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Cortical Changes of Dual Cognitive-Task Balance Training in Patients With Chronic Ankle Instability: A Randomized Trial

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Context: Researchers have shown that patients with chronic ankle instability (CAI) have deficits in memory and attention allocation. This functional deficit affects lower extremity performance. Motor-cognitive dual-task training may improve lower limb dysfunction caused by central nervous system injury. Further study is needed to determine whether dual-task training is more favorable than single-task training for improving neuromuscular control in patients with CAI.

Objective: To compare the effects of balance-cognition dual-task training and balance single-task training on lower limb function and electroencephalography changes during static postural control in patients with CAI.

Design: Randomized clinical trial (Chinese Clinical Trial Registry: ChiCTR2300073875).

Setting: Rehabilitation training room.

Patients or Other Participants: A total of 24 patients with CAI (age = 22.33 ± 2.43 years, height = 175.62 ± 7.7 cm, mass = 70.63 ± 14.59 kg) were block randomized into 2 groups.

Intervention(s): Protocols were performed 3 times per week for 6 weeks. The single-task group underwent 1-legged static balance training with eyes open and closed and hopping balance training. The dual-task group underwent balance and cognitive training (backward-counting task).

Main Outcome Measure(s): Cortical activity, proprioception, muscle onset time (difference between the muscle activation time and touchdown time), and dynamic balance were assessed before and after the interventions. We performed multivariate analyses of variance to identify main effects and interactions across groups and time. A post hoc Bonferroni test was performed for pairwise comparisons when interactions were present.

Results: All participants successfully completed the 6-week interventions. Proprioception, peroneus longus (PL) muscle onset time, and dynamic postural control improved after the interventions in both groups ($P < .05$). Dual-task training was superior to single-task training in improving joint position sense in plantar flexion, shortening PL muscle onset time, and altering cortical activity ($P < .05$).

Conclusions: A 6-week program of balance training or balance combined with cognitive training could improve the functional deficits associated with CAI. The dual-task training could also improve joint position sense in plantar flexion, PL muscle onset time, and cortical activity.

Key Words: ankle sprain, cortical activity, cognitive task, balance training, dual task

Key Points

- Both balance single-task and balance-cognitive dual-task training improved proprioception and dynamic postural control and shortened muscle onset time in patients with chronic ankle instability.
- Combined balance and cognitive training over a 6-week period was able to increase alpha-1 and theta wave power during single-legged stance more than balance training alone in patients with chronic ankle instability.
- Dual-task training had a greater advantage in addressing residual deficits in patients with chronic ankle instability.

Chronic ankle instability (CAI) is a common outcome that can occur after an ankle sprain, affecting approximately 34% to 73% of individuals who have experienced such sprains.[1,2] Symptoms of CAI include pain, weakness, and instability of the affected ankle.[3] Researchers have shown that CAI is caused by neuromuscular inhibition, muscle weakness, balance deficits, and damage to peripheral proprioceptors.[4,5] These functional impairments may result in reduced muscle activation rate and number as well as prolonged muscle onset time. Current interventions for improving functional deficits in CAI often focus on the peripheral nervous system, particularly through balance training that stimulates ankle proprioceptors, resulting in enhanced lower limb function in patients with CAI.[6] However, recent models of CAI have suggested that motor control and performance are not only influenced by peripheral proprioception but also involve changes in supraspinal motor control.[5] This implies

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that addressing the central nervous system mechanisms may also be essential in comprehensive treatment approaches for CAI.

Recently, researchers found that patients with CAI also have deficits in memory and attention allocation, as evidenced by poorer compound memory, visual memory, and simple attention than healthy individuals, as well as an inability to cope with environmental changes due to increased cognitive load when performing postural-control tasks.[7,8] Changes in cortical excitability may be related to the amount of peripheral sensory activity, and peripheral sensory deficits may lead to deficits in sensorimotor cortex activation, corticomotor excitability, and reflexive excitability.[9] During single-limb postural control, participants with CAI have exhibited heightened theta wave power and oxyhemoglobin levels, as detected by electroencephalography (EEG) and functional near-infrared spectroscopy.[10,11] The changes in cortical activity suggest that postural stabilization requires more cortical activity and increased attention dependence. Motor-cognitive dual-task training can acutely direct participants' attention toward an external source of attention and influence the prioritization of central sharing to enhance cognitive task performance, rate of learning, and ability to maintain skill level.[12] Sherman et al reported that external focus of attention led to increased cortical activity in cognitive, motor, somatosensory, and visual processing, and these changes were independently associated with improving balance performance.[13] Therefore, dual-task training may be able to further improve balance performance.

The purpose of this study was to compare the effects of balance-cognition dual-task training and balance single-task training on lower limb function and EEG changes during static postural control in patients with CAI. Specifically, we sought to (1) identify the effects of 2 different training tasks on the reliance on cortical activity during static postural control and (2) determine whether balance combined with cognitive training would improve proprioception, muscle onset time, and dynamic postural control more than balance training alone. We hypothesized that dual-task training would increase cortical activity during static postural control and improve lower limb function more effectively than single-task training in patients with CAI.

METHODS

Participants

An a priori sample size was calculated using effect sizes estimated from previously published data.[14] Assuming an α level of .05, power ($1 - \beta$ error) of 0.95, and effect size of 0.79 (G*Power 3.1), 23 participants were required to detect between- and within-group differences when performing multivariate analyses of variance (MANOVAs).[15] Oversampling was conducted to account for a 15% attrition rate. Participants were recruited using online advertisements at the Capital University of Physical Education and Sport in October 2022. Volunteers who met the inclusion criteria were assigned unique identification numbers using a random number table and were evenly allocated to either the single- or dual-task group through a random drawing process.

Inclusion criteria for participants with CAI comprised the following: a history of at least 1 significant ankle sprain in the 12 months before the study that was associated with inflammatory symptoms (eg, pain and swelling) and resulted in at least 1 interrupted day of desired physical activity; a history of the previously injured ankle joint "giving way" at least twice in the 6 months before the study; a score of $<$24 on the Cumberland Ankle Instability Tool (CAIT); and willingness to provide signed informed consent.[16] When both lower extremities of the study population met the inclusion criteria, the limb with the lower CAIT score was selected. Exclusion criteria included any form of neurological disorder or other injuries to the lower extremities, history of lower extremity surgery, and positive results for the anterior drawer test and talar tilt test.

All participants provided written informed consent, and the study was approved by the Chinese Clinical Trial Registry (ChiCTR2300073875).

Training Program

Three supervised training sessions, each lasting approximately 20 minutes, were conducted each week for 6 weeks. The single-task group underwent balance training only, and the dual-task group underwent cognitive and balance training. Intervention sessions were scheduled, and participants were reminded to complete the training using WeChat (Tencent Holdings Ltd). All the participants were enrolled, trained, and tested in an exercise rehabilitation training room at the Capital University of Physical Education and Sports. The study investigator (X.S.) tracked and supervised all training sessions. Two investigators (L.C. and T.H.) measured all outcomes. All 3 investigators have physical therapy certifications in China. To allow blinding, the investigator (Q.H.) responsible for the data analysis was not involved in the process of participant inclusion, assignment, training, and evaluation.

Single-Task Training. For single-task training, we used the progressive balance training that was designed by McKeon et al and included 3 different training programs: dynamic balance training and static balance training with eyes open and closed.[17] Each program contained 7 levels of difficulty in which the participants advanced (Appendices 1 and 2). An interval of 2 minutes was given between programs. The difficulty level increased every 2 weeks or when the participants could complete the balance task stably. Performance was deemed *unstable* based on the following criteria: touching down with the opposite limb, excessive trunk motion ($>$30° of lateral flexion), removing of the arms from across the chest during specified activities, bracing the nonstance limb against the stance limb, and missing the target.

Dual-Task Training. For dual-task training, balance training was supplemented by a cognitive task involving backward counting. Specifically, random audio of 4 digits (eg, 8357) were provided via a computer (E-Prime 3.0; Psychology Software Tools, Inc), and the participants were asked to recall these 4 digits quickly and accurately in backward order (eg, 7538).[18] Participants were allowed to practice the cognitive task before training began. For the static program, participants were asked to recall these 4 digits as quickly and accurately as possible while maintaining static stability. For the dynamic program, participants started jumping after hearing a random number and, upon landing, attempted to accurately recall these 4 digits in backward order within 5 seconds of maintaining stability (Figure 1).

Procedures

Cortical Activity. Participants were instructed to transition from a double- to a single-legged stance on the affected side with closed eyes for 30 seconds when hearing the start command (Figure 2).[19] This test was repeated 5 times, with a

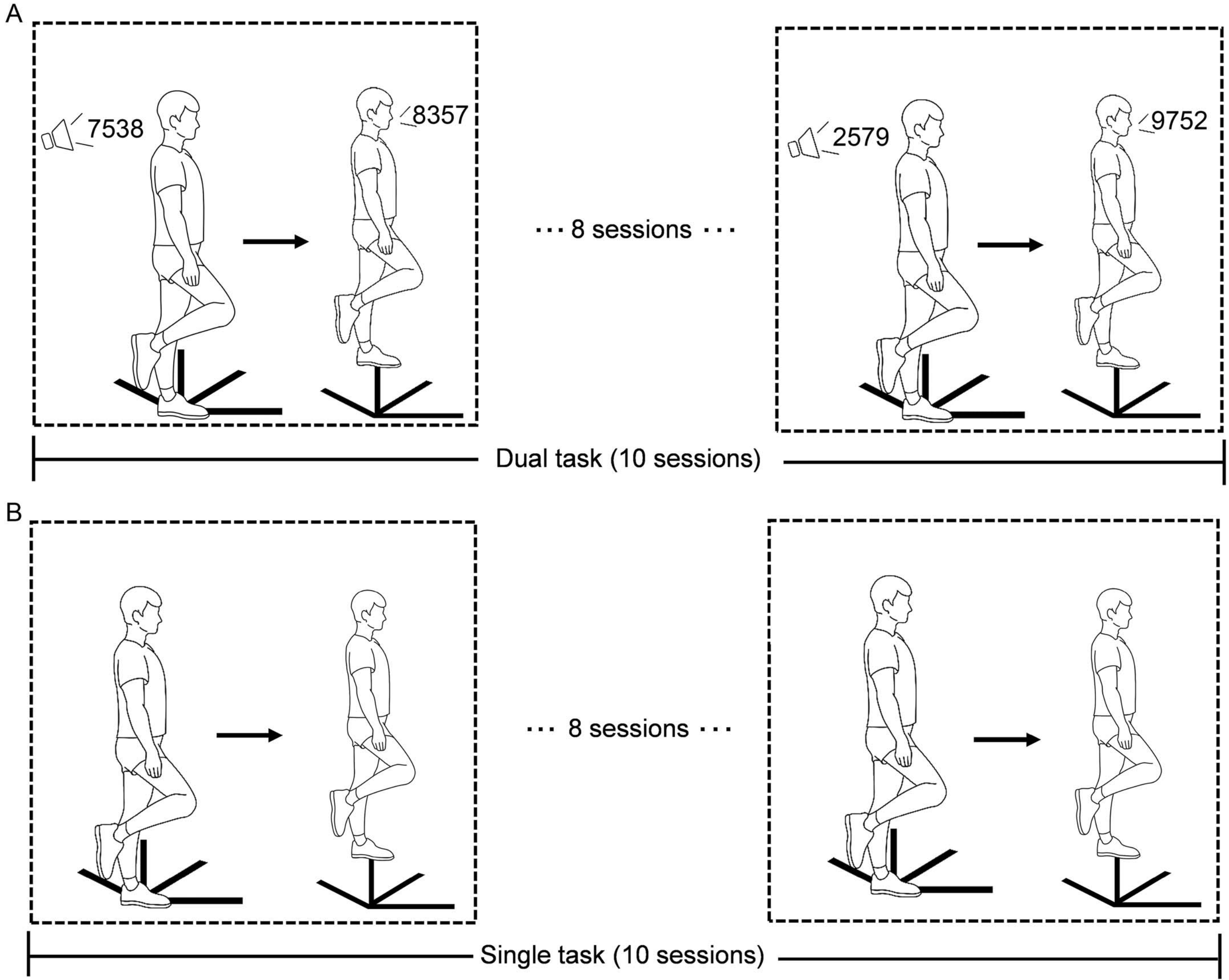

Figure 1. A, Dual- versus, B, single-task training.

1-minute break provided between each task. Before the test trials, participants were given a single practice trial to familiarize themselves with the task. Any trial in which the participants did not maintain stability or keep their eyes closed for the entire required duration was considered a *failure*. In such cases, the test was halted, and the trial was repeated. Electroencephalography data were collected using a 64-channel QuickCap (Compumedics Neuroscan) that was connected to a 64-channel NuAmps (Compumedics Neuroscan) digital EEG amplifier. Custom-custom montages were used for data from 14 EEG channels (FP1, FP2, F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, and CP4).[20] Two EEG channels were recorded in the medial-upper and lateral orbital regions of the right eye. Electrical impedance was kept below 5 kΩ throughout testing. The EEG signals were amplified with a gain of 19, filtered in direct current at 400 Hz, sampled at 1000 Hz using the Curry 7 (Compumedics Neuroscan) software on a dedicated computer, and saved for offline analysis.[20]

Proprioception. Joint position sense (JPS) changes were measured to assess proprioception.[21] The angle changes were measured using an electronic protractor and were recorded to 2 decimal places. To measure ankle dorsiflexion and plantar-flexion, we located the axis of the protractor 2.5 cm below the tip of the lateral malleolus, with the fixed arm close to the long axis of the fibula and the mobile arm close to the lateral edge of the fifth metatarsal. To measure inversion and eversion, we located the axis at the midpoint of the lateral metatarsal, with the fixed arm parallel to the long axis of the fibula and the mobile arm parallel to the metatarsal plane. Before the test, participants lay supine with the test ankle suspended from the treatment bed. During the test, the ankle was passively rotated to the target angle (dorsiflexion: 10°, plantar-flexion: 20°, inversion: 15°, and eversion: 10°).[22] Participants were instructed to close their eyes, hold the ankle at the target angle for 10 seconds, and passively return the ankle to the 0° position after relaxing. Next, they were instructed to actively return the ankle to the target angle. The difference between the target and actual angles was recorded (Figure 3). The measurement was repeated 3 times, and the mean value was used for analysis. The greater the error between the target and actual angles, the worse the proprioception.[4]

Muscle Onset Time. A Trigno Wireless (Delsys Inc) system sampling at 1000 Hz was used to collect electromyographic (EMG) signals from the tibialis anterior (TA) and peroneus longus (PL) muscles of the tested limb.

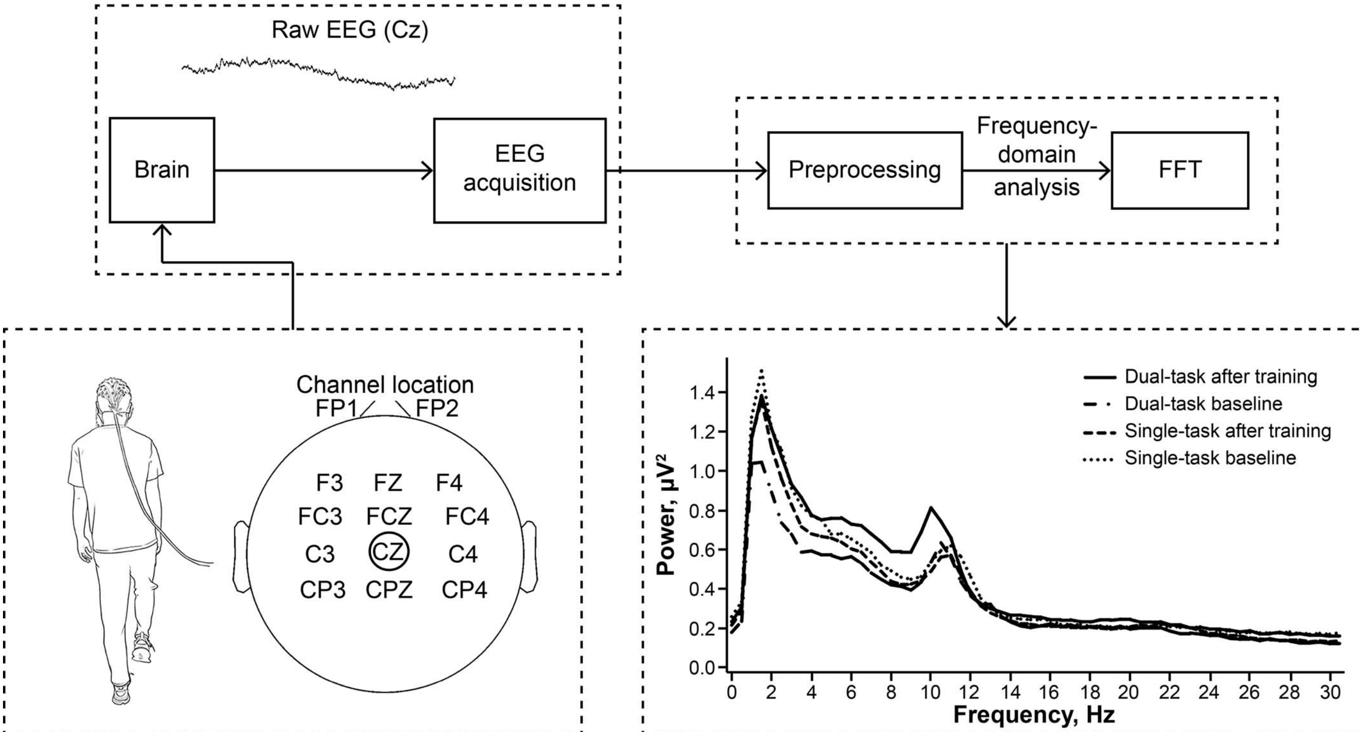

Figure 2. Electroencephalography (EEG) signal procedures. FFT, Fast Fourier transform.

Recording sites were prepared by shaving the areas and wiping them with alcohol pads to decrease the electrical impedance. Two 20 × 41 mm rectangular Ag/AgCl electrodes were placed along the long axis of the PL (about 8 cm below the fibular head, near the line connecting the fibular head and lateral ankle) and TA (about 8 cm below the tibial tuberosity and 3 cm lateral to the tibial edge) on the affected limb.[23] The PL and TA maximal voluntary isometric contractions were measured at the 0° position after participants warmed up with light muscle activation.[24] Next, they were asked to stand on 1 foot with the healthy lower extremity on a 40 cm high jump box, and the affected lower extremity was suspended outside the box and kept relaxed. When the EMG signals generated by the testing system reached a steady state, the tester instructed participants to execute a "jump down" motion. After receiving the command, participants leapt off the box and balanced on 1 foot with the affected lower limb for 3 seconds while fixating their gaze straight ahead throughout the testing procedure (Figure 4). Before testing commenced, testers gave the instructions to participants and allowed them to practice twice to acquaint themselves with the testing procedure. The test was performed 3 times, and data were saved for offline analysis.

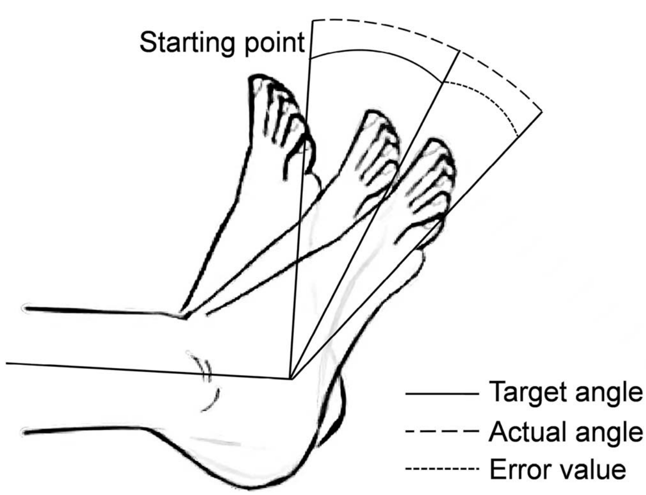

Figure 3. Joint position sense.

Dynamic Postural Control. The Star Excursion Balance Test (SEBT) was used to test the changes in dynamic postural control. Participants stood with the affected lower limb at the center of a grid laid on the floor with 8 lines extending at 45° increments from the center of the grid and with the opposite limb touching as far as possible along the chosen line. Before testing, testers provided instructions to the participants and allowed them to practice twice to familiarize themselves with the testing procedures. The following 3 directions were recorded: anteromedial (AM), medial (M), and postmedial (PM; Figure 5). These directions have been reported to respond sensitively to differences in the dynamic balance between participants with and those without CAI.[25] During the test, participants were asked to place their hands on their waist to limit their reliance on the extremities. They were instructed to keep the supporting lower limb stable without displacement and return the opposite limb stably to a bilateral stance after lightly touching the test line. The reach distance was normalized to participant lower extremity length (in centimeters) measured from the anterior-superior iliac spine to the distal tip of the medial malleolus. The average of 3 trials for each direction was used for the analysis.

Data Analysis

EEG Analysis. MATLAB R2022b (The MathWorks, Inc) was used for EEG data analysis, in which the data collected using Curry software (in .dap format) were converted into

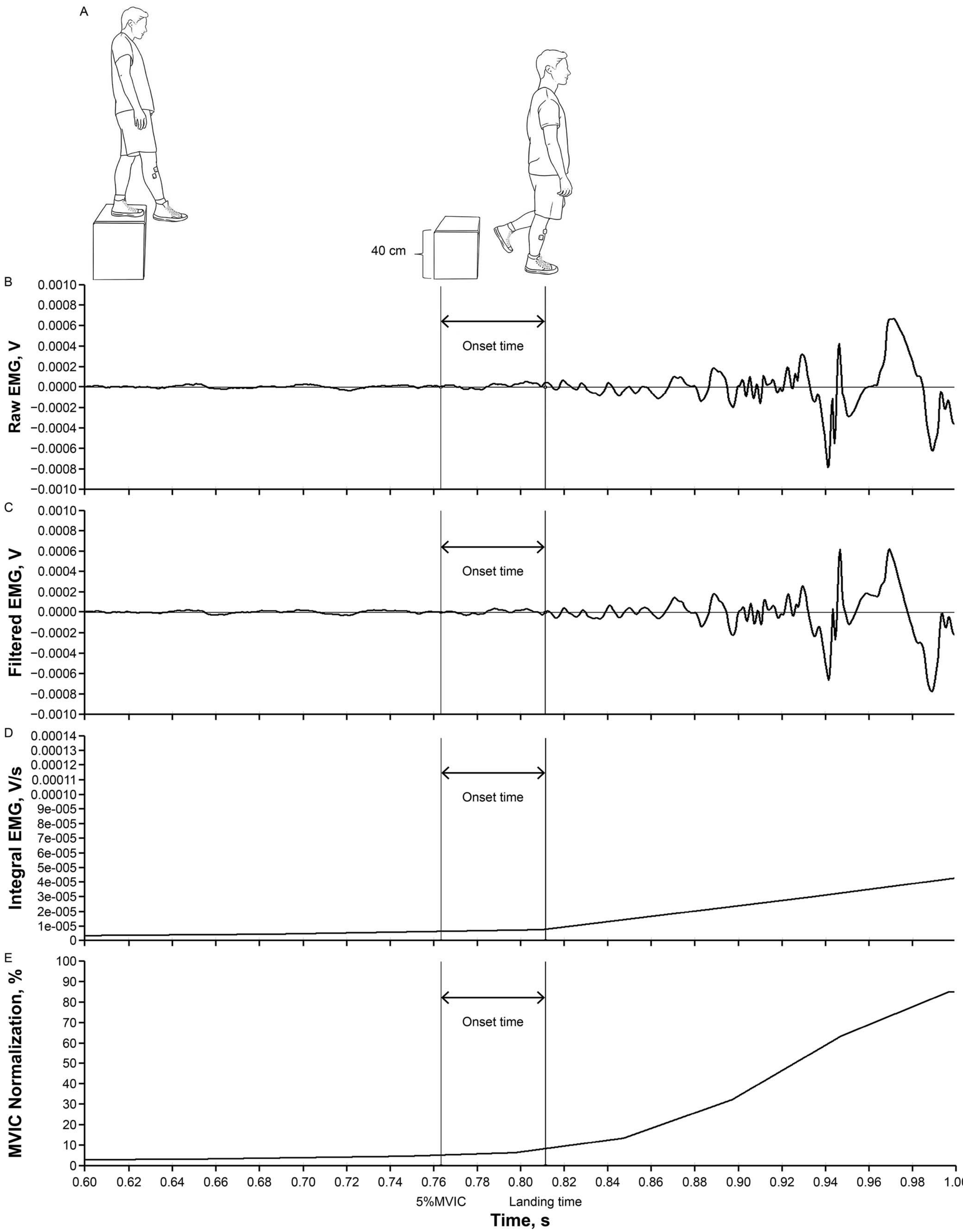

Figure 4. Muscle onset time. A, Illustration of jump-landing task. B, Raw electromyography (EMG). C, Filtered EMG. D, Integral EMG. E, Maximal voluntary isometric contraction (MVIC) normalization. *Muscle onset time* was defined as the difference between muscle activation time and touchdown time.

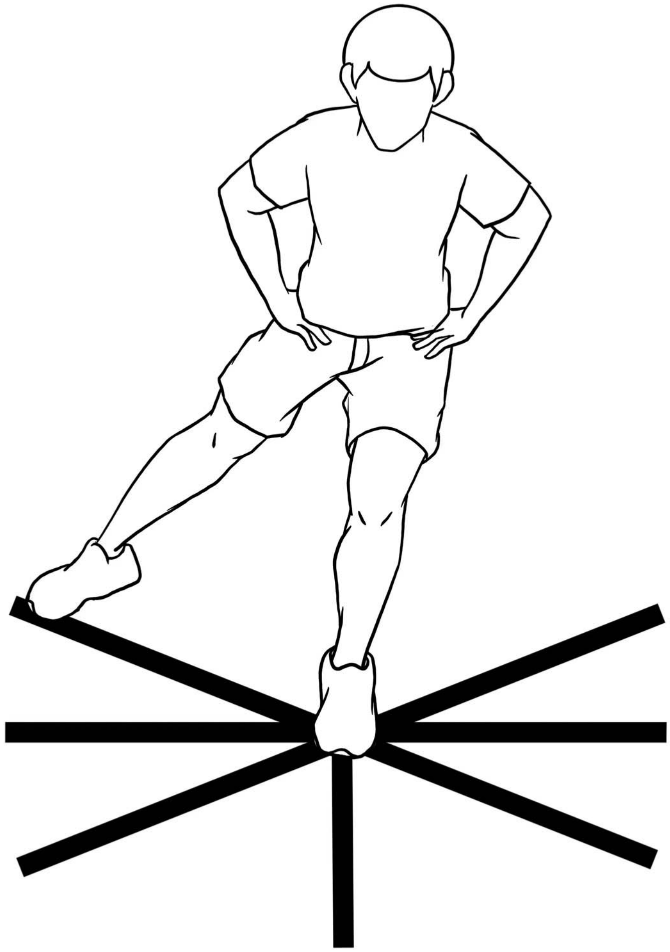

Figure 5. Star Excursion Balance Test.

the format (ie, .set) suitable for analysis in MATLAB. Continuous EEG recordings were primarily filtered with a 0.01- to 50-Hz bandpass filter and 48- to 52-Hz notch filter. The sampling rate was reduced to 500 Hz and segmented into 2000-millisecond epochs.[26] An automatic artifact detection algorithm (maximum allowed voltage step = 50 μV, maximum allowed voltage difference within 10 milliseconds = 100 μV) was used to exclude artifact-contaminated segments before performing independent component analysis (ICA).[27] The data were processed for the ICA using an EEGLAB script based on MATLAB implementation.[27] An extended run ICA algorithm, including online bias adjustment, was used for ICA decomposition. Components representing ocular or muscular artifacts determined based on cortical mapping, frequency spectra, and time courses were deleted.[19] The fast Fourier transform was applied to all artifact-free epochs to calculate the mean power of different frequency waves of each participant for each test.[19] Different frequency waves were divided as theta (4–8 Hz), alpha-1 (8–10 Hz), alpha-2 (10–13 Hz), and beta (14–25 Hz).[20] The EEG signals were calculated separately for all 4 bands at the Cz electrode. The signals at the central electrodes are most commonly evaluated during sensorimotor tasks, and the Cz is located closest to the premotor and supplementary motor cortices, minimizing the influence of other ongoing brain processes that may be detected because of the volume conduction of the EEG signal (Figure 2).[28]

EMG Analysis. We used EMGworks Analysis 4.0 (Delsys Inc) to analyze EMG data. The EMG signal was uniformly filtered using a Butterworth bandpass filter at 10 to 400 Hz and rectified.[29] The landing time point was manually recorded as the time at which the integral EMG amplitude (window length = 0.125, window overlap = 0) changed from steady to sharply elevated. The mean EMG signal was calculated using the root mean square amplitude (window length = 0.1, window superposition = 0.05), using the time at which 5% maximal voluntary isometric contraction was reached as the muscle activation time.[29] The difference between the muscle activation time and touchdown time was considered the *muscle onset time* and was included in the analysis (Figure 4). Smaller error values indicated more rapid muscle activation.

Statistical Analysis

Differences in baseline characteristics between those included in the analysis and those who withdrew from the study were examined using *t* tests for continuous variables and χ^2 tests for categorical variables.

The independent variables were group (single- and dual-task) and time (pretest and posttest). Multivariate analysis of variance was used to compare changes in the indicators of participants across groups and times. Repeated-measures analysis of variance for general linear models was performed. A post hoc Bonferroni test was performed for pairwise comparisons when interactions were found with the MANOVA. Effect sizes were calculated using partial η^2 (η_p^2) and interpreted as *weak* ($\eta_p^2 < 0.25$), *moderate* ($\eta_p^2 = 0.25$–0.64), or *strong* ($\eta_p^2 > 0.64$).[30] We used SPSS (version 19.0; IBM Corp) for analyses, and the α level was set at .05.

RESULTS

Twenty-seven individuals with CAI were initially included in the study. During the intervention period, 3 individuals did not complete the prescribed intervention tasks, so their data were excluded from the data analysis. Consequently, the final analysis was conducted on the measurements obtained from the remaining 24 participants who completed the full 6-week intervention consisting of 18 training sessions and the preintervention and postintervention assessments as per the training schedule (Figure 6).

Participant Characteristics and Self-Reported Function

No differences were found between groups in terms of sex, affected limb, age, body mass index, number of episodes of giving way, number of ankle sprains, duration since the last ankle sprain, and CAIT scores (Table 1).

Cortical Activity

No group × time interactions were noted for alpha-2 and beta powers during static postural control with the affected limb in either group. Group × time interactions were noted for alpha-1 ($F_{1,22} = 17.21$, $P < .001$, $\eta_p^2 = 0.44$) and theta powers ($F_{1,22} = 8.44$, $P = .008$, $\eta_p^2 = 0.28$).

We observed no differences between each band power before the training in either group ($P > .05$). Post hoc comparisons revealed that alpha-1 and theta power increased from pretest to posttest in the dual-task group (alpha-1: $P < .001$;

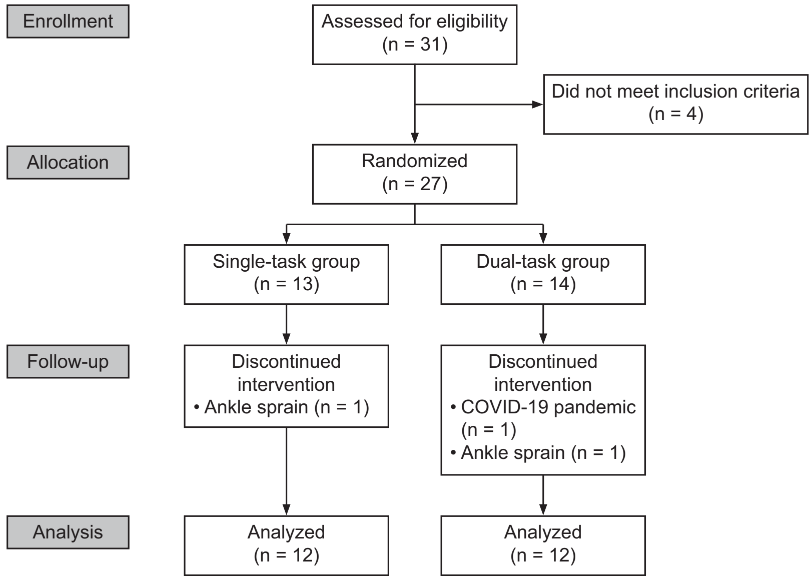

Figure 6. Consolidated Standards of Reporting Trials diagram of participant enrollment, allocation, follow-up, and analysis.

theta: $P = .003$), whereas alpha-1 and theta power did not change in the single-task group (alpha-1: $P = .46$; theta: $P = .43$). The dual-task group had higher alpha-1 and theta power than the single-task group after training (alpha-1: $P = .004$, $\eta_p^2 = 0.32$; theta: $P = .047$, $\eta_p^2 = 0.17$; Table 2).

Proprioception

No between-group differences existed in the 4 JPS errors before training ($P > .05$). Except for the JPS-plantar flexion error ($F_{1,22} = 4.72$, $P = .04$, $\eta_p^2 = 0.18$), no group × time interaction was noted for the JPS error (JPS-dorsiflexion: $F_{1,22} = 0.21$, $P = .66$, $\eta_p^2 = 0.009$; JPS-inversion: $F_{1,22} = 0.03$, $P = .87$, $\eta_p^2 = 0.001$; and JPS-eversion: $F_{1,22} = 1.43$, $P = .25$, $\eta_p^2 = 0.06$). The post hoc results revealed that the dual-task group had decreased JPS-plantar flexion error compared with the single-task group after training ($P = .01$) but no differences ($P > .05$) between the groups in other JPS errors (Table 2).

Muscle Onset Time

No differences between the 2 groups were noted for the TA and PL onset times before training ($P > .05$). No group × time interactions were found for the TA muscle onset time in the 2 groups ($F_{1,22} = 0.38$, $P = .01$, $\eta_p^2 = 0.02$).

We observed a group × time interaction for the PL muscle onset time ($F_{1,22} = 7.10$, $P = .01$, $\eta_p^2 = 0.24$). The post hoc results revealed that PL muscle onset time was shorter from before to after training in both groups (single-task group: $P = .02$; dual-task group: $P < .001$), and the dual-task group had a shorter PL muscle onset time than the single-task group after the training ($P = .047$, $\eta_p^2 = 0.17$; Table 2).

Dynamic Postural Control

No group × time interaction effects were observed for the 3 SEBT directions in either group (SEBT-AM: $F_{1,22} = 0.08$, $P = .78$, $\eta_p^2 = 0.004$; SEBT-M: $F_{1,22} = 0.37$, $P = .55$, $\eta_p^2 = 0.02$; and SEBT-PM: $F_{1,22} = 0.21$, $P = .65$, $\eta_p^2 = 0.01$). Both groups showed improvements in the 3 directions from pretest to posttest (single-task: SEBT-AM, $P = .004$; SEBT-M, $P = .002$; SEBT-PM, $P < .001$; dual-task: SEBT-AM, $P < .001$; SEBT-M, $P < .001$; SEBT-PM, $P < .001$). No differences were found between the groups after training ($P > .05$; Table 2).

Table 1. Study Population Characteristics

Characteristic	Group: Single Task	Group: Dual Task	χ^2	P
	No.			
Sex, male/female	8/4	7/5	0.18	.67
Affected side, left/right	4/8	5/7	0.18	.67
	Mean ± SD		t	
Age, y	22.58 ± 2.23	22.08 ± 2.68	0.50	.62
Body mass index	23.59 ± 2.64	21.73 ± 4.11	1.32	.20
No. of episodes of "giving way"[a]	3.50 ± 1.31	3.17 ± 1.19	0.65	.52
No. of ankle sprains[b]	2.50 ± 0.52	2.58 ± 0.67	0.34	.74
Time since last ankle sprain, d	27.08 ± 13.53	31.50 ± 15.60	0.74	.47
Cumberland Ankle Instability Tool score, points	16.50 ± 3.53	15.40 ± 4.17	0.69	.50

[a] Number of episodes of giving way since the last significant ankle sprain within the 12 months before the study.
[b] Number of ankle sprains since the last significant ankle sprain within the 12 months before the study.

Table 2. Changes in Cortical Activity, Proprioception, Muscle Onset Time, and Dynamic Balance Before and After Intervention in Both Groups

Variable	Single-Task Group			Dual-Task Group			Group × Time Effect		
	Pretest	Posttest	η_p^2	Pretest	Posttest	η_p^2	F	P	η_p^2
Cortical activity, μV^2									
Alpha-1	0.50 ± 0.13	0.46 ± 0.12	0.03	0.46 ± 0.14	0.69 ± 0.21[b,d]	0.54	17.21	<.001	0.44
Alpha-2	0.51 ± 0.20	0.45 ± 0.13	0.04	0.46 ± 0.21	0.50 ± 0.14	0.03	1.46	.24	0.06
Theta	0.64 ± 0.11	0.60 ± 0.15	0.03	0.54 ± 0.25	0.73 ± 0.15[b,d]	0.33	8.44	.008	0.28
Beta	0.23 ± 0.04	0.25 ± 0.11	0.03	0.21 ± 0.12	0.25 ± 0.05	0.08	0.17	.68	0.01
Joint position sense, °									
Dorsiflexion	3.63 ± 2.08	1.77 ± 1.08[b]	0.30	3.03 ± 1.62	1.56 ± 0.89[c]	0.21	0.21	.66	0.009
Plantar flexion	3.91 ± 1.67	2.22 ± 1.17[b]	0.28	4.51 ± 1.83	1.06 ± 0.85[b,d]	0.62	4.72	.04	0.18
Inversion	3.63 ± 2.66	1.23 ± 1.04[b]	0.27	3.61 ± 2.63	1.41 ± 0.77[c]	0.24	0.03	.87	0.001
Eversion	3.44 ± 2.23	2.10 ± 1.38	0.14	4.24 ± 3.11	1.68 ± 1.24[b]	0.37	1.43	.25	0.06
Muscle onset time,[a] ms									
Tibialis anterior	−17.85 ± 30.91	3.37 ± 55.21	0.05	−20.90 ± 42.39	−16.23 ± 53.13	0.003	0.38	.55	0.02
Peroneus longus	−30.93 ± 41.49	−53.80 ± 29.61[c]	0.21	−16.41 ± 36.53	−73.94 ± 15.01[b,d]	0.64	7.10	.01	0.24
Star Excursion Balance Test direction, cm									
Anteromedial	0.78 ± 0.07	0.85 ± 0.06[b]	0.32	0.74 ± 0.09	0.82 ± 0.08[b]	0.38	0.08	.78	0.004
Medial	0.83 ± 0.10	0.95 ± 0.09[b]	0.36	0.08 ± 0.07	0.95 ± 0.11[b]	0.47	0.37	.55	0.02
Posteromedial	0.87 ± 0.12	1.05 ± 0.10[b]	0.45	0.85 ± 0.10	1.05 ± 0.11[b]	0.53	0.21	.65	0.01

[a] Difference between muscle activation time and touchdown time.
[b] Within-group difference from pretest to posttest ($P < .01$).
[c] Within-group difference from pretest to posttest ($P < .05$).
[d] Between-group difference at posttest ($P < .05$).

DISCUSSION

For primary outcome measures, we found that 6 weeks of combined balance and cognitive training resulted in increased alpha-1 and theta power at Cz during static postural control compared with 6 weeks of the balance training alone. As secondary outcome measures, both interventions demonstrated improvements in JPS, shorter muscle onset time of the PL during landing, and enhanced dynamic balance among participants with CAI. Compared with balance training alone, combined balance and cognitive training had greater benefits in improving JPS in plantar flexion and shortening PL muscle onset time after the intervention. No other results were statistically different.

Primary Outcome: Cortical Activity

A systematic review revealed that patients with CAI did not use somatosensory information to the same extent as uninjured controls. Instead, they up-regulated the use of visual information during single-limb stance.[31] Therefore, we investigated alterations in EEG signals during single-limb static postural control without vision.

Theta power is associated with attention resource allocation use, central information encoding, situational memory, and spatial orientation; increasing theta power reflects greater attention demands and cognitive load in balance tasks.[10] During jump landings, patients with CAI had increased theta power compared with healthy individuals, indicating that they need to mobilize more attention resources to maintain postural stability.[10] The backward-counting task can affect postural stabilization by directing the attention of patients with CAI toward changes in external auditory cues during postural control, and sustained cognitive task with changes in external cues can reduce conscious postural control.[32] Because postural control in daily activities, sport and leisure activities, and team games usually requires at least 1 other simultaneous task (eg, maintaining balance when thinking about teammates' performance and placement), athletes should be able to devote attention to other activities without compromising motor function and postural control.[33] Combined balance and cognitive training allows them to practice maintaining postural stability while responding to external cognitive tasks or environmental changes to decrease the need for controlled processing and motor performance during competition.[34] Therefore, patients with CAI who exhibit increased theta power during postural control after a dual-task intervention may be able to direct more attentional resources to attend to changes in the external environment to better maintain postural stability.

To ensure the task was challenging, balance training included static balance training with eyes open and closed and dynamic balance training. The use of backward counting, which does not require visual input, aligns with the training requirements. The task can lead to shifts in attention focus and changes in cortical activity, manifested by an increase in theta power.[35] Similarly, the backward-counting task is categorized as working memory that can lead to increased theta power.[36] Therefore, prolonged dual cognitive and balance training can increase theta power during postural control.[34]

The alpha wave is divided into 2 different frequency waves, slow (alpha-1) and fast (alpha-2), which are widely distributed in the cerebral cortex and represent the sensorimotor rhythms of motor preparation and planning associated with cortical inactivation and inhibition related to sensorimotor function.[37]

Increases in alpha-1 power after training have indicated that subcortical structures have greater vigor, motor-planning processes gradually become automated, and movements are completed more proficiently.[38] In our study, the increases in alpha-1 power after the dual-task training suggest that patients with CAI gradually learn to reduce cortical excitation and activate more sensorimotor areas during postural control. Alpha-2 is associated with specific proprioceptive-demand tasks.[39] In our study, static postural control required only coordinated spinal-cerebellar cooperation to complete coordinated muscle contractions without fine motor control or somatosensory input.[40] Thus, no changes in the alpha-2 power were observed after the interventions in our study.

Changes in beta power are mainly associated with cortical alertness and processing of external information, judgment, and decision-making.[41] Tse et al compared the effects of balance tasks of varying difficulty levels on cortical activity.[42] They reported that participants exhibited increased beta-wave power during more complex balance tasks. The changes of beta-band power may be related to the difficulties and complexities of postural control.[28] However, we only monitored changes in EEG during static postural control. It is possible that the static postural-control task was so simple that changes in beta-band power were not observed.

Secondary Outcomes

Joint Position Sense. Ankle proprioceptive deficits resulting from ankle sprains are the main cause of recurrent sprains in patients.[43] Balance training can stimulate proprioceptors in the muscles and ligaments around the ankle joint through repeated postural disturbances, thereby enhancing proprioceptor sensitivity.[44] This viewpoint supports our findings, as training with both tasks effectively improved JPS in patients with CAI. Excessive plantar flexion and inversion during walking or landing tasks increases the risk of sprains, and patients with CAI experience deficits in the sensorimotor function of plantar flexion, which leads to greater plantar-flexion angles during landing, allowing for more inversion and eversion movement space, further increasing the injury risk.[43,45]

In a recent study, Li et al reported that, owing to proprioceptive deficits, patients with CAI exhibit abnormal cortical activation when performing plantar-flexion movements.[46] We observed that the dual-task training group demonstrated improved JPS-plantar flexion in patients with CAI. This result may be related to long-term dual-task training enhancing motor and cognitive abilities, establishing new perceptual-motor strategies, and improving perceptual-motor performance.[34]

In addition to deficits in JPS-plantar flexion, deficits in JPS-inversion may increase the risk of ankle sprains.[47] However, dual-task training did not improve JPS-inversion compared with single-task training. One possible reason is the test position of inversion. As inversion angles approach their end range of movement, JPS acuity will improve (ie, reduced absolute JPS error).[48] In our study, the target angle for inversion was 15°. According to a recent systematic review and meta-analysis, the Ruffini endings within the anterior talofibular ligament or the calcaneofibular ligament and the tibial/fibular muscle spindles contribute to both active and passive JPS, whereas central processing provides more support to active JPS.[49] A 6-week intervention of dual-task training aimed at central adaptive neuroplasticity may be relatively short. To restore JPS deficits in CAI, the addition of more JPS-targeted components to existing exercise therapies is needed. In addition, the sample size was relatively small for a more robust conclusion.

Muscle Onset Time. The PL may be vital for ankle stabilization because it eccentrically controls ankle inversion and may play a key role in preventing ankle sprains.[50] Researchers have found that, during the recovery period after ankle sprains, the PL often exhibits delayed and insufficient activation, which is related to joint-related muscle inhibition caused by injury and alters the pattern of muscle activation at the spine, prolonging the onset time of the PL during landing tasks.[51] We demonstrated that both balance combined with cognitive training and balance training alone effectively reduced the onset time of PL during landing tasks. This finding was related to the ability of balance training to induce a high level of adaptation in the spinal neural system, effectively modulating instantaneous reflex activation of the PL.[52]

In addition to joint-related muscle inhibition, patients with CAI exhibit a smaller cortical motor area and volume associated with the PL than healthy individuals.[53] This results in a smaller number of cortical neurons specifically dedicated to controlling PL activation and movement, thereby increasing the challenge of executing voluntary PL movement commands.[53] Combined with cognitive training, balance training can establish new perceptual strategies, improve decision-making abilities, and enhance the efficiency of the central nervous system in mobilizing peripheral muscles.[34] This led to a shorter PL onset time in our study and explains why the dual-task intervention more effectively reduced the delay in PL activation during landing.

The TA also plays a role in stabilizing the ankle joint during landing.[50] Researchers have shown that, in the prelanding phase, patients with CAI exhibit decreased PL activity and increased cocontraction index between the TA and PL but exhibit no difference in TA activation compared with healthy control participants.[54] Neither of the training methods in our study resulted in changes in TA activation time, which may be attributed to the fact that balance training primarily activates the PL and improves the coordination between the TA and PL but has a minimal direct effect on TA activation.[23]

Dynamic Postural Control. The SEBT assesses dynamic stability in the AM, M, and PM directions with high confidence and correlation coefficients of approximately 0.81 to 0.93.[25] Balance training can improve proximal joint stability in the lower extremities by reducing proximal joint coronal displacement during landing and improving muscle coordination by increasing muscle strength, among other factors that influence dynamic postural control in patients with CAI.[24]

Although cortical activity is also involved in postural-control tasks, we did not observe interaction effects in either group.[19] Observing the advantages of dual-task training on SEBT is difficult because the SEBT is influenced by various factors including postural control of the hip, knee, and ankle; lower extremity strength; joint mobility; and proprioception.[25] Dual-task training demonstrated no advantages for improving the performance of SEBT compared with single-task training. Recent research also supports the finding that dual-task training brings a greater attentional allocation advantage and may have less of an effect on dynamic postural control.[33]

Limitations

Our study had some limitations. First, the sample size was consistent with the a priori power analysis estimate, but its small size may have resulted in several measures that did not reach statistical significance and low η_p^2 values. Second, we concentrated on neuromuscular and proprioceptive deficiencies and, therefore, did not use self-reported functional outcomes (eg, Foot and Ankle Ability Measure and Foot and Ankle Outcome Score) as inclusion criteria. Moreover, the cognitive tasks did not progressively increase in difficulty, remaining the same throughout the experiment. This may have led to participants in the dual-task group gradually adapting to the cognitive task difficulty, potentially reducing the effect of cognitive tasks on attention. Finally, we used single-task outcome measures to assess the effect of balance training on postural control during a single task. However, specific outcome measures for the balance-cognition dual task, such as postural control under cognitive load, were not used. This limitation makes it difficult to fully capture the training benefits of the balance-cognition dual task. Therefore, future research should be done to consider gradually increasing the difficulty for the cognitive task and integrating postural control under cognitive load as an evaluation measure to more effectively observe the training effects of balance-cognition dual tasks.

CONCLUSIONS

The findings of this study demonstrated that 6 weeks of dual-task training was superior to single-task training in improving JPS-plantar flexion and PL muscle onset time in patients with CAI and was able to alter cortical activity, further positively influencing static postural control in these patients.

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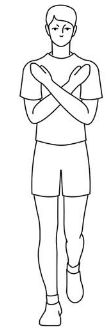
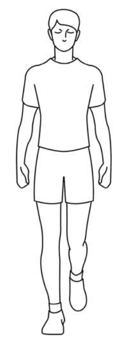
Appendix 1. Single-Task Training: Static Balance

Intervention	Content (Levels 1–7)	Volume	Illustration
Static balance (eyes open)	1. Standing on 1 foot for 60 s with both upper limbs crossing the chest 2. Standing on 1 foot on the foam pad for 30 s with both upper limbs crossing the chest 3. Standing on 1 foot on the foam pad for 60 s with both upper limbs crossing the chest 4. Standing on 1 foot on the foam pad for 90 s with both upper limbs crossing the chest 5. Standing on 1 foot on the foam pad for 30 s with both upper limbs crossing the chest, followed by throwing a 6-lb (2.7-kg) medicine ball 20 times 6. Standing on 1 foot on the foam pad for 60 s with both upper limbs crossing the chest, followed by throwing a 6-lb (2.7-kg) medicine ball 20 times 7. Standing on 1 foot on the foam pad for 90 s with both upper limbs crossing the chest, followed by throwing a 6-lb (2.7-kg) medicine ball 20 times	2 sets	
Static balance (eyes closed)	1. Standing on 1 leg for 30 s without a required upper limb position 2. Standing on 1 foot with both upper limbs crossing the chest for 30 s 3. Standing on 1 foot with both upper limbs crossing the chest for 60 s 4. Standing on 1 foot on the foam pad for 30 s 5. Standing on 1 foot on the foam pad for 30 s with both upper limbs crossing the chest 6. Standing on 1 foot on the foam pad for 60 s with both upper limbs crossing the chest 7. Standing on 1 foot on the foam pad for 90 s with both upper limbs crossing the chest	2 sets	

Appendix 2. Single-Task Training: Dynamic Balance

Intervention	Content (Levels 1–7)	Volume	Illustration
Dynamic balance (8 directions for jumping: anterior/posterior, medial/lateral, antero-lateral/posteromedial, anteromedial/postero-lateral)	1. Ten consecutive jumps in each direction, jumping a distance of 18 in (45.72 cm), maintaining stability for 5 s after each jump 2. Ten consecutive jumps in all directions, jumping a distance of 18 in (45.72 cm) with both upper limbs crossed over the chest, maintaining stability for 5 s after each jump 3. Ten consecutive jumps in each direction, jumping a distance of 27 in (68.58 cm), maintaining stability for 5 s after each jump 4. Ten consecutive jumps in all directions, jumping a distance of 27 in (68.58 cm) with both upper limbs crossed over the chest, maintaining stability for 5 s after each jump 5. Ten consecutive jumps in all directions, jumping a distance of 27 in (68.58 cm), maintaining stability for 5 s after each jump 6. Ten consecutive jumps in all directions, jumping a distance of 36 in (91.44 cm) with both upper limbs crossed over the chest, maintaining stability for 5 s after each jump 7. Jump from a 5-cm high platform to a distance of 36 in (91.44 cm); jump 10 times and maintain stability for 5 s after each jump	1 set