reduction in the standard deviation of AP sway velocity in the BTF (F = 3.694, $p < 0.01$) and BTC (F = 2.940, $p < 0.05$) groups, while the BT group exhibited no significant changes between pre- and post-intervention assessments. Further analysis indicated that the standard deviation of AP sway velocity for the non-operated leg was significantly lower in the BTC group compared to both the BT and BTF groups. Additionally, post-intervention values were lower in the BTC and BTF groups in comparison to the BT group.

Standard Deviation of AP Sway Velocity - Operated Side on Foam Surface: The results demonstrated significant differences in the standard deviation of AP sway velocity when standing on foam with the operated leg across time points (Ftime = 5.19, $p < 0.05$). A significant interaction was noted between the intervention groups and time (Finteraction = 4.54, $p < 0.05$). A significant reduction was found in the standard deviation of AP sway velocity post-intervention in both the BTF (F = 6.612, $p < 0.001$) and BTC (F = 3.111, $p < 0.01$) groups, while no significant differences were seen in the BT group before and after the intervention. The analysis also revealed that the standard deviation of AP sway velocity while standing with the operated leg was significantly lower in the BTC group when compared to the BT and BTF groups. Post-intervention, values were lower in both BTC and BTF groups compared to the BT group.

Standard Deviation of ML Sway Velocity - Non-Operated Side on Firm Surface: The repeated measures analysis indicated significant differences in the standard deviation of mediolateral (ML) sway velocity while standing with the non-operated leg on a firm surface, across time points (Ftime = 7.86, $p < 0.01$) and groups (Fbetween = 4.95, $p < 0.05$). No significant interaction was found between the intervention groups and time (Finteraction = 1.49, $p > 0.05$). Although not statistically significant, a reduction in the standard deviation of ML sway velocity post-intervention was noted in the BTF group (F = 2.025, $p = 0.083$), while no significant differences were observed for the BT and BTC groups. Analysis revealed that pre-intervention, the standard deviation of ML sway velocity for the non-operated leg was lower in the BTC group compared to both the BT and BTF groups. Post-intervention, there were no significant differences among the groups.

Standard Deviation of ML Sway Velocity - Operated Side on Firm Surface: The results from the repeated measures analysis indicated significant differences in the standard deviation of ML sway velocity when standing with the operated leg on a firm surface across time points (Ftime = 23.06, $p< 0.001$). No statistically significant interaction was found between the intervention groups and time was found (Finteraction = 1.65, $p> 0.05$). The standard deviation of ML sway velocity decreased significantly post-intervention in both the BTF (F = 3.970, $p< 0.05$) and BTC (F = 2.369, $p< 0.05$) groups, while the BT group showed no significant differences between pre- and post-intervention assessments. Finally, analysis of variance indicated no differences in the standard deviation of AP sway velocity between groups at either pre- or post-intervention stages.

Standard Deviation of ML Sway Velocity - Non-Operated Side on Foam Surface: The repeated measures revealed significant differences in the standard deviation of mediolateral (ML) sway velocity while standing with the non-operated leg on a foam surface, both across time points (Ftime = 23.03, $p < 0.001$) and between groups (Fbetween = 4.73, $p < 0.05$). There was no interaction observed between the intervention groups and time points (Finteraction = 2.82, $p > 0.05$). Post-intervention, there was a significant reduction in the standard deviation of ML sway velocity in both the BTF (F = 3.08, $p < 0.05$) and BTC (F = 2.822, $p < 0.05$) groups; however, the BT group did not show significant differences between pre- and post-intervention assessments. Additionally, analysis indicated that prior to the intervention, the standard deviation of anterior-posterior (AP) sway velocity while standing with the non-operated leg was significantly lower in the BTC group compared to both the BT and BTF groups. Post-intervention, values were lower in both the BTC and BTF groups when compared to the BT group.

Standard Deviation of ML Sway Velocity - Operated Side on Foam Surface: The results from the repeated measures demonstrated significant differences in the standard deviation of ML sway velocity when standing with the operated leg on a foam surface, both across time points (Ftime = 15.63, p < 0.001) and between groups (Fbetween = 4.08, p < 0.05). There was no noteworthy interaction detected between the intervention groups and time (Finteraction = 2.47, p > 0.05). Following the intervention, a significant reduction in the standard deviation of ML sway velocity was noted for the BTF (F = 3.131, p < 0.05) and BTC (F = 3.711, p < 0.01) groups, while no significant differences were observed in the BT group between pre- and post-intervention. Furthermore, analysis indicated no significant differences prior to the intervention; however, post-intervention, the standard deviation of AP sway velocity while standing with the non-operated leg was lower in both the BTF and BTC groups compared to the BT group.

Table 2- effect of group intervention on AP sway, ML sway, mean total sway velocity, Std of AP sway velocity, and Std of ML sway velocity; when standing with operated and non-operated leg on firm and foam surfaces

Variable	group	Pre-intervention Mean(SD)	Post-intervention Mean(SD)	F	*p*	$F_{between}$(*p*)	F_{time}(*p*)	$F_{interaction}$(*p*)
AP sway_Non-Operatedside_ Firm Surface	BT	8.654(2.114)	8.170(1.692)	0.593	0.569	F = 0.07 (p = 0.934)	**F = 9.00 (p = 0.006)**	F = 2.65 (p = 0.088)
	BTF	9.624(3.956)	7.046(1.902)	2.868	**0.024**			
	BTC	8.427(1.568)	7.791(1.463)	1.161	0.267			
AP sway_ Operatedside_ Firm Surface	BT	8.300(2.567)	8.127(2.344)	0.215	0.835	F = 0.03 (p = 0.967)	**F = 6.56 (p = 0.016)**	F = 1.14 (p = 0.335)
	BTF	8.765(1.574)	7.305(3.092)	1.499	0.178			
	BTC	8.993(2.010)	7.48(1.254)	3.316	**0.006**			
AP sway_Non-Operatedside_ Foam Surface	BT	9.955(1.740)	11.048(4.466)	-1.023	0.336	F = 1.10 (p = 0.347)	F = 2.16 (p = 0.153)	**F = 3.92 (p = 0.031)**
	BTF	8.765(1.574)	7.305(3.092)[a]	1.499	0.178			
	BTC	10.253(1.775)	8.372(1.310)[b]	3.979	**0.002**			
AP sway_ Operatedside_ Foam Surface	BT	9.513(1.612)	10.522(5.139)	-0.698	0.505	F = 037 (p = 0.692)	F = 2.41 (p = 0.132)	**F = 3.23 (p = 0.045)**
	BTF	9.986(1.601)	8.615(1.507)	2.389	**0.048**			
	BTC	10.472(2.124)	8.261(1.258)	3.297	**0.006**			
ML sway_Non-Operatedside_ Firm Surface	BT	7.447 (1.99)	7.869 (1.082)	-1.148	0.284	F = 2.77 (p = 0.080)	**F = 6.6 (p = 0.016)**	**F = 4.83 (p = 0.016)**
	BTF	9.191 (3.545)	6.489 (0.806)[a]	1.962	0.091			
	BTC	7.134 (0.081)	6.436 (0.966)[b]	3.698	**0.003**			
ML sway_ Operatedside_ Firm Surface	BT	7.704 (2.148)	7.828 (1.493)	-0.181	0.861	F = 0.64 (p = 0.536)	**F = 8.86 (p = 0.006)**	F = 2.98 (p = 0.067)
	BTF	7.778 (1.074)	6.370 (1.122)[a]	3.531	**0.010**			
	BTC	8.095 (2.182)	6.358 (1.177)[b]	3.288	**0.006**			
ML sway_Non-Operatedside_ Foam Surface	BT	8.286 (1.116)	8.491 (1.764)	-0.472	0.650	F = 2.62 (p = 0.091)	**F = 9.67 (p = 0.004)**	**F = 4.66 (p = 0.018)**
	BTF	8.194 (1.320)	6.432 (1.621)[a]	2.898	**0.023**			
	BTC	7.858 (1.148)	7.126 (0.761)[b]	2.533	**0.025**			

ML sway_ Operatedside_ Foam Surface	BT	8.118 (1.404)	8.712 (2.369)	-0.668	0.523	F = 1.36 (p = 0.273)	**F = 6.93 (p = 0.014)**	**F = 4.40 (p = 0.022)**
	BTF	8.593 (0.869)	6.805 (1.214)[a]	3.028	**0.019**			
	BTC	8.617 (1.058)	6.914 (1.368)[b]	3.692	**0.002**			
mean total sway Vel_Non-Operatedside_ Firm Surface	BT	55.299 (16.292)	47.978 (10.018)	1.513	0.169	**F = 4.13 (p = 0.027)**	**F = 13.84 (p = 0.001)**	F = 1.58 (p = 0.223)
	BTF	54.655 (13.974)	41.444 (13.919)	3.588	**0.009**			
	BTC	41.697 (7.719)[ef]	37.821 (10.053)	1.361	0.197			
mean total sway Vel__ Operatedside_ Firm Surface	BT	59.650 (17.038)	51.275 (12.940)	2.065	0.073	**F = 3.46 (p = 0.045)**	**F = 28.36 (p < 0.001)**	F = 1.06 (p = 0.361)
	BTF	58.155 (17.028)	42.370 (14.134)	3.916	**0.006**			
	BTC	47.515 (8.776)	37.993 (9.571)[b]	3.264	**0.006**			
mean total sway Vel_Non-Operatedside_ Foam Surface	BT	64.083 (14.081)	57.229 (13.194)	1.569	0.155	**F = 6.41 (p = 0.005)**	**F = 25.46 (p < 0.001)**	F = 2.49 (p = 0.101)
	BTF	62.391 (15.453)	43.448 (13.342)[a]	3.776	**0.007**			
	BTC	49.162 (8.442)[ef]	40.695 (9.929)[b]	3.036	**0.010**			
mean total sway Vel_ Operatedside_ Foam Surface	BT	64.474 (14.627)	59.342 (12.818)	1.052	0.323	**F = 4.41 (p = 0.022)**	**F = 21.59 (p < 0.001)**	F = 2.22 (p = 0.127)
	BTF	67.348 (16.871)	46.424 (12.123)[a]	3.584	**0.009**			
	BTC	56.120 (10.395)	42.179 (11.974)[b]	3.365	**0.005**			
Std of AP sway velocity_Non-Operatedside_ Firm Surface	BT	33.576 (17.249)	26.606 (8.164)	1.100	0.304	**F = 3.34 (p = 0.049)**	**F = 11.22 (p = 0.002)**	F = 1.20 (p = 0.316)
	BTF	36.470 (20.670)	21.312 (7.078)	2.205	0.063			
	BTC	24.221 (6.483)	18.965 (5.150)[b]	3.041	**0.009**			
Std of AP sway velocity_ Operatedside_Firm Surface	BT	36.706 (14.836)	26.520 (8.389)	2.026	0.077	F = 3.02 (p = 0.065)	**F = 27.50 (p < 0.001)**	F = 0.70 (p = 0.507)
	BTF	35.593 (12.739)	20.981 (7.805)	3.628	**0.008**			
	BTC	27.757 (9.746)	19.115 (4.636)[b]	3.736	**0.002**			
Std of AP sway velocity _Non-Operatedside_Foam Surface	BT	34.008 (9.791)	39.100 (20.767)	-0.883	0.403	**F = 4.64 (p = 0.018)**	F = 3.22 (p = 0.083)	**F = 4.19 (p = 0.026)**
	BTF	33.656 (8.637)	23.790 (5.940)[a]	3.694	**0.008**			
	BTC	28.511 (7.926)	21.753 (5.653)[b]	2.940	**0.011**			
Std of AP sway velocity _ Operatedside_Foam Surface	BT	34.908 (8.178)	40.936 (26.400)	-0.759	0.469	F = 2.52 (p = 0.099)	**F = 5.19 (p = 0.031)**	**F = 4.54 (p = 0.020)**
	BTF	39.782 (9.032)	24.506 (8.177)[a]	6.612	**<0.001**			

	BTC	33.296 (12.249)	22.580 (6.064)[b]	3.111	**0.008**			
Std of ML sway velocity_Non-Operatedside_ Firm Surface	BT	33.383 (9.163)	29.490 (5.343)	1.422	0.193	**F = 4.95 (p = 0.014)**	**F = 7.86 (p = 0.009)**	F = 1.49 (p = 0.242)
	BTF	34.349 (9.485)[f]	26.076 (8.987)	2.025	0.083			
	BTC	25.196 (5.057)[ef]	23.665 (6.042)	0.782	0.448			
Std of ML sway velocity_ Operatedside_Firm Surface	BT	35.506 (10.457)	31.968 (8.217)	2.297	0.051	F = 2.47 (p = 0.103)	**F = 23.06 (p < 0.001)**	F = 1.65 (p = 0.210)
	BTF	35.504 (10.135)	26.657 (7.988)	3.970	**0.005**			
	BTC	29.162 (5.532)	24.538 (7.355)	2.369	**0.034**			
Std of ML sway velocity _Non-Operatedside_Foam Surface	BT	38.260 (8.668)	33.939 (7.613)	1.841	0.103	**F = 4.73 (p = 0.017)**	**F = 23.03 (p < 0.001)**	F = 2.82 (p = 0.077)
	BTF	38.316 (12.346)[f]	25.531 (8.746)[a]	3.080	**0.018**			
	BTC	29.836 (5.040)[ef]	24.858 (6.158)[b]	2.822	**0.014**			
Std of ML sway velocity _ Operatedside_Foam Surface	BT	38.351 (9.324)	36.963 (11.019)	0.399	0.700	**F = 4.08 (p = 0.028)**	**F = 15.63 (p < 0.001)**	F = 2.47 (p = 0.103)
	BTF	38.935 (11.070)	28.204 (5.464)[a]	3.131	**0.017**			
	BTC	34.280 (6.916)	24.479 (7.098)[b]	3.711	**0.003**			

a : indicates that there was a significant difference between BT and BTF group post-intervention. b : indicates that there was a significant difference between BT and BTC groups post-intervention. c : indicates that there was a significant difference between BTC and BTF groups post-intervention. d : indicates that there was a significant difference between BT and BTF groups pre-intervention. e : indicates that there was a significant difference between BT and BTC groups pre-intervention. f : indicates that there was a significant difference between BTC and BTF groups pre-intervention.

Table 3- effect of group intervention on time to stability after applying mechanical perturbation when standing with operated and non-operated leg on firm and foam surfaces

Variable	group	Pre-intervention Mean(SD)	Post-intervention Mean(SD)	F	*p*	$F_{between}(p)$	$F_{time}(p)$	$F_{interaction}(p)$
TtS_Non-Operatedside_ Firm Surface	BT	2252.593 (901.877)	2777.038 (2373.961)	-0.725	0.489	F = 1.29 (p = 0.292)	F = 2.08 (P = 0.160)	F = 1.57 (p = 0.225)
	BTF	2983.125 (1454.951)	2747.291 (930.255)	0.236	0.820			
	BTC	2782.143 (753.512)	1427.381 (1410.802)	-3.686	0.003			
TtS_ Operatedside_	BT	2723.704 (2923.778)	2224.814 (1632.988)	0.364	0.725	F = 1.08	F = 0.36	F = 0.71

Firm Surface	BTF	2546.876 (792.166)	3135.000 (1379.788)	-0.947	0.362	(p = 0.345)	(p = 0.556)	(p = 0.501)
	BTC	3710.953 (2635.779)	2483.809 (1343.312)	1.247	0.234			
TtS_Non-Operatedside_ Foam Surface	BT	1655.926 (988.908)	3445.740 (2520.800)	-2.2802	0.058	F = 0.38 (p = 0.685)	F = 7.47 (p = 0.011)	F = 0.21 (p = 0.813)
	BTF	1758.125 (2226.745)	2910.834 (1815.669)	-1.154	0.287			
	BTC	2303.261 (1521.063)	3392.501 (2083.197)	-1.507	0.156			
TtS_ Operatedside_ Foam Surface	BT	2488.926 (1785.723)	3291.111 (2000.680)	-0.750	0.475	F = 1.35 (p = 0.276)	F = 0.55 (p = 0.464)	F = 2.26 (p = 0.123)
	BTF	5317.918 (3056.505)	2921.041 (1024.125)	2.069	0.077			
	BTC	3712.739 (2033.343)	3536.667 (2883.376)	-0.246	0.810			

a : indicates that there was a significant difference between BT and BTF group post-intervention. b : indicates that there was a significant difference between BT and BTC groups post-intervention. c : indicates that there was a significant difference between BTC and BTF groups post-intervention. d : indicates that there was a significant difference between BT and BTF groups pre-intervention. e : indicates that there was a significant difference between BT and BTC groups pre-intervention. f : indicates that there was a significant difference between BTC and BTF groups pre-intervention.

Time to stability: The results of repeated measurement analysis of variance showed no significant interaction between intervention (group) and time in any test condition. Time to stability when standing with non-operated leg on foam surface was significantly different between time points ($F_{time} = 7.47$, $p < 0.05$). It was increased almost significantly post intervention in BT group (F = -2.28, p =0.058) but there was no significant difference between pre- and post-intervention in BT and BTC groups.

Discussion

This study evaluated balance performance during single-leg standing on both foam and firm surfaces, as well as the time required to regain a stable state following external perturbations. The aim was also to compare the efficacy of balance training when combined with EFA and cognitive tasks (CTs) on postural control in participants who have undergone ACL reconstruction (16, 17).

Overall, our findings suggest that integrating balance training with either EFA or CTs enhances single-leg balance performance more significantly than conventional balance training alone. The analysis of center of pressure fluctuations during single-leg standing revealed a decreasing trend on both sides. A notable within-group effect was observed regarding AP sway on firm surfaces, indicating a reduction in sway. Additionally, a significant interaction effect between time and group was found on foam surfaces, showing that both the BTC and BTF groups achieved reductions in AP sway, particularly under more challenging conditions where proprioceptive feedback is less stable.

Furthermore, significant reductions in medio-lateral (ML) sway were noted on firm surfaces with the operated leg, alongside a marked interaction effect of time and group. This reinforces the conclusion that both intervention strategies were more effective than standard training in minimizing ML sway, especially in challenging sensory conditions.

While conventional balance exercises enhanced balance performance in simpler settings, these improvements were insufficient for more demanding sensory environments. Conversely, both the BTC and BTF groups demonstrated significant enhancements in their balance system's performance under these conditions, although no discernible difference was found between the two groups.

The analysis of average center of pressure fluctuation speed before and after the 8-week intervention indicated a downward trend in the BTC and BTF groups for both the healthy and reconstructed limbs. This reduction signifies a lowered control cost (effort) following the training programs 3. The decreased effort required when integrating cognitive load or external focus with traditional balance training may result from a shift towards a more automated control mechanism, a phenomenon supported by some studies examining balance performance. However, this hypothesis necessitates further validation using advanced methodologies such as multi-scale entropy measure.

After the 8-week intervention, there was a notable decrease in sway velocity variability, with significant reductions observed in the intervention groups compared to the control group. On a firm surface, the BTC group exhibited less post-intervention variability in sway velocity than the BT group, indicating that the introduction of cognitive demands was more effective in promoting smoother control of standing balance than merely adding an external focus of attention (16).

In more challenging conditions, such as standing on a foam surface, a general trend of reduced sway velocity variability was noted in the non-operated leg. However, in the operated leg, an interaction effect revealed that both cognitive and external focus interventions were more effective than traditional balance training in fostering smooth postural control.

Therefore, unlike conventional balance exercises, both cognitive load and external focus exercises not only improved balance in challenging settings reflected in decreased center of pressure fluctuations but also achieved this with greater efficiency, characterized by lower fluctuation speeds and enhanced smoothness. The variability of center of pressure fluctuations in the medio-lateral direction showed a decreasing trend for both intervention groups. While no significant differences emerged between groups (no intraction), the control group did not show any substantial reductions.

This suggests that the enhancements in control effort and optimization of balance achieved through exercises incorporating external focus and cognitive load were superior to those of conventional balance training, with the improvements being particularly evident in the anterior-posterior direction. Given that medio-lateral imbalance is crucial for preventing re-injuries, it may be beneficial to place greater emphasis on exercises targeting the medial-lateral direction.

This study represents the first RCT that investigated the effectiveness of integrating conventional balance training with external focus and cognitive demands to enhance balance performance in individuals who have undergone ACLR. In a case-control study by Ahmadi, it was found that continuous cognitive tasks led to a reduction in postural sway, which is consistent with our findings. However, while Ahmadi reported no considerable impact of external focus on postural sway, our results indicated a marked decrease in postural sway among ACLR patients who engaged in balance exercises with an external focus of attention (16). Additionally, a study by Mohammadi et al. examined the effects of the Stroop cognitive task on postural control in ACLR individuals. This task necessitates verbal responses and jaw movements, potentially increasing postural sway, while our study involved participants performing balance exercises with and without CTs and EFA (18). Similarly, research by Lion et al. used a continuous cognitive task (silent backward counting) and reported a reduction in postural sway as a result.

Moreover, this research assessed the performance of the balance maintenance system in response to external disturbances, specifically through the application of a pulling force equivalent to 10% of the individual's weight while standing on one leg (17). However, the reliability of these findings was limited. A significant within-group effect was noted only when participants were standing on the foam surface with their non-operated leg, reflecting an increased time taken to regain balance. Our results clearly illustrate a trend towards longer recovery times when standing on the healthy leg. As participants were not instructed to expedite regaining their balance, this increase may stem from greater confidence in maintaining stability, leading to a reduced urgency in returning to a steady posture. Future research should further investigate this phenomenon by examining the activity of agonist and antagonist muscles and analyzing joint kinematics in response to disturbances. Notably, if an increase in recovery time correlates with decreased co-contraction of the lower limb joints, it would suggest an improvement in postural control following the intervention (19, 20).

The findings regarding reactive balance, especially in light of the improvements observed in both static and dynamic balance systems, were somewhat surprising. Although a statistical analysis of return times while standing on firm versus foam surfaces was not conducted, the data suggest that the time taken to regain balance on a foam surface was significantly longer, approximately double, on the reconstructed leg under challenging conditions. Therefore, this indicates that rehabilitation programs for persons post-ACLR should prioritize enhancing reactive balance.

Negahban and colleagues explored the impact of cognitive tasks on the time required to regain a balanced state while standing on one leg. Their results indicated that cognitive tasks actually increased the time to restore balance, which aligns with our findings (21, 22). In contrast, the study conducted by Ahmadi et al. suggested that both external focus and continuous cognitive tasks shortened the time needed to achieve stability, conflicting with our results (16). Their research examined the immediate effects of these tasks, while our study involved participants engaging in an 8-week training regimen.

Conclusion

Our study demonstrated that individuals with ACL reconstruction who engaged in exercises involving cognitive tasks and external focus of attention exhibited a significant reduction in center of pressure (COP) fluctuations compared to those who performed standard balance exercises alone. The decrease in COP fluctuations among ACLR individuals was also associated with meaningful alterations in nonlinear variables and automatic control parameters, suggesting an enhancement in postural control due to the adoption of automated strategies. Therefore, therapists should consider integrating this type of balance training into rehabilitation protocols to improve balance control and foster automaticity in postural adjustments for individuals returning to sports after ACLR.

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