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Cross-Education Effects of Unilateral Neuromuscular Training on Bilateral Postural Control and Functional Performance in Athletes with Chronic Ankle Instability: A Randomized Controlled Trial

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Abstract

Background

Chronic ankle instability (CAI) is commonly associated with deficits in postural control and functional performance in athletes. While unilateral neuromuscular training has been demonstrated to enhance postural control in the contralateral limb, it remains unclear whether these cross-education effects translate to broader functional performance outcomes in this population. Therefore, this study aimed to examine the cross-education effects of a 4-week unilateral neuromuscular training program on bilateral postural control and functional performance in athletes with CAI.

Methods

Twenty-eight athletes with CAI (15 female, 13 male; 20.96 ± 1.50 years) were randomly assigned to Stable Ankle Training Group (SG) (n = 9, trained exclusively on the uninjured limb), Unstable Ankle Training Group (UG) (n = 9, trained exclusively on the injured limb), and Control Group (CG) (n = 10). A unilateral neuromuscular training program consisting of postural control and hop-stabilization exercises was performed twice weekly for 4 weeks. The Cumberland Ankle Instability Tool (CAIT), Foot and Ankle Ability Measure Activity of Daily Living Subscale (FAAM-ADL), Sports Subscale (FAAM-S), Balance Error Scoring System (BESS), Y Balance Test (YBT), Single-Legged Vertical Countermovement Jump (SLVCJ) Test, figure-of-eight hop test, and side hop test were used to determine the bilateral postural control and functional performance.

Results

Both the SG and UG demonstrated significantly greater improvements compared to the CG in FAAM, BESS, YBT, figure-of-eight hop, and side-hop tests ($p < 0.05$), with large effect sizes (Hedges' $g \geq 0.80$) and 95% confidence intervals excluding zero. Conversely, no statistically significant between-group differences were observed for the SLVCJ test ($p > 0.05$). Furthermore, no significant difference was observed between the SG and UG across any of the measured outcomes ($p > 0.05$).

Conclusion

A 4-week unilateral neuromuscular training program induces significant cross-education effects, resulting in bilateral improvements in postural control and functional performance in athletes with CAI. These findings support unilateral neuromuscular training as a practical rehabilitation strategy, particularly when direct loading of the injured limb is limited.

Trial registration:

ClinicalTrials.gov, NCT04139044. Registered 25 October 2019 (retrospectively registered). https://clinicaltrials.gov/study/NCT04139044

Key Points

- Unilateral neuromuscular training is an effective strategy to significantly improve self-reported lower extremity function, postural control, and functional performance in athletes with CAI, regardless of whether the intervention targets the uninjured or injured limb.
- By leveraging the cross-education effect, clinicians can utilize uninjured-limb training to prevent neuromuscular detraining and maintain functional capacity during acute phases of rehabilitation when the injured limb cannot tolerate direct mechanical loading.
- Integrating this unilateral cross-education approach into comprehensive rehabilitation offers a safe pathway to initiate bilateral neuromuscular re-education earlier in the healing process, potentially accelerating return-to-sport timelines.

1. Introduction

Lateral ankle sprains are recognized as one of the most prevalent musculoskeletal injuries in sports. 20–40% of acute lateral ankle sprains are shown to lead to chronic ankle instability (CAI) because of inappropriate treatment, without strong evidence-based strategies [1].

Patients with CAI demonstrate a spectrum of deficits, including altered ankle arthrokinematics, restricted range of motion, and impaired strength, proprioception, and neuromuscular control [2, 3]. Following an initial ankle sprain, neuromuscular control of the ankle is often compromised due to structural damage to the peroneal nerve and ligamentous mechanoreceptors [4]. Such injury disrupts normal afferent feedback and impairs central sensorimotor integration, leading to prolonged deficits in dynamic joint stability. Consequently, this process results in neuromuscular dysfunction and functional ankle instability among athletes [5]. Given the central neuromuscular control impairments associated with CAI, evidence-based exercise therapies—particularly neuromuscular and proprioceptive training—are considered crucial for rehabilitation and prevention [6, 7]. High-level evidence demonstrates that these interventions provide short-term improvements in CAI-related symptoms such as the sensation of 'giving way' [3, 8] and significantly reduce the recurrence rate of ankle sprains in athletes [9]. However, the neurophysiological consequences of CAI are not strictly localized. Inflammation and structural damage associated with recurrent sprains can induce neuromuscular inhibition, impairing postural control in both the injured and uninjured limbs. The manifestation of these bilateral deficits following a unilateral injury strongly indicates maladaptive alterations within the central nervous system [7, 10, 11]. Conversely, unilateral rehabilitation has been shown to yield bilateral improvements in neuromuscular control [6, 12–14]. This phenomenon — where unilateral training elicits cross-education effects — is primarily attributed to neuroplasticity and central neural adaptations [15].

Despite evidence suggesting bilateral neural adaptations following unilateral training, it remains unclear whether training the uninjured limb alone can induce clinically meaningful improvements in the injured limb, particularly regarding dynamic joint stability and functional performance in athletic populations. Therefore,

this study aimed to examine the cross-education effects of a 4-week unilateral neuromuscular training program on bilateral postural control and functional performance in athletes with CAI. We hypothesized that unilateral training of the uninjured limb would yield clinically meaningful improvements in the contralateral (injured) limb, comparable to the adaptations achieved by directly training the injured limb.

2. Material and Method

2.1. Participants

This study was designed as a randomised controlled trial conducted in accordance with the Consolidated Standards of Reporting Trials (CONSORT) statement. The study protocol was approved by the Yeditepe University Ethical Committee (Issue Number: 37068608-6100-15-1609). The trial was retrospectively registered at ClinicalTrials.gov (Identifier: NCT04139044). The research was conducted with 28 university athletes (15 females, 13 males) who successfully completed the study. All participants had experienced chronic ankle instability (CAI) for at least six months and actively played for the basketball, volleyball, or handball teams at the Yeditepe University Sports Club. In the context of this study, the "stable" ankle refers to the uninjured contralateral limb, whereas the "unstable" ankle refers to the limb with CAI. All procedures complied with the Declaration of Helsinki. Before enrollment, a detailed explanation of the study's objectives and procedures was provided to all participants, and written informed consent was obtained.

An a priori power analysis was conducted using G*Power (version 3.1; Heinrich Heine University, Düsseldorf, Germany). Based on a mixed ANOVA design (within-between interaction) with three groups and two measurement time points, an expected large effect size (Cohen's ƒ = 0.40), an α level of 0.05, a statistical power of 0.80, and a correlation among repeated measures of 0.50, the minimum total sample size was determined to be 21 participants (7 per group). Accounting for potential dropouts, a total of 28 athletes were enrolled in the study.

The progression of participants through the trial, including enrollment, allocation, and specific reasons for attrition, is detailed in the CONSORT flow diagram (Fig. 1). Briefly, 36 volunteers were initially assessed for eligibility, and 32 eligible participants were randomly allocated using a computer-generated sequence into three groups: a stable ankle training group (SG; trained only on the uninjured limb), an unstable ankle training group (UG; trained only on the injured limb), and a control group (CG). Group assignments were concealed in sequentially numbered, sealed envelopes, which were opened by each participant following formal enrollment. Due to the nature of the intervention, blinding of participants, the treating physiotherapist, and the outcome assessor was not feasible, as all outcome assessments were performed by the supervising physiotherapist (AYS) who also administered the training protocol.

During the intervention, a total of four participants discontinued the study. Complete data were ultimately collected and analyzed for 28 participants (SG: n = 9; UG: n = 9; CG: n = 10), which successfully satisfied the minimum sample size requirement established by the power analysis.

2.1.1. Eligibility Criteria

Athletes were recruited if they fulfilled the criteria established by the International Ankle Consortium for CAI [16]. The inclusion criteria consisted of a history of at least two significant grade II lateral ankle sprains (LAS) diagnosed by a physician, accompanied by inflammatory symptoms (e.g., pain, swelling); a self-reported sensation of “giving way” and perceived instability of the injured ankle, confirmed by a Cumberland Ankle Instability Tool (CAIT) score of ≤ 25 [17]; recurrent LAS episodes in the injured ankle occurring within the 12 months prior to the study; and decreased self-reported function, defined as a Foot and Ankle Ability Measure (FAAM) score of < 90% on the Activities of Daily Living (ADL) subscale and < 80% on the Sports subscale. The exclusion criteria consisted of a history of orthopedic surgery in either lower extremity, an acute injury to the musculoskeletal structures of the lower extremity within the previous three months, the presence of bilateral ankle instability, and any diagnosed balance or vestibular disorders.

2.2. Testing Procedures

All participants were evaluated with the Foot and Ankle Ability Measure (FAAM), Balance Error Scoring System (BESS), Y Balance Test, Single-Leg Vertical Countermovement jump (SLVCJ) test, figure-of-eight hop test, and side hop test. All measurements were performed at baseline and after 4 weeks to assess patient-reported outcomes, static and dynamic postural control, and functional performance.

2.2.1. Foot and Ankle Ability Measure (FAAM)

The Turkish version of the Foot and Ankle Ability Measure (FAAM-T) was utilized to quantify self-reported functional limitations in athletes with CAI. This 29-item questionnaire includes a 21-item Activities of Daily Living (ADL) subscale and an 8-item Sports subscale. Responses to individual questions are graded using a 5-point Likert system (0 to 4), and these values are subsequently converted into a normalized final score ranging from 0% to 100%. The FAAM-T has been established as a valid and reliable outcome measure demonstrating test-retest reliability with intraclass correlation coefficients (ICC) of 0.97 and 0.94 for the ADL and Sports subscales, respectively [18, 19].

2.2.2. The Balance Error Scoring System (BESS)

The BESS was performed to examine deficits in static postural control. Testing was conducted with eyes closed across three stances (double-leg, single-leg, and tandem) on both firm and foam surfaces. These conditions were applied to both ankles. Prior to testing, participant removed their shoes, taping, or braces. Each trial lasted 20 seconds, and scores were calculated by counting errors on the BESS scorecard. The intratester reliability for BESS scoring ranges from an ICC of 0.87 to 0.98 [20, 21].

2.2.3. The Y Balance Test (YBT)

The YBT was administered to assess dynamic postural control in three directions (anterior, posteromedial, and posterolateral). Athletes performed a maximal reach with the contralateral limb while maintaining a single-leg stance with hands on hips. To eliminate learning effects, athletes practiced three times in each direction before the recorded trials. Three formal trials were recorded per direction with a 15-second rest between attempts. Composite reach distance was calculated in cm (Composite reach distance = (sum of the 3 reach directions / (3 × limb length)) × 100). The test has been shown to have high intratester (ICC = 0.82–0.96) and intertester (ICC = 0.81–0.93) reliability [22, 23].

2.2.4. The Single-Leg Vertical Countermovement Jump (SLVCJ) Test

To assess vertical jump performance, athletes were instructed to squat to approximately 120–140 degrees of knee flexion as quickly as possible, and then jump on each leg to the highest vertical point three times (uninjured and injured limbs, respectively). Athletes were allowed to practice a few jumps to become comfortable with the test, and then three jumps were performed. The distance between the starting point and finishing point of the jump, touched by the middle finger, was recorded, and the average value was noted in cm. It is a valid, reliable, and reproducible outcome measure, with the ICC ranging from 0.882 to 0.968 for test-retest reliability [24].

2.2.5 Figure-of-Eight Hop Test

Athletes hopped on one limb (uninjured and injured, respectively) as fast as possible twice around a 5-meter figure-of-eight course. Athletes were allowed to practice one trial to become comfortable with the test. The test was repeated three times with a 60-second rest between hops. Test duration was recorded in seconds with a stopwatch. The average duration was analyzed. This is a valid and highly reliable measure (ICC = 0.95) [25].

2.2.6. Side Hop Test

Athletes hopped laterally on one limb (uninjured and injured, respectively) over a 30-cm distance. One repetition consisted of a lateral hop and a return hop to the starting position. Athletes completed ten repetitions as quickly as possible. The test was repeated three times per limb with a 60-second rest between trials, and the average duration (in seconds) was recorded. This test demonstrates strong test-retest reliability (ICC = 0.84) [25].

2.3. Training Protocol

The unilateral training protocol, consisting of progressive postural control and hop-stabilization exercises, was supervised by a physiotherapist (AYS). The protocol was performed exclusively on the uninjured limb in the SG, and exclusively on the injured limb for the UG. Both intervention groups completed 30-minute training sessions twice weekly for four weeks. This dosage was selected based on prior evidence demonstrating its efficacy in inducing measurable cross-education benefits without overtraining in athletic populations [6, 26]. The exercise prescription was based on evidence-based neuromuscular training protocols established in current literature [6, 26–28]. Details of the training protocol are given in Fig. 2. The control group (CG) continued their usual daily routines and sports activities without receiving any specific intervention. In addition, all participants in the intervention and control groups continued their regular sports training, consisting of two 90-minute sessions per week.

2.4. Statistical Analysis

All statistical analyses were performed using IBM Statistical Package for the Social Sciences (SPSS) Statistics for Windows, version 25.0 (IBM Corp., Armonk, NY, USA). Descriptive data are presented as means

± standard deviations (SD). Normality of all continuous variables was assessed using the Shapiro-Wilk test, supplemented by visual inspection of histograms and Q-Q plots.

Baseline equivalence among the stable ankle training group (SG), unstable ankle training group (UG), and control group (CG) was examined using one-way analysis of variance (ANOVA) or the Kruskal-Wallis H test, depending on data distribution. Within-group changes from baseline to post-intervention were assessed using paired-samples t-tests for normally distributed variables and the Wilcoxon signed-rank test for non-normally distributed variables.

To evaluate cross-education effects and compare intervention efficacy across groups, mean change scores (Delta, Δ) were calculated for each participant by subtracting the pre-intervention values from the post-intervention values. These change scores were subsequently compared across groups using one-way ANOVA. Where significant main effects were identified, Tukey's honestly significant difference (HSD) post-hoc test was applied to determine specific between-group differences. For variables violating parametric assumptions, the Kruskal-Wallis test was used, with Mann-Whitney U tests for pairwise comparisons.

Effect sizes were calculated using Hedges' g with 95% confidence intervals (CIs), derived from mean change scores (Δ) between groups, and selected to account for potential upward bias in small sample sizes. Effect sizes were interpreted as small (0.20–0.49), moderate (0.50–0.79), and large (≥ 0.80). Statistical significance was set at $p < 0.05$ for all analyses.

3. Results

3.1. Baseline Characteristics

There were no statistically significant differences among the groups regarding baseline demographic characteristics, CAIT scores, ankle sprain history, or playing time ($p > 0.05$), with the exception of weight ($p = 0.03$) and body mass index (BMI) ($p = 0.005$) between the SG and CG (Table 1). No significant baseline differences were observed among the groups for any of the pre-training primary outcome measures (FAAM-ADL, FAAM-S, BESS, YBT, SLVCJ, figure-of-eight hop, and side hop tests) for either limb ($p > 0.05$) (Table 2).

3.2. Within-Group Outcomes

Pre- and post-intervention findings, mean differences, and effect sizes for all outcome measures are presented in Table 3. Within-group analyses revealed that both training groups (SG and UG) demonstrated significant improvements over time in self-reported functional status (FAAM-ADL and FAAM-S; $p < 0.01$) and static postural control (BESS total score; SG: $p < 0.001$, UG: $p < 0.05$), whereas the CG showed no significant changes ($p > 0.05$).

Table 3
Intra- and Intergroup Pre- and Post-training Comparisons and Effect Sizes

Outcomes	Ankle	Pre-training	Post-training	P-value	Δ After 4 weeks	P-value	Effect Size (95% Confidence Interval)	
							Versus Control Group[a]	Versus Training Groups[b]
Patient-reported outcomes								
FAAM-ADL (%)								
Stable ankle training	Both	76.11 ± 8.57	90.33 ± 5.09	.007[c]	14.22 ± 8.61	< .001[c]	2.18 (0.93, 3.43)	0.37 (-0.64, 1.38)
Unstable ankle training		80.00 ± 7.50	91.66 ± 5.59	.005[c]	11.66 ± 3.53		3.98 (2.42, 5.53)	
Control		82.50 ± 5.89	83.00 ± 6.32	.317	0.50 ± 1.58			
FAAM-S (%)								
Stable ankle training	Both	70.55 ± 12.10	85.55 ± 9.82	.007[c]	15.00 ± 7.50	< .001[c]	2.37 (1.20, 3.55)	0.00 (-1.00, 1.00)
Unstable ankle training		73.33 ± 5.00	88.33 ± 2.50	.007[c]	15.00 ± 5.00		3.35 (1.95, 4.74)	
Control		78.00 ± 4.83	79.50 ± 4.37	.083	1.50 ± 2.41			
Static balance								
BESS total								
Stable ankle training	Stable	12.55 ± 2.92	6.66 ± 2.00	< .001[c]	-5.88 ± 1.90	.001[c]	-1.98 (-3.19, -0.78)	-0.86 (-1.91, 0.19)

Abbreviations: Δ, Post Variables minus Pre Variables; FAAM, Foot and Ankle Ability Measure; ADL, Activity of Daily Living; S, Sports; BESS, Balance Error Scoring System; YBT, Y Balance Test; SLVCJ, The Single-Leg Vertical Countermovement Jump.

[a] Hedges' *g* was used to calculate the size of the difference between the training groups and the control group outcomes.

[b] Hedges' *g* was used to calculate the size of the difference between the stable ankle training group and the unstable ankle training group outcomes.

[c] Indicates statistical difference (P < .05).

Outcomes	Ankle	Pre-training	Post-training	P-value	Δ After 4 weeks	P-value	Effect Size (95% Confidence Interval)	
							Versus Control Group[a]	Versus Training Groups[b]
Unstable ankle training		13.22 ± 4.46	9.44 ± 3.50	.003[c]	-3.77 ± 2.72		-1.09 (-2.13, -0.04)	
Control		16.20 ± 5.09	15.80 ± 4.58	.699	-0.40 ± 3.16			
Stable ankle training	Unstable	18.77 ± 3.89	12.55 ± 3.32	< .001[c]	-6.22 ± 1.48	< .001[c]	-2.37 (-3.66, -1.08)	0.39 (-0.62, 1.40)
Unstable ankle training		18.22 ± 7.69	9.55 ± 2.40	.013[c]	-8.66 ± 8.20		-1.37 (-2.46, -0.28)	
Control		22.50 ± 5.75	22.60 ± 7.94	.924	0.10 ± 3.21			
Dynamic balance								
YBT anterior (cm)								
Stable ankle training	Stable	78.01 ± 8.17	86.58 ± 5.46	< .001[c]	8.56 ± 4.09	< .001[c]	2.70 (1.32, 4.07)	1.22 (0.12, 2.32)
Unstable ankle training		79.83 ± 2.27	83.62 ± 4.02	.017[c]	3.79 ± 3.33		1.40 (0.31, 2.50)	
Control		77.55 ± 6.38	77.65 ± 7.14	.678	0.10 ± 1.44			
Stable ankle training	Unstable	76.90 ± 4.69	83.29 ± 5.51	.001[c]	4.58 ± 5.58	.001[c]	0.93 (-0.10, 1.95)	-0.86 (-1.91, 0.19)
Unstable ankle training		75.95 ± 7.97	82.29 ± 4.75	.008[c]	8.91 ± 3.91		2.45 (1.13, 3.76)	

Abbreviations: Δ, Post Variables minus Pre Variables; FAAM, Foot and Ankle Ability Measure; ADL, Activity of Daily Living; S, Sports; BESS, Balance Error Scoring System; YBT, Y Balance Test; SLVCJ, The Single-Leg Vertical Countermovement Jump.

[a] Hedges' *g* was used to calculate the size of the difference between the training groups and the control group outcomes.

[b] Hedges' *g* was used to calculate the size of the difference between the stable ankle training group and the unstable ankle training group outcomes.

[c] Indicates statistical difference (P < .05).

Outcomes	Ankle	Pre-training	Post-training	P-value	Δ After 4 weeks	P-value	Effect Size (95% Confidence Interval)	
							Versus Control Group[a]	Versus Training Groups[b]
Control		73.85 ± 6.89	74.25 ± 7.14	.648	0.40 ± 2.69			
YBT posteromedial (cm)								
Stable ankle training	Stable	94.10 ± 7.26	104.36 ± 8.48	< .001[c]	10.25 ± 3.49	< .001[c]	3.43 (2.02, 4.85)	0.59 (-0.43, 1.61)
Unstable ankle training		95.28 ± 10.22	102.22 ± 11.73	.015[c]	6.93 ± 6.73		1.41 (0.32, 2.51)	
Control		95.38 ± 6.72	95.02 ± 7.64	.639	-0.36 ± 2.37			
Stable ankle training	Unstable	92.08 ± 9.18	102.25 ± 8.64	< .001[c]	10.17 ± 5.23	< .001[c]	2.03 (0.81, 3.24)	-0.08 (-1.08, 0.92)
Unstable ankle training		91.51 ± 8.81	102.21 ± 11.37	.002[c]	10.70 ± 7.27		1.68 (0.53, 2.82)	
Control		91.03 ± 5.91	91.97 ± 7.55	.406	0.93 ± 3.40			
YBT posterolateral (cm)								
Stable ankle training	Stable	88.20 ± 8.73	98.27 ± 7.90	< .001[c]	10.07 ± 4.29	.001[c]	2.87 (1.45,4.29)	0.97 (-0.10, 2.03)
Unstable ankle training		91.26 ± 7.70	95.67 ± 7.32	.081	4.40 ± 6.62		0.94 (-0.09, 1.96)	
Control		88.65 ± 8.20	88.24 ± 7.33	.625	-0.41 ± 2.57			

Abbreviations: Δ, Post Variables minus Pre Variables; FAAM, Foot and Ankle Ability Measure; ADL, Activity of Daily Living; S, Sports; BESS, Balance Error Scoring System; YBT, Y Balance Test; SLVCJ, The Single-Leg Vertical Countermovement Jump.

[a] Hedges' *g* was used to calculate the size of the difference between the training groups and the control group outcomes.

[b] Hedges' *g* was used to calculate the size of the difference between the stable ankle training group and the unstable ankle training group outcomes.

[c] Indicates statistical difference (P < .05).

Outcomes	Ankle	Pre-training	Post-training	P-value	Δ After 4 weeks	P-value	Effect Size (95% Confidence Interval)	
							Versus Control Group[a]	Versus Training Groups[b]
Stable ankle training	Unstable	86.04 ± 8.65	93.54 ± 8.56	< .001[c]	8.12 ± 4.15	.001[c]	2.15 (0.91, 3.39)	0.17 (-0.83, 1.17)
Unstable ankle training		87.13 ± 8.80	94.65 ± 8.01	.013[c]	7.07 ± 7.06		1.37 (0.28, 2.45)	
Control		86.87 ± 6.67	85.87 ± 6.09	.446	-0.99 ± 3.96			
Sports Performance								
SLVCJ test (cm)								
Stable ankle training	Stable	30.17 ± 10.23	31.77 ± 9.85	.028	1.59 ± 2.69	.296	0.43 (-0.55, 1.41)	-0.34 (-1.35, 0.66)
Unstable ankle training		26.46 ± 5.26	29.42 ± 6.05	.035[c]	2.96 ± 4.66		0.66 (-0.34, 1.66)	
Control		28.24 ± 8.99	28.89 ± 8.57	.182	0.64 ± 1.43			
Stable ankle training	Unstable	30.74 ± 9.67	31.68 ± 9.34	.123	0.94 ± 2.14	.171	-0.22 (-1.20, 0.75)	-0.85 (-1.90, 0.20)
Unstable ankle training		25.50 ± 4.53	28.75 ± 4.89	.014[c]	3.25 ± 2.98		0.59 (-0.40, 1.58)	
Control		26.88 ± 9.36	28.39 ± 8.82	.083	1.51 ± 2.66			
Figure-of-8 hop test (sec)								

Abbreviations: Δ, Post Variables minus Pre Variables; FAAM, Foot and Ankle Ability Measure; ADL, Activity of Daily Living; S, Sports; BESS, Balance Error Scoring System; YBT, Y Balance Test; SLVCJ, The Single-Leg Vertical Countermovement Jump.

[a] Hedges' *g* was used to calculate the size of the difference between the training groups and the control group outcomes.

[b] Hedges' *g* was used to calculate the size of the difference between the stable ankle training group and the unstable ankle training group outcomes.

[c] Indicates statistical difference (P < .05).

Outcomes	Ankle	Pre-training	Post-training	P-value	Δ After 4 weeks	P-value	Effect Size (95% Confidence Interval)	
							Versus Control Group[a]	Versus Training Groups[b]
Stable ankle training	Stable	11.79 ± 1.96	10.32 ± 2.04	< .001[c]	-1.47 ± 0.49	< .001[c]	-2.36 (-3.66, -1.07)	-2.16 (-3.44, -0.87)
Unstable ankle training		11.62 ± 1.07	11.01 ± 1.12	< .001[c]	-0.61 ± 0.22		-0.85 (-1.87, 0.16)	
Control		11.78 ± 0.76	11.51 ± 0.90	.109	-0.27 ± 0.48			
Stable ankle training	Unstable	12.51 ± 1.72	11.29 ± 1.40	< .001[c]	-1.21 ± 0.64	.002[c]	-1.30 (-2.38, -0.22)	0.36 (-0.65, 1.37)
Unstable ankle training		12.57 ± 1.54	11.10 ± 1.20	< .001[c]	-1.46 ± 0.69		-1.60 (-2.73, -0.47)	
Control		12.41 ± 0.78	12.09 ± 1.05	.176	-0.31 ± 0.68			
Side hop test (sec)								
Stable ankle training	Stable	10.28 ± 1.85	8.26 ± 1.06	.001[c]	-2.01 ± 1.17	.008[c]	-1.46 (-2.56, -0.35)	-0.56 (-1.58, 0.46)
Unstable ankle training		10.15 ± 1.53	8.74 ± 1.01	.001[c]	-1.41 ± 0.84		-1.05 (-2.09, -0.01)	
Control		10.34 ± 1.06	9.75 ± 0.93	.019[c]	-0.59 ± 0.65			
Stable ankle training	Unstable	10.81 ± 2.13	8.67 ± 0.81	.004[c]	-2.14 ± 1.62	.003[c]	-1.36 (-2.44, -0.27)	0.26 (-0.75, 1.26)

Abbreviations: Δ, Post Variables minus Pre Variables; FAAM, Foot and Ankle Ability Measure; ADL, Activity of Daily Living; S, Sports; BESS, Balance Error Scoring System; YBT, Y Balance Test; SLVCJ, The Single-Leg Vertical Countermovement Jump.

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[b] Hedges' *g* was used to calculate the size of the difference between the stable ankle training group and the unstable ankle training group outcomes.

[c] Indicates statistical difference (P < .05).

Outcomes	Ankle	Pre-training	Post-training	P-value	Δ After 4 weeks	P-value	Effect Size (95% Confidence Interval)	
							Versus Control Group[a]	Versus Training Groups[b]
Unstable ankle training		10.80 ± 1.79	8.25 ± 0.95	.001[c]	-2.55 ± 1.39		-1.92 (-3.11, -0.73)	
Control		10.92 ± 1.11	10.46 ± 1.30	.037[c]	-0.45 ± 0.59			
Abbreviations: Δ, Post Variables minus Pre Variables; FAAM, Foot and Ankle Ability Measure; ADL, Activity of Daily Living; S, Sports; BESS, Balance Error Scoring System; YBT, Y Balance Test; SLVCJ, The Single-Leg Vertical Countermovement Jump.								
[a] Hedges' *g* was used to calculate the size of the difference between the training groups and the control group outcomes.								
[b] Hedges' *g* was used to calculate the size of the difference between the stable ankle training group and the unstable ankle training group outcomes.								
[c] Indicates statistical difference (P < .05).								

Regarding dynamic postural control (YBT), the SG exhibited bilateral improvements in all reach directions ($p < 0.01$). The UG demonstrated bilateral improvements in the anterior and posteromedial directions ($p < 0.05$), but posterolateral reach increased only in the injured limb ($p = 0.01$). No YBT improvements were observed in the CG.

In terms of functional performance, both training groups significantly improved their figure-of-eight hop test times bilaterally ($p < 0.001$). For the SLVCJ test, the UG improved bilaterally ($p < 0.05$), while the SG improved only in the uninjured limb ($p = 0.02$). The CG showed no improvements in these parameters. Notably, all three groups demonstrated a significant improvement over time in the side hop test for both limbs ($p < 0.05$).

3.3. Between-Group Outcomes and Effect Sizes

Tukey's post hoc testing revealed that both the SG and UG achieved significantly greater improvements in the FAAM, BESS, YBT, figure-of-eight hop, and side hop tests compared to the CG. Most importantly, no statistically significant differences were observed between the SG and UG across these measures.

Compared to the CG, both training groups demonstrated predominantly large effect sizes (Hedges' $g \geq 0.80$) with 95% confidence intervals (CIs) excluding zero for bilateral outcome measures, with the exception of the SLVCJ test. For the SLVCJ, the SG exhibited a small effect size, while the UG showed a moderate effect size. When comparing the two training groups directly (SG vs. UG), predominantly small effect sizes were observed for all outcome variables regarding the injured limb (Table 3).

3.4. Adverse Events

No adverse events or training-related injuries were reported during the intervention period.

4. Discussion

The primary objective of this randomized controlled trial was to investigate the cross-education effects of a 4-week unilateral neuromuscular training program on postural control and functional performance in athletes with chronic ankle instability (CAI). The most prominent finding of this study is that athletes in both training groups demonstrated significant, clinically meaningful improvements across all outcome variables, regardless of which limb was trained. This indicates that the injured limb benefits robustly from targeted interventions, even when exclusively the uninjured (contralateral) limb undergoes training.

4.1. Patient-Reported Outcomes and Postural Control

Both the SG (training the uninjured limb) and UG (training the injured limb) exhibited substantial improvements in FAAM scores over time, with large effect sizes underscoring the clinical relevance of unilateral training for lower extremity function. These findings strongly align with existing literature demonstrating that 4- to 6-week single-leg postural control and hop-stabilization protocols significantly enhance self-reported lower extremity function in both athletic and non-athletic populations with CAI [6, 26, 27].

Following the 4-week unilateral training protocol, total BESS errors decreased significantly in both the SG and UG, reflecting substantial improvements in static postural control of the injured limb. The large effect sizes indicate that the protocol utilized in this study exerts a robust clinical impact. While some previous research reported improvements limited only to the tandem stance on a foam surface [6], the present study demonstrates comprehensive improvements across all BESS conditions for both training groups. These results strongly suggest that a 4-week targeted training program effectively enhances static postural control of the injured limb in athletes, regardless of which limb undergoes training.

Dynamic postural control was evaluated using the Y-Balance Test (YBT). In the present study, both training groups demonstrated significant improvements in reach distances across all directions, supported by large effect sizes. These comprehensive results align with and expand upon prior literature, which previously reported specific improvements limited to the anterior and posteromedial reach directions following uninjured-limb training [6]. Furthermore, these findings are consistent with broader evidence demonstrating enhanced dynamic postural control of the injured limb following 4-week unilateral rehabilitation in both non-athletic and athletic populations [26, 28–30]. Collectively, these findings confirm that dynamic postural control of the injured limb improves significantly, regardless of which limb is subjected to the training stimulus.

4.2. Functional Performance

Functional performance was evaluated using the single-leg vertical countermovement jump (SLVCJ), figure-of-eight hop, and side hop tests. These functional tests evaluate the capacity to tolerate increased mechanical stress and perform multi-planar movements commonly encountered during sports activities [25]. Both intervention groups demonstrated reduced completion times and improved jump metrics in the figure-of-eight hop and side hop tests, with moderate-to-large effect sizes, whereas no significant between-group differences were observed for the SLVCJ. The absence of a training effect for the SLVCJ may reflect the task-

specific nature of the training protocol, which targeted postural control and dynamic stabilization over explosive vertical power generation. Consequently, the cross-education benefits were more evident in functional tasks necessitating multi-planar neuromuscular control compared to vertical jump performance.

A significant within-group improvement in side hop performance was also observed in the CG despite the absence of a structured intervention. This finding may reflect a practice effect associated with repeated test exposure or natural performance variation over the four-week study period. Nevertheless, both training groups demonstrated significantly greater improvements than the CG, indicating that the observed improvements cannot be explained solely by repeated testing or spontaneous changes.

The present findings extend the current evidence on cross-education by showing that unilateral neuromuscular training can enhance multi-planar functional performance in athletes with CAI. While previous studies and systematic reviews have primarily focused on postural control outcomes [13], our findings suggest that bilateral adaptations may also translate to sport-specific functional tasks necessitating dynamic stability and neuromuscular coordination.

4.3. Neurophysiological Mechanisms

The bilateral improvements observed in this study can likely be attributed to neuroplastic adaptations within the central nervous system (CNS). Following an ankle sprain, bilateral postural control deficits arise due to central maladaptations [7]. Previous neurophysiological studies have consistently demonstrated that CAI is associated with decreased spinal reflex excitability and bilaterally reduced corticomotor excitability of the ankle stabilizers [31–33]. In athletic populations, these maladaptations manifest at both cortical and peripheral levels, compromising feed-forward neuromuscular control during sport-specific tasks [34]. Unilateral training likely facilitates neuromuscular re-education by enhancing central processing and efferent responses to somatosensory input [6, 12, 35–37]. Although the CG demonstrated a significant improvement in the side hop test, potentially attributable to a practice effect [11], the absence of significant changes in the other outcome measures supports the interpretation that the bilateral improvements observed in the training groups were primarily attributable to training-induced neuroplastic adaptations rather than spontaneous or natural recovery.

4.4. Clinical Implications

The integration of unilateral uninjured-limb training into clinical practice is supported by strong clinical rationale. Traditionally, CAI rehabilitation is delayed due to pain, effusion, or reduced tissue tolerance on the injured side, leading to bilateral neuromuscular detraining. Unilateral training circumvents this barrier by leveraging the cross-education effect, enabling clinicians to stimulate bilateral corticomotor excitability without mechanically overloading healing lateral ligaments. For athletes, this strategy protects recovering tissue while facilitating earlier improvements in postural control and functional performance, ultimately shortening rehabilitation timelines and accelerating return-to-sport.

4.5. Limitations

While these findings offer valuable clinical applications, several limitations warrant consideration. The absence of blinding at both the participant and assessor levels, coupled with the fact that some participants

were teammates, may have enhanced intrinsic motivation or fostered a competitive environment; this could have contributed to the observed functional improvements independently of the training intervention. Additionally, statistically significant differences in body weight and BMI were observed between the SG and CG at baseline, which may represent a potential confounding variable that could have influenced the outcome measures. Furthermore, although bilateral improvements may reflect neuroplasticity and central neural adaptations, these mechanisms were not directly assessed using neurophysiological measures such as Transcranial Magnetic Stimulation (TMS) or electromyography (EMG) and therefore remain inferential based on the observed functional outcomes. Although the sample size exceeded the power analysis threshold, the relatively small number of participants (n = 28) may limit the generalisability of the findings to broader athletic populations. Finally, the absence of a long-term follow-up prevents conclusions regarding the sustained duration of the cross-education benefits on either the stable or unstable ankle.

5. Conclusion

Determining optimal treatment guidelines for CAI rehabilitation remains challenging due to substantial methodological variability in the literature. The present findings suggest that a 4-week, unilateral neuromuscular training is sufficient to induce significant cross-education effects, resulting in clinically meaningful bilateral improvements in postural control and functional performance. These results indicate that potential central nervous system adaptations elicited by uninjured-limb training effectively mitigate neuromuscular detraining in the contralateral injured limb. Consequently, integrating this unilateral approach into comprehensive rehabilitation protocols provides clinicians with a safe and highly effective mechanism to accelerate neuromuscular recovery and maintain functional capacity before the injured limb can safely tolerate direct mechanical stress. Future research should investigate these cross-education mechanisms across broader athletic populations, including acute ankle sprains and varying professional levels, utilizing long-term follow-up designs.

Abbreviations

ADL
Activities of Daily Living
ANOVA
Analysis of Variance
BESS
Balance Error Scoring System
BMI
Body Mass Index
CAI
Chronic Ankle Instability
CAIT
Cumberland Ankle Instability Tool
CG
Control Group

CNS
Central Nervous System
CONSORT
Consolidated Standards of Reporting Trials
EMG
Electromyography
FAAM
Foot and Ankle Ability Measure
FAAM-S
Foot and Ankle Ability Measure — Sports
HSD
Honestly Significant Difference
ICC
Intraclass Correlation Coefficient
LAS
Lateral Ankle Sprain
SD
Standard Deviation
SG
Stable Ankle Training Group
SLVCJ
Single-Leg Vertical Countermovement Jump
SPSS
Statistical Package for the Social Sciences
TMS
Transcranial Magnetic Stimulation
UG
Unstable Ankle Training Group
YBT
Y Balance Test
Δ
Change score (post minus pre)

Declarations

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Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki. Ethical approval was granted by the Yeditepe University Ethical Committee (Issue Number: 37068608-6100-15-1609). Written informed

consent was obtained from all participants prior to enrollment.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

AYS has participated in the design of the study, contributed to the data collection, and performed the statistical analysis; GM and FS have participated in the study design and contributed to data analysis and interpretation of results; ŞD and ŞBH has contributed to the interpretation of the results and helped draft the manuscript. All authors have contributed to the writing of the manuscript. All authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors.

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Table 1 and 2

Table 1 and 2 are available in the Supplementary Files section.

Figures

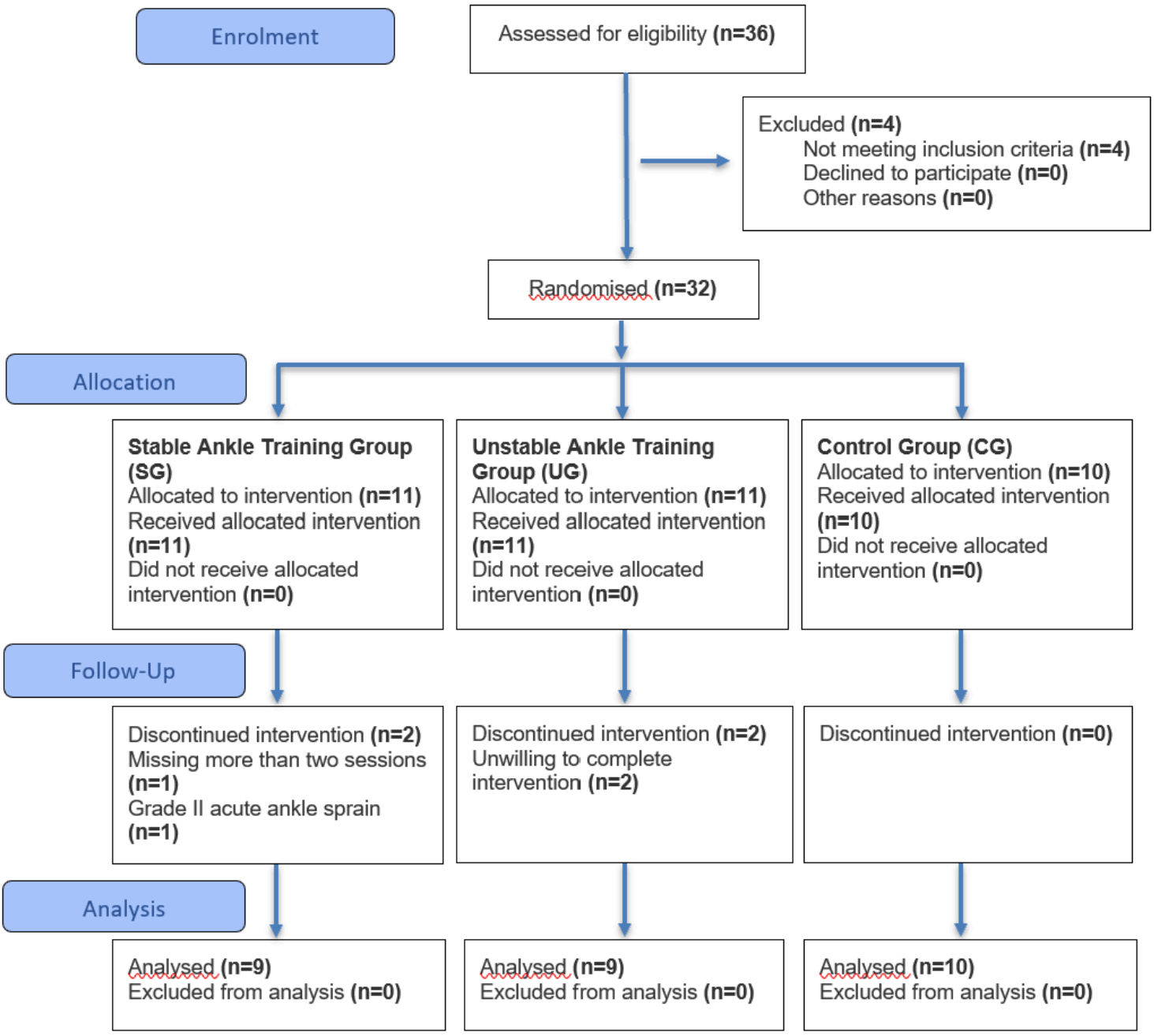


Figure 1

CONSORT 2025 Flow Diagram illustrating the enrollment, allocation, and follow-up of participants throughout the trial. Of 36 volunteers assessed for eligibility, 32 met the inclusion criteria and were randomly allocated to three groups: the stable ankle training group (SG, n = 9), the unstable ankle training group (UG, n = 9), and the control group (CG, n = 10). Four participants withdrew during the intervention period

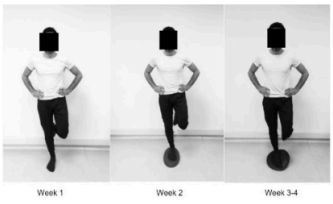
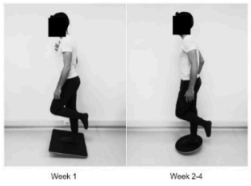
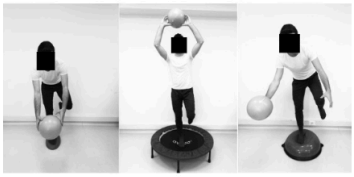
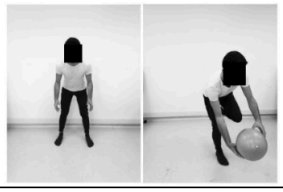
Exercise Program	Exercise Explanation
A. Single-Leg Stance  Week 1 Week 2 Week 3-4	Week 1: Performed up to 60 s per repetition for up to 3 repetitions with and without visual feedback on a firm surface
	Week 2: Performed up to 60 s per repetition for up to 3 repetitions with/out visual feedback on a soft surface using Thera-Band Stability Trainer[a]
	Week 3-4: Performed up to 60 s per repetition for up to 3 repetitions with/out visual feedback on a soft surface using balance disc[a]
B. Wobble Board  Week 1 Week 2-4	Week 1: Began with using a two-dimensional wobble board[a]. Slowly moved the board in the plantarflexion/dorsiflexion and inversion/eversion directions without contacting the floor
	Week 2: Slowly moved the board using multi-dimensional wobble board[a] with upper extremity support
	Week 3-4: Slowly moved the board using multi-dimensional wobble board without upper extremity support
C. Steamboats  Week 1 Week 2 Week 3-4	Week 1: Tied a 120 cm Thera-Band[a] around the unstable ankle for SG and stable ankle for UG. Positioned stance foot 70 cm away from where Thera band was tied, on a firm surface. Performed up to 3 sets of 15 repetitions in each direction (hip flexion, extension, adduction, abduction)
	Week 2: Positioned stance foot on a soft surface using a Thera-Band Stability Trainer. Performed up to 3 sets of 15 repetitions in each direction (hip flexion, extension, adduction, abduction)
	Week 3-4: Positioned stance foot on a soft surface using a balance disc
D. Single-Leg Hop	Week 1: Hopped as far as comfortable in the anterior direction. Performed up to 5 repetitions
	Week 2: Performed up to 10 repetitions adding medial, lateral, and posterior directions
	Week 3: Performed up to 15 repetitions in all directions
	Week 4: Performed up to 3 sets of 10 hops
E. Single-Leg Ball Catch  Week 1 Week 2 Week 4	Week 1: Performed during stance on a firm surface
	Week 2: Performed during stance on a trampoline[b]
	Week 3: Performed during stance on a balance disc
	Week 4: Performed during stance on a Bosu ball[c]
F. Quadrant Hop 	Week 2: Performed up to 3 sets of 5 hops in numbered squares clockwise and counterclockwise while maintaining a single-legged stance
	Week 3-4: Added unanticipated directional changes, investigator randomly called out numbers
G. Single-Leg Hop and Ball Catch 	Week 3-4: Performed up to 3 sets of 10 hops Positioned double-legged stance on a flat surface Hopped with one foot in the direction the ball is thrown and catches the ball[a] Returned to starting position

Figure 2

Unilateral neuromuscular training protocol consisting of progressive postural control and hop-stabilization exercises performed twice weekly for four weeks. Exercises were applied exclusively to the uninjured limb in the SG and exclusively to the injured limb in the UG. Exercise progression was based on participant performance and tolerance. [a]TheraBand®, Akron, OH 44310, [b]Avessa®, [c]BOSU®, Ashland, Ohio 44805

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table12.docx