Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Transcranial direct current stimulation improves physical performance in high-level volleyball players during fatigue

Ying Yu
Beijing Sport University
Michael A. Nitsche
Leibniz Research Centre for Working Environment and Human Factors
Carmelo Mario Vicario
University of Messina
Alessio Avenanti
University of Bologna
Fengxue Qi
fengxue.qi@hotmail.com

Beijing Sport University

Research Article

Keywords: dual fatigue, volleyball player, physical performance, transcranial direct current stimulation

Posted Date: March 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9029090/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Abstract

The current study investigated the effects of dual-site transcranial direct current stimulation (tDCS) over primary motor cortex (M1) and dorsolateral prefrontal cortex (DLPFC) on the physical performance in high-level volleyball players during fatigue. Twenty volleyball players conducted fatigue induced by 60-min trial at 60% peak power output combined with a Stroop test, then received four 10 min sessions of 2 mA anodal tDCS over M1 ($tDCS_{M1}$), DLPFC ($tDCS_{DLPFC}$), M1 + DLPFC ($tDCS_{M1+DLPFC}$), or sham stimulation ($tDCS_{SHAM}$) in a counterbalanced order. Spike test (ST), medicine ball test (MBT), countermovement jump (CMJ), T-test, 30-m sprint, and 15-s rebound jump were conducted at baseline, immediately after (post1), and 40-min after tDCS intervention (post2). At post1, $tDCS_{M1+DLPFC}$, $tDCS_{M1}$, and $tDCS_{DLPFC}$ significantly improved performance in ST, MBT, CMJ, 30-m sprint, and T-test compared to sham ($P < 0.05$). At post2, $tDCS_{M1+DLPFC}$ improved ST, MBT, T-test, and 30-m sprint, $tDCS_{M1}$ enhanced MBT, and $tDCS_{DLPFC}$ improved MBT, 30-m sprint, and T-test compared to sham ($P < 0.05$). The simultaneous application of tDCS over M1 and DLPFC alleviates the impact of fatigue on physical performance for a duration of up to 40 min in high-level volleyball players.

Introduction

Volleyball is a complex team sport, essential physical skills for volleyball players include explosive power in the upper and lower body, agility for executing short-distance movements, and jumps during defensive and offensive actions [1]. Competitive events require athletes to sustain high-intensity performance for an extended duration, engaging physical activities and cognitive resources [2]. Volleyball players entail open-skill movements to perform various actions while adapting to rapidly changing game situations. This results in dual fatigue in volleyball players, a combination of physical and mental fatigue [3, 4].

Fatigue is a critical component that affects multiple dimensions of athletic performance. Physical fatigue manifests as reduced motor cortex excitability and peripheral muscle component, primarily affecting physical performance [5, 6]. Mental fatigue, on the other hand, lead to alterations in the prefrontal cortex's activity and diminishes attentional resources, thereby influencing cognitive function [7] and endurance [8]. Neuroimaging research has found shared neural circuits involved in both physical and mental fatigue [9, 10], and dual fatigue accelerates the onset of fatigue [11].

Transcranial direct current stimulation (tDCS) is a neuromodulation tool that modulates cortical excitability and spontaneous brain activity via low-intensity currents. Modulation of tDCS is associated with stimulation targets. The primary motor cortex (M1) is crucial in regulating motor performance, while the dorsolateral prefrontal cortex (DLPFC) primarily regulates inhibitory control and motivation. It is indicated that tDCS over M1 and DLPFC significantly improves various aspects of athletic performance, for example volleyball spiking, time trial performance in cyclists, and agility, shooting, and dribbling in basketball players [12–14].

Notably, tDCS-induced neuronal modulation could affect exercise-related central fatigue, potentially delaying physical fatigue and enhancing performance [15]. Interestingly, studies reported that the dual tDCS with anodes over M1 and DLPFC yields longer-lasting and stronger alterations in motor excitability than single-site stimulation [16, 17]. Yet, this dual-site approach remains unexplored in the context of sports settings. It remains unclear whether tDCS can mitigate the performance decrease induced by dual fatigue in high-level athletes, and whether the concurrent application of tDCS over M1 and DLPFC can yield favorable outcomes.

In our previous study [18], dual fatigue induced by cycling combined with Stroop task significantly reduced physical performance in volleyball players. We used the same intervention to induce dual fatigue. We hypothesized that tDCS over M1 or DLPFC would improve volleyball performance in high-level volleyball players during dual fatigue, and that dual-site stimulation would yield superior effects.

Method

Participants

Twenty high-level volleyball players (8 females and 13 males; mean ± SD, age: 21.7 ± 1.3 years, body mass = 74.44 ± 8.18 kg, body mass index = 21.32 ± 1.97, experience level = 7.50 ± 1.70 years, peak power = 223.75 ± 28.65 W) were recruited. Prior to the experimental sessions, subjects were informed about the precautions, familiarized with the procedures, and provided written informed consent. 24 hours before each visit, subjects abstained from alcohol and caffeinated beverages, and avoided strenuous mental and physical activity. Additionally, subjects were asked to avoid eating within 2 hours before the test. All experiments were conducted according to the standards established by the Declaration of Helsinki and approved by the ethics committee of Beijing Sport University (2022166H).

Fatigue Protocol

Fatigue Protocol
An incremental load test was performed to determine PPO. Subjects cycled at 75/50 W (male/female) for 3 min to warm up. Then the load was progressively incremented by 25 W per min while maintaining a cadence of 60 revolutions per minute (rpm), accompanied by verbal encouragement, until the subject reached exhaustion. PPO was taken immediately following exhaustion. Heart rate (HR) and rating of perceived exertion (RPE) were collected every minute during exercise. Exhaustion was determined based on three criteria: (a) speed below 70 rpm, (b) RPE score of 17–20, and (c) HR within 90%–100% of the maximum HR (207 − 0.7 x age) [19].

The fatigue intervention consisted of a 60 min cycling trial at 60% PPO while performing a Stroop task. In the Stroop task, subjects were instructed to promptly and accurately react to words presented on a monitor, ensuring alignment between the color of the word, and disregarding its semantic meaning. The

experiment included 50% of incongruent trials. Each word displayed 1000-ms on the screen, succeeded by a 1500-ms pause with a black screen prior to the subsequent word's presentation. The accuracy (ACC) and average reaction time (RT) of the first 5 min and last 5 min were collected. Fatigue was determined based on three criteria: (a) RPE ≥ 15, (b) VAS ≥ 50, and (c) maximal HR +/- 15% of the incremental load test [19].

Transcranial direct current stimulation

A two-channel stimulation device (YINGCI TCS-E2, Shenzhen, China) was connected with surface saline-soaked sponge electrodes. For the M1-channel, the anode electrode was placed on Cz, C1 and C2 (5 x 7 cm), and the reference (5 x 5 cm) was placed on the right shoulder. For the DLPFC-channel, the anode electrode was placed on the F3 (5 x 5 cm), and the reference (5 x 5 cm) was placed on the left shoulder. For $tDCS_{M1+DLPFC}$, dual a-tDCS was performed in both channels, and dual sham stimulation was applied in both channels in $tDCS_{SHAM}$. For $tDCS_{M1}$, a-tDCS was performed in the M1-channel, and sham stimulation was performed in the DLPFC-channel. For $tDCS_{DLPFC}$, a-tDCS was performed in the DLPFC-channel, and sham stimulation was performed in M1-channel. All electrodes were positioned using elastic straps. For a-tDCS, the current intensity was set at 2 mA with a duration of 10 min. In sham stimulation, the stimulator was turned off after 30 s of stimulation. Ramp up and down period lasted 15 s in all conditions.

Physical performance

The spike test (ST) was used as previously described [20] to measure spiking performance. Subjects self-tossed the ball (Molten V5M5000), and then spike toward a 1.5 × 1.5-m target zone with maximal strength without jumping off the ground. Ball velocity was measured by radar gun (Bushnell Outdoor Products, Kansas, USA) situated in the target zone. Each player completed three trials, and the fastest ball speed was used in the analyses.

The medicine ball test (MBT) was used to measure upper limb strength [21]. Subjects stood behind a line with their feet side by side but slightly separated, the 2-kg ball was initially drawn back behind the head, then propelled forward to achieve maximum distance. Each player completed two trials, and the best one was used in the analyses.

The countermovement jump (CMJ) was used to measure lower limb strength and jumping performance [5]. Following an auditory cue, the participant flexed his knees and jumped as high as possible, keeping his hands on his waist, and landed with both feet on the optical jump system (Microgate, Bolzano, Italy). Each subject carried out three trials, and the highest jump was used in the analyses.

A modified T-test was used to measure agility and change of direction ability. As previously described [22], subjects started with both feet positioned behind a starting line (cone A), then sprinted forward 5 m

and touched the cone B. Then, they shuffled sideways to the left (2.5 m) and touched cone C. They then did the same side shuffling to the right (5 m) and touched cone D. They then shuffled back to the cone B, and backpedal to the cone A. All subjects completed two attempts, and the fastest time was measured by timing gates (Wireless timing systems, Shiniangong, China) used in the analyses.

Linear sprinting performance was measured by a 30-m sprint [23], and the speed measure was obtained by a timing gate. All subjects started approximately 0.4 m behind the starting gate. All subjects completed two attempts and the highest speed was used in the analyses.

The 15-s rebound jump was used to measure continuous jumping performance [5]. The subjects put their hands on their hips and performed continuous vertical jumps on the Optojump system. The average jump height was used in the analyses.

Psychophysiological Parameters

HR was monitored using an HR recorder (H10, Polar™, Finland). The Borg's RPE scale was used to measure perceived exertion [24]. Subjects were required to indicate a point on a scale ranging from 6 to 20 to rate perceived physical effort exerted in completing a task. Visual analogue scale (VAS) was used to evaluate mental fatigue. Subjects were asked to draw a vertical line, anchored by the extremities of "minimum" (0) and "maximum" (100) to indicate their perception of mental fatigue. Given the known association between mental fatigue and decreased cognitive function [8], changes in Stroop performance were also used to evaluated mental fatigue [25]. Exercise intensity was determined by analyzing blood lactate, measured using a portable lactate analyzer (Lactate Scout +, EKF diagnostics, Cardiff, UK) through a capillary blood sample from the fingertip.

Procedure

This study was a randomized, single-blind within-participant design. Each subject performed five sessions, each at least 7 days apart. In the first session, subjects performed an incremental load test to determine PPO. The formal experiments started with a 15-min standardized warm-up. After 1 min rest, subjects then underwent physical performance testing (Baseline). Physical performance tests took approximately 20 min in total. The subjects then completed the fatigue intervention, blood samples were collected immediately after fatigue intervention. After the fatigue intervention, subjects completed one of four counterbalanced tDCS sessions. Lastly, subjects completed the physical performance test immediately following stimulation (post 1), and 40-min following stimulation (post 2) after 20 min rest. HR, RPE, and VAS data were collected at the start (T1), after the fatigue intervention (T2), after the tDCS intervention (T3), after post 1 (T4), after 20 min of rest (T5), and after post 2 (T6). A schematic overview of all procedures conducted is presented in Fig. 1.

Statistical analysis

All statistical analyses were performed using SPSS 25.0 (SPSS IBM, Chicago, IL, USA). The physical performance data were standardized with baseline transformation [26]. Data distribution normality was evaluated utilizing the Shapiro-Wilk test. One-way repeated-measures analysis of variance (RM-ANOVA) was conducted to compare blood lactate in different sessions. Within-subject RM-ANOVAs were conducted to compare the effects of time (first 5 min, last 5 min) and session ($tDCS_{M1+DLPFC}$, $tDCS_{DLPFC}$, $tDCS_{M1}$, $tDCS_{SHAM}$) on ACC and RT of Stroop task. Within-subject RM-ANOVAs were conducted to compare the effects of time (start, after fatigue intervention, after tDCS intervention, after post 1, after 20 min rest, after post 2) and session ($tDCS_{M1+DLPFC}$, $tDCS_{DLPFC}$, $tDCS_{M1}$, $tDCS_{SHAM}$) on RPE, HR, and VAS. Within-subject RM-ANOVAs were conducted to compare the effects of time (baseline, post 1, post 2) and session ($tDCS_{M1+DLPFC}$, $tDCS_{DLPFC}$, $tDCS_{M1}$, $tDCS_{SHAM}$) on the physical performance measures. The Mauchley test was conducted, and Greenhouse–Geisser correction were used for violations of sphericity. Fisher's least significant difference test was performed to compared significance between conditions. For all analyses, the significance level was $p \leq 0.05$. Effect size were calculated using partial eta-squared (η_p^2) for ANOVAs and Cohen's d (d) for post hoc comparison.

Results

No subjects reported serious adverse effects or injuries. The commonly reported sensations were slight itching, while a few reported slight pain and an iron taste. Only a very small number of subjects experienced burning sensations. Baseline physical performance measures were not significantly different across sessions (all $p \geq 0.147$).

Fatigue-inducing Conditions

The results of RPE, HR, VAS, Blood lactate and Stroop performance to assess fatigue-inducing are shown in Table 1. In RM-ANOVAs, the between-session differences for RPE, HR, VAS, blood lactate and Stroop RT were not significant. The main effect of time for Stroop in ACC was significant ($F_{1, 19} = 28.771$, $p < 0.001$, $\eta_p^2 = 0.602$), with decreased ACC after fatigue intervention, but neither the main effect of session nor the session × time interaction were significant (all F ≥ 0.764, all p ≥ 0.393). According to fatigue criteria, the results (HR ≥ 169.41 ± 13.33, RPE ≥ 18.80 ± 1.54, VAS ≥ 59.05 ± 20.12; mean ± SD) indicated that subjects successfully reached a state of dual fatigue.

Table 1
Values of RPE, HR, VAS, Blood lactate and Stroop performance (Mean ± SD).

Sessions		RPE	HR	VAS	Blood lactate	Stroop RT	Stroop ACC
M1 + DLPFC	Before	10.40 ± 2.39	77.04 ± 10.60	17.30 ± 11.53		794.78 ± 125.20	0.93 ± 0.04
	After	18.80 ± 1.54	170.37 ± 12.27	62.85 ± 15.14	10.02 ± 4.28	796.87 ± 110.32	0.88 ± 0.08*
DLPFC	Before	10.70 ± 2.45	79.96 ± 6.40	16.25 ± 9.91		820.12 ± 130.72	0.92 ± 0.05
	After	19.10 ± 0.79	172.62 ± 7.44	59.95 ± 15.14	9.25 ± 2.80	829.25 ± 130.60	0.87 ± 0.08*
M1	Before	10.15 ± 2.49	76.41 ± 6.00	17.55 ± 9.92		802.60 ± 29.24	0.94 ± 0.04
	After	18.75 ± 1.51	169.41 ± 13.33	60.35 ± 14.56	9.61 ± 2.76	799.55 ± 108.21	0.90 ± 0.06*
Sham	Before	10.45 ± 2.39	78.25 ± 7.50	19.20 ± 9.58		819.84 ± 25.45	0.90 ± 0.06
	After	19.00 ± 1.41	176.83 ± 9.59	59.05 ± 20.12	8.88 ± 2.90	801.92 ± 117.26	0.89 ± 0.06*

The first 5 min and last 5 min of accuracy (ACC) and average reaction time (RT) in Stroop task was used to assess mental fatigue before and after fatigue intervention. The level of significance was set at $p \leq 0.05$. *, significant difference between before and after fatigue intervention. *M1* primary motor cortex, *DLPFC* dorsolateral prefrontal cortex, *HR* heart rate, *RPE* rating of perceived exertion, *VAS* visual analogue scale, *Before* before fatigue intervention, *After* after fatigue intervention.

Psycho-physiological Parameters

Results of the psycho-physiological parameters are shown in Fig. 2. The RM-ANOVA revealed a significant main effect of time in RPE, HR, and VAS (all $F \leq 816.882$, all $p < 0.001$), but not with session or session × time interaction (all $F \geq 0.219$, all $p \geq 0.213$).

Physical performance

ST

The RM-ANOVA revealed a significant main effects of time ($F_{1.349, 25.624} = 121.849$, $p < 0.001$, $\eta_p^2 = 0.865$), session ($F_{3, 57} = 14.842$, $p < 0.001$, $\eta_p^2 = 0.439$), and session × time interaction ($F_{6, 114} = 8.743$, $p < 0.001$, $\eta_p^2 = 0.315$). Ball speed was significantly faster at post 1 in $tDCS_{M1+DLPFC}$ ($p < 0.001$, d = 0.69), $tDCS_{DLPFC}$

($p < 0.001$, d = 0.62), and $tDCS_{M1}$ ($p < 0.001$, d = 0.66), and at post 2 in $tDCS_{M1+DLPFC}$ ($p = 0.009$, d = 0.50) compared to $tDCS_{SHAM}$. Ball speed was significantly decreased in $tDCS_{M1+DLPFC}$, $tDCS_{M1}$, $tDCS_{DLPFC}$, and $tDCS_{SHAM}$ at post 1 (all $p < 0.001$, all d ≥ 0.74) and post 2 (all $p \leq 0.027$, all d ≥ 0.35) compared to baseline, and improved at post 2 (all $p \leq 0.007$, all d ≥ 0.44) compared to post 1 (Fig. 3a).

MBT

The RM-ANOVA revealed a significant main $_{effects}$ of time ($F_{2, 38} = 74.728$, $p < 0.001$, $\eta_p^2 = 0.797$), session ($F_{3, 57} = 4.726$, $p = 0.005$, $\eta_p^2 = 0.199$), and session × time interaction ($F_{3.634, 69.048} = 3.115$, $p = 0.007$, $\eta_p^2 = 0.141$). MBT scores were significantly improved at post 1 and post 2 in $tDCS_{M1+DLPFC}$ (all $p \leq 0.034$, all d ≥ 0.34), $tDCS_{DLPFC}$ (all $p \leq 0.023$, all d ≥ 0.27), and $tDCS_{M1}$ (all $p \leq 0.027$, d ≥ 0.23) compared to $tDCS_{SHAM}$. MBT scores were significantly decreased in $tDCS_{M1+DLPFC}$, $tDCS_{M1}$, $tDCS_{DLPFC}$, and $tDCS_{SHAM}$ at post 1 (all $p < 0.001$, all d ≥ 0.60) and post 2 (all $p < 0.001$, all d ≥ 0.56) compared to baseline, and improved at post 2 (all $p \leq 0.036$, all d ≥ 0.04) compared to post 1 (Fig. 3b).

CMJ

The RM-ANOVA revealed a significant effects of time ($F_{2, 38} = 87.140$, $p < 0.001$, $\eta_p^2 = 0.821$), session ($F_{3, 57} = 5.122$, $p = 0.003$, $\eta_p^2 = 0.212$), and session × time interaction ($F_{6, 114} = 5.787$, $p < 0.001$, $\eta_p^2 = 0.233$). Jump height was significantly higher at post 1 in $tDCS_{M1+DLPFC}$ ($p < 0.001$, d = 0.56), $tDCS_{DLPFC}$ ($p = 0.003$, d = 0.40), and $tDCS_{M1}$ ($p < 0.001$, d = 0.39) compared to $tDCS_{SHAM}$. Jump height was significantly decreased in $tDCS_{M1+DLPFC}$, $tDCS_{M1}$, $tDCS_{DLPFC}$, and $tDCS_{SHAM}$ at post 1 (all $p < 0.001$, all d > 0.67) and post 2 (all $p \leq 0.019$, all d ≥ 0.38) compared to baseline, and improved at post 2 (all $p \leq 0.002$, all d ≥ 0.28) compared to post 1 (Fig. 3c).

T-test

The RM-ANOVA revealed a *significant* main effects of time ($F_{1.471, 27.943} = 48.395$, $p < 0.001$, $\eta_p^2 = 0.718$), session ($F_{3, 57} = 9.013$, $p < 0.001$, $\eta_p^2 = 0.322$), and session × time interaction ($F_{6, 114} = 6.610$, $p < 0.001$, $\eta_p^2 = 0.258$). Time was significantly faster at post 1 in $tDCS_{M1+DLPFC}$ ($p < 0.001$, d = 0.54), $tDCS_{M1}$ ($p < 0.001$, d = 0.50), and $tDCS_{DLPFC}$ ($p = 0.003$, d = 0.42), and at post 2 in $tDCS_{M1+DLPFC}$ ($p < 0.001$, d = 0.44) and $tDCS_{DLPFC}$ ($p = 0.029$, d = 0.31) compared to $tDCS_{SHAM}$. T-test times were significantly slower in $tDCS_{M1+DLPFC}$, $tDCS_{M1}$, $tDCS_{DLPFC}$, and $tDCS_{SHAM}$ at post 1 (all $p < 0.001$, all d ≥ 0.65), and at post 2 in $tDCS_{M1+DLPFC}$, $tDCS_{M1}$, and $tDCS_{SHAM}$ (all $p \leq 0.042$, all d ≥ 0.32) compared to baseline. T-test time was shorter at post 2 (all $p \leq 0.031$, all d ≥ 0.25) in $tDCS_{M1+DLPFC}$, $tDCS_{DLPFC}$, and $tDCS_{SHAM}$ compared to post 1 (Fig. 3d).

30-m Sprint

The RM-ANOVA revealed a significant main effects of time ($F_{2, 38} = 44.167$, $p < 0.001$, $\eta_p^2 = 0.699$), session ($F_{3, 57} = 6.271$, $p < 0.001$, $\eta_p^2 = 0.248$), and session × time interaction ($F_{3.356, 63.767} = 3.247$, $p = 0.006$, $\eta_p^2 = 0.146$). Times were significantly faster at post 1 in $tDCS_{M1+DLPFC}$ ($p = 0.007$, d = 0.50),

$tDCS_{DLPFC}$ ($p = 0.002$, d = 0.47), and $tDCS_{M1}$ ($p < 0.001$, d = 0.41), and at post 2 in $tDCS_{M1+DLPFC}$ ($p = 0.039$, d = 0.26) and $tDCS_{DLPFC}$ ($p = 0.039$, d = 0.27) compared to $tDCS_{SHAM}$. Time was decreased in $tDCS_{M1+DLPFC}$, $tDCS_{M1}$, $tDCS_{DLPFC}$, and $tDCS_{SHAM}$ at post 1 (all $p \leq 0.024$, all d ≥ 0.36), and decreased in $tDCS_{M1+DLPFC}$, $tDCS_{M1}$, and $tDCS_{SHAM}$ at post 2 (all $p \leq 0.042$, all d ≥ 0.33) compared to baseline. Time was improved at post 2 ($p < 0.001$, d = 0.37) in $tDCS_{SHAM}$ compared to post 1 (Fig. 3e).

15-s rebound Jump

The RM-ANOVA revealed a main effects of time ($F_{2, 38} = 50.042$, $p < 0.001$, $\eta_p^2 = 0.725$), but not with session or session × time interaction (all F ≥ 1.726, all $p \geq 0.144$). Jump height was decreased at post 1 ($p < 0.001$, d = 0.98) and post 2 ($p < 0.001$, d = 0.96) compared to baseline and significantly improved at post 2 ($p < 0.001$, d = 0.94) compared to post 1 (Fig. 3f).

Discussion

The present study investigated the effects of tDCS over M1 and DLPFC on physical performance in volleyball players with dual fatigue. We found that a-tDCS reduced the negative impacts of fatigue on explosive power in the upper and lower power, spiking, sprinting, and agility immediately after its induction. Within the 40-min post-tDCS period, improvements were observed in upper limb power, spiking, sprinting, and agility in $tDCS_{M1+DLPFC}$. Moreover, we observed enhancements in upper limb power in $tDCS_{M1}$, and enhancements in upper limb power, sprinting, and agility in $tDCS_{DLPFC}$. The results suggests not only that tDCS reduces adverse impacts of fatigue on physical performance, but also that $tDCS_{M1+DLPFC}$ is more effective, and elicits longer-lasting effects than single-site stimulation. However, tDCS did not influence heart rate, RPE, or VAS among sessions at all time points.

To our knowledge, this is the first report to investigate tDCS effects in athletes under dual fatigue. The mechanism of a-tDCS involves a reduction of GABAergic inhibition, an enhancement of glutamatergic facilitation, and an increase in brain-derived neurotrophic factor, a factor notably higher in high-level athletes than in the non-athletes [27, 28]. A comprehensive review by Maudrich et al. [29] found heterogeneous outcomes of tDCS on sport-specific performance in athletes. It is emphasized that potential stimulation effects in highly trained individuals may be reduced or absent due to ceiling effects. We aimed to improve performance in a situation characterized by reduced performance levels after intensive training, namely during fatigue, where a ceiling effect is less likely. Here, the results showed that enhancing fatigue-induced excitability reduction via a-tDCS would ameliorate respective performance reductions.

M1 and DLPFC play pivotal roles in modulating fatigue and exercise performance as integral components of the motor network, establishing them as the most commonly used targets for tDCS in sports science studies. $tDCS_{M1}$ altered motor unit firing and muscle recruitment strategies, thereby improving physical performance [30, 31]. Enhanced spiking performance was observed among

professional female volleyball players following $tDCS_{M1}$ [12]. The results suggests that $tDCS_{M1}$ enhances corticospinal excitability, facilitating the recruitment of motor units and modifying muscle recruitment strategies after fatigue. The DLPFC is mainly relevant for executive functions and emotional processes, the results are concordant with a study conducted by Salehi et al. [32], in which $tDCS_{DLPFC}$ alleviated the negative effects of mental fatigue on swimming performance. $tDCS_{DLPFC}$ could increase functional connectivity between DLPFC and motor areas, and increase blood perfusion in anatomically connected regions [33], might have increased DLPFC functionality via these mechanisms.

Notably, $tDCS_{M1+DLPFC}$ relieved the effects of fatigue immediately after tDCS intervention, and have extended effects lasting for at least 40 min. The current study provides compelling evidence that $tDCS_{M1+DLPFC}$ is more effective with respect to physical performance modulation after fatigue than single-site stimulation. One mechanistic reason for the superior effect of $tDCS_{M1+DLPFC}$ might be well-known temporally and spatially specific interactions between the DLPFC and M1 [34]. Vaseghi et al. compared tDCS-induced effects over $tDCS_{M1}$, $tDCS_{M1+DLPFC}$, $tDCS_{M1+\text{ sensory cortex}}$, and $tDCS_{M1+\text{ visual cortex}}$ on neural excitability and reported that $tDCS_{M1+DLPFC}$ induced stronger and longer lasting excitability changes compared to other conditions [17]. However, behavioral improvements may not necessarily reflect synergistic effects of $tDCS_{M1+DLPFC}$, they could also involve additive effects, implying that the outcome of dual a-tDCS is simply the sum of the individual effects of M1 and DLPFC stimulation. Another possible reason is that compared to single-site stimulation, dual tDCS stimulated a larger set of areas.

The results indicated that subjects successfully reached dual fatigue sate, and no significant differences in HR, VAS, RPE and blood lactate between different sessions at all time points. Prolonged exercise-induced physical fatigue reduces neural excitability and diminished M1 activation [35], and dual fatigue reduces furthermore DLPFC activation [9]. However, tDCS did not affect RPE, VAS, or HR after dual fatigue. In accordance, Machado et al. [15] reported missing effects of tDCS on RPE or HR after completing a cycling test at 80% PPO following both, high-definition and conventional $tDCS_{M1}$. Gallo et al. [36] reported that neither HR nor RPE were affected following $tDCS_{DLPFC}$ in elite road cyclists. M1 has no clear relationship with cardiac autonomic control or perceptual responses [15], and although the DLPFC is related to the regulation of emotion and fatigue perception, tDCS will not change subjective perception and HR during fatigue.

Conclusions

We conclude that applying $tDCS_{M1+DLPFC}$ can effectively mitigates fatigue-induced impairment of upper and lower limb strength, spiking, sprinting, and agility immediately after stimulation. Furthermore, its effectiveness on the aforementioned abilities, except for lower limb strength, persisted for up to 40 min after stimulation. However, tDCS did not influence subjective perception and HR in high-level athletes during dual fatigue. Practitioners can integrate this brief stimulation protocol into pre-competition

training regimens or real competition scenarios, which could be a promising avenue for optimizing athletic performance.

Declarations

Authors' contributions

Y.Y., and F.Q. contributed to the conception and design. Y.Y., C.M.V. and A.A. contributed to data collection and data extraction. Y.Y., F.Q. drafted the paper. F.Q., M.A.N., and C.M.V revised it critically for important intellectual content. All authors have read and approved the final version of the manuscript, and agree with the order of the presentation of the authors.

Acknowledgments

This study was funded by Humanities and Social Sciences Research Funds of the Ministry of Education of China (22YJCZH136), the Fundamental Research Funds for the Central Universities (2022QN013), the Research Foundation for Advanced Talents of Beijing Sport University, the Fondazione Italiana Sclerosi Multipla (2022/R-Single/071), the Bial Foundation (304/2022), the Universidad Católica Del Maule (CDPDS2022).

References

1. SATTLER T, HADŽIĆ V (2015) Vertical jump performance of professional male and female volleyball players: effects of playing position and competition level [J]. J Strength Cond Res 29(6):1486–1493
2. RUSSELL S, JENKINS D, HALSON S et al (2020) Changes in subjective mental and physical fatigue during netball games in elite development athletes [J]. J Sci Med Sport 23(6):615–620
3. COSTA Y, FORTES L D S, HAYES L D et al (2023) Mental fatigue measured in real-world sport settings: A case study of world class beach volleyball players [J]. J Phys Educ Sport 23(5):1237–1243
4. RIBEIRO F, SANTOS F, GONçALVES P et al (2008) Effects of volleyball match-induced fatigue on knee joint position sense [J]. Eur J Sport Sci 8(6):397–402
5. DEL, COSO J, PEREZ-LOPEZ A, ABIAN-VICEN J et al (2014) Enhancing physical performance in male volleyball players with a caffeine-containing energy drink [J]. Int J Sports Physiol Perform 9(6):1013–1018
6. LIN H-T, HUANG Y-C, LI Y-Y et al (2021) The Effect of Rectus Abdominis Fatigue on Lower Limb Jumping Performance and Landing Load for Volleyball Players [J]. Appl Sci, 11(15)
7. BOKSEM M A, MEIJMAN T F, LORIST MM (2005) Effects of mental fatigue on attention: an ERP study [J]. Brain Res Cogn Brain Res 25(1):107–116

8. DANTAS QUEIROSVS (2021) Mental Fatigue Reduces Training Volume in Resistance Exercise: A Cross-Over and Randomized Study [J]. Percept Mot Skills 128(1):409–423
9. MEHTA R K, PARASURAMAN R. Effects of Mental Fatigue on the Development of Physical Fatigue: A Neuroergonomic Approach [J]. Hum Factors, (2014) 56(4): 645–656
10. TANAKA M, ISHII A, WATANABE Y (2014) Neural effect of mental fatigue on physical fatigue: a magnetoencephalography study [J]. Brain Res 1542:49–55
11. XU R, ZHANG C, HE F et al (2018) How Physical Activities Affect Mental Fatigue Based on EEG Energy, Connectivity, and Complexity [J]. Front Neurol 9:915
12. PARK SB, HAN D H, HONG J et al (2022) Transcranial Direct Current Stimulation of Motor Cortex Enhances Spike Performances of Professional Female Volleyball Players [J]. J Mot Behav, : 1–13
13. POLLASTRI L, GALLO G, ZUCCA M et al (2021) Bilateral Dorsolateral Prefrontal Cortex High-Definition Transcranial Direct-Current Stimulation Improves Time-Trial Performance in Elite Cyclists [J]. Int J Sport Physiol 16:224–231
14. VELDEMA J, ENGELHARDT A (2021) JANSEN P. Does anodal tDCS improve basketball performance? A randomized controlled trial [J]. Eur J Sport Sci, : 1–10
15. MACHADO D G D S, BIKSON M, DATTA A et al (2021) Acute effect of high–definition and conventional tDCS on exercise performance and psychophysiological responses in endurance athletes: a randomized controlled trial [J]. Sci Rep-Uk 11(1):13911
16. ORCIOLI-SILVA D, ISLAM A, BAKER M R et al (2021) Bi-Anodal Transcranial Direct Current Stimulation Combined With Treadmill Walking Decreases Motor Cortical Activity in Young and Older Adults [J]. Front Aging Neurosci 13:739998
17. VASEGHI B, ZOGHI M (2015) The effects of anodal-tDCS on corticospinal excitability enhancement and its after-effects: conventional vs. unihemispheric concurrent dual-site stimulation [J]. Front Hum Neurosci 9:533
18. YU Y, ZHANG L, CHENG M Y et al (2025) The effects of different fatigue types on action anticipation and physical performance in high-level volleyball players [J]. J Sports Sci, : 1–13
19. YU Y, ZHANG L, CHENG M-Y et al (2023) The Effects of Different Fatigue Types on Action Anticipation and Physical Performance in High-level Volleyball Players [J]. bioRxiv, : 2023.11.26.568694
20. VALADES J M P (2009) A D. Testing Protocol for Monitoring Spike and Serve Speed in Volleyball [J]. Strength Conditioning J 31(6):47–51
21. JM DVC, FEMIA P U P (2018) A. Effect of eight weeks of upper-body plyometric training during the competitive season on professional female volleyball players [J]. J Sports Med Phys Fit 58:1423–1431
22. SASSI RH, DARDOURI W, MAHFOUDHI M E et al (2009) Relative And Absolute Reliability Of a Modified Agility T-test And Its Relationship With Vertical Jump And Straight Sprint [J]. J Strength Cond Res 23(6):1644–1651

23. MECKEL Y, MAY-ROM M, EKSHTIEN A et al (2015) Relationships Among Two Repeated Activity Tests and Aerobic Fitness of Volleyball Players [J]. J Strength Conditioning Res 29(8):2122–2127
24. CABRAL L L, LOPES P B, WOLF R et al (2017) A Systematic Review of Cross-Cultural Adaptation and Validation of Borg's Rating of Perceived Exertion Scale [J]. J Phys Educ, 28(1)
25. NIKOOHARF SALEHI E, JAYDARI FARD S JABERZADEHS (2022) Mental Fatigue Impairs Postural Stability in Older Adults [J]. Res Q Exerc Sport, : 1–8
26. JAMIL A, BATSIKADZE G, KUO H-I et al (2017) Systematic evaluation of the impact of stimulation intensity on neuroplastic after-effects induced by transcranial direct current stimulation [J]. J Physiology-London 595(4):1273–1288
27. DONATI F, SIAN V, BIASINI G M et al (2021) Serum Levels of Brain-Derived Neurotrophic Factor and Other Neurotrophins in Elite Athletes: Potential Markers of the Use of Transcranial Direct Current Stimulation in Sport [J]. Front Sports Act Living, 3
28. AL-KHELAIFI F, DIBOUN I, DONATI F et al (2018) A pilot study comparing the metabolic profiles of elite-level athletes from different sporting disciplines [J]. Sports Medicine-Open, 4
29. MAUDRICH T, RAGERT P (2022) Single-session anodal transcranial direct current stimulation to enhance sport-specific performance in athletes: A systematic review and meta-analysis [J]. Brain Stimul 15(6):1517–1529
30. DUTTA A, KRISHNAN C, KANTAK SS et al (2015) Recurrence quantification analysis of surface electromyogram supports alterations in motor unit recruitment strategies by anodal transcranial direct current stimulation [J]. Restor Neurol Neurosci 33(5):663–669
31. KRISHNAN C, RANGANATHAN R, KANTAK SS et al (2014) Anodal transcranial direct current stimulation alters elbow flexor muscle recruitment strategies [J]. Brain Stimul 7(3):443–450
32. SALEHI E N, FARD S J, JABERZADEH S et al (2021) Transcranial Direct Current Stimulation Reduces the Negative Impact of Mental Fatigue on Swimming Performance [J]. J Mot Behav
33. STAGG C J, LIN R L, MEZUE M et al (2013) Widespread modulation of cerebral perfusion induced during and after transcranial direct current stimulation applied to the left dorsolateral prefrontal cortex [J]. J Neurosci 33(28):11425–11431
34. HASAN A, GALEA J M, CASULA E P et al (2013) Muscle and Timing-specific Functional Connectivity between the Dorsolateral Prefrontal Cortex and the Primary Motor Cortex [J]. J Cogn Neurosci 25(4):558–570
35. THOMAS K, DENT J, HOWATSON G et al (2017) Etiology and Recovery of Neuromuscular Fatigue after Simulated Soccer Match Play [J]. Med Sci Sports Exerc 49(5):955–964
36. GALLO G, GEDA E, CODELLA R et al (2022) Effects of Bilateral Dorsolateral Prefrontal Cortex High-Definition Transcranial Direct-Current Stimulation on Physiological and Performance Responses at Severe-Intensity Exercise Domain in Elite Road Cyclists [J]. Int J Sports Physiol Perform, : 1–9

Figures

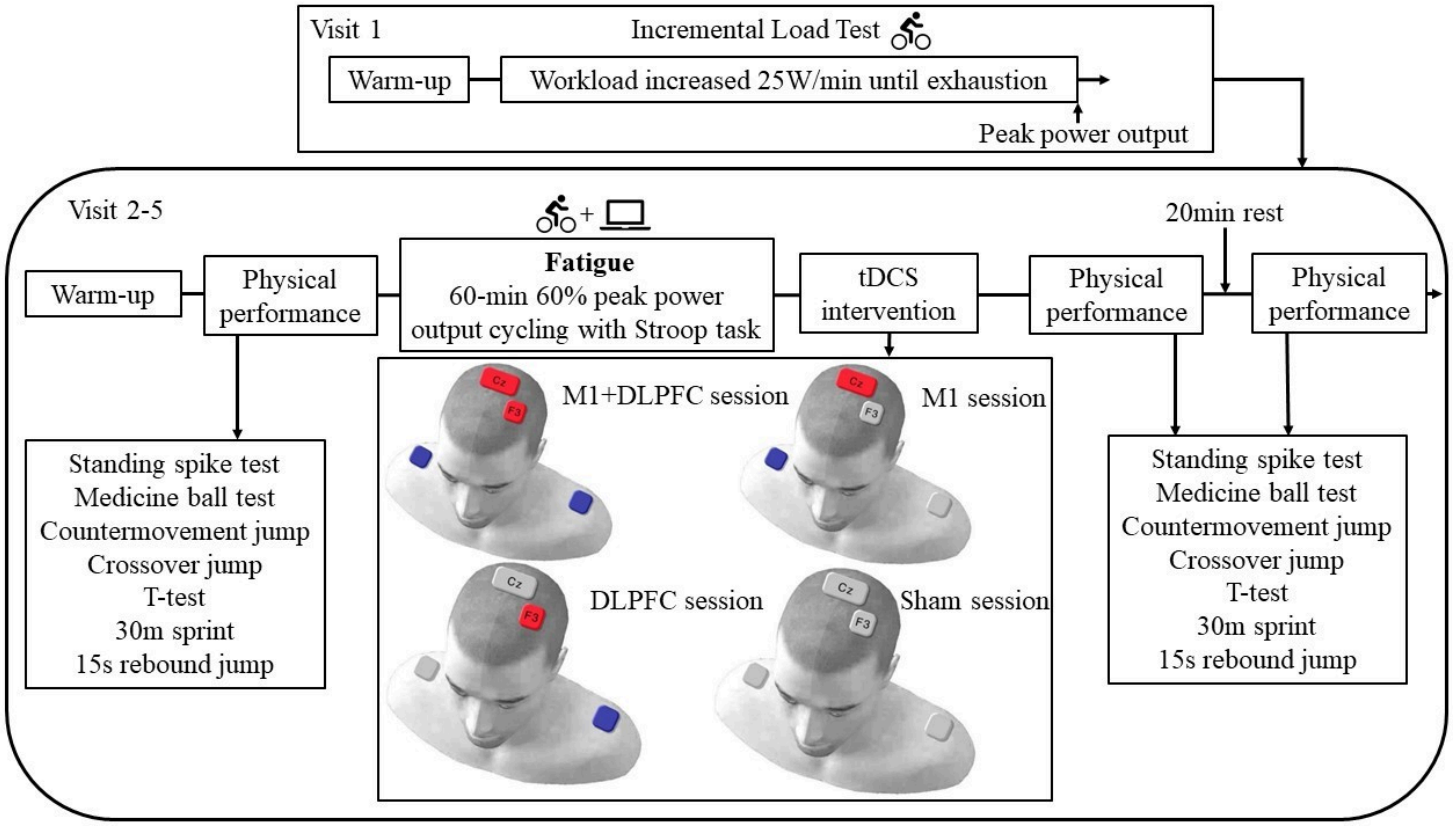


Figure 1

Experimental overview. The first session performed an incremental load test on a cycle ergometer to determine peak power output. The formal experiments started with warm-up, and then underwent baseline physical performance testing. Subsequently, the subjects completed the fatigue intervention and tDCS intervention. Lastly, subjects completed the physical performance test immediately following tDCS intervention, and 40 min after tDCS intervention. Each visit separated at least 7 days.

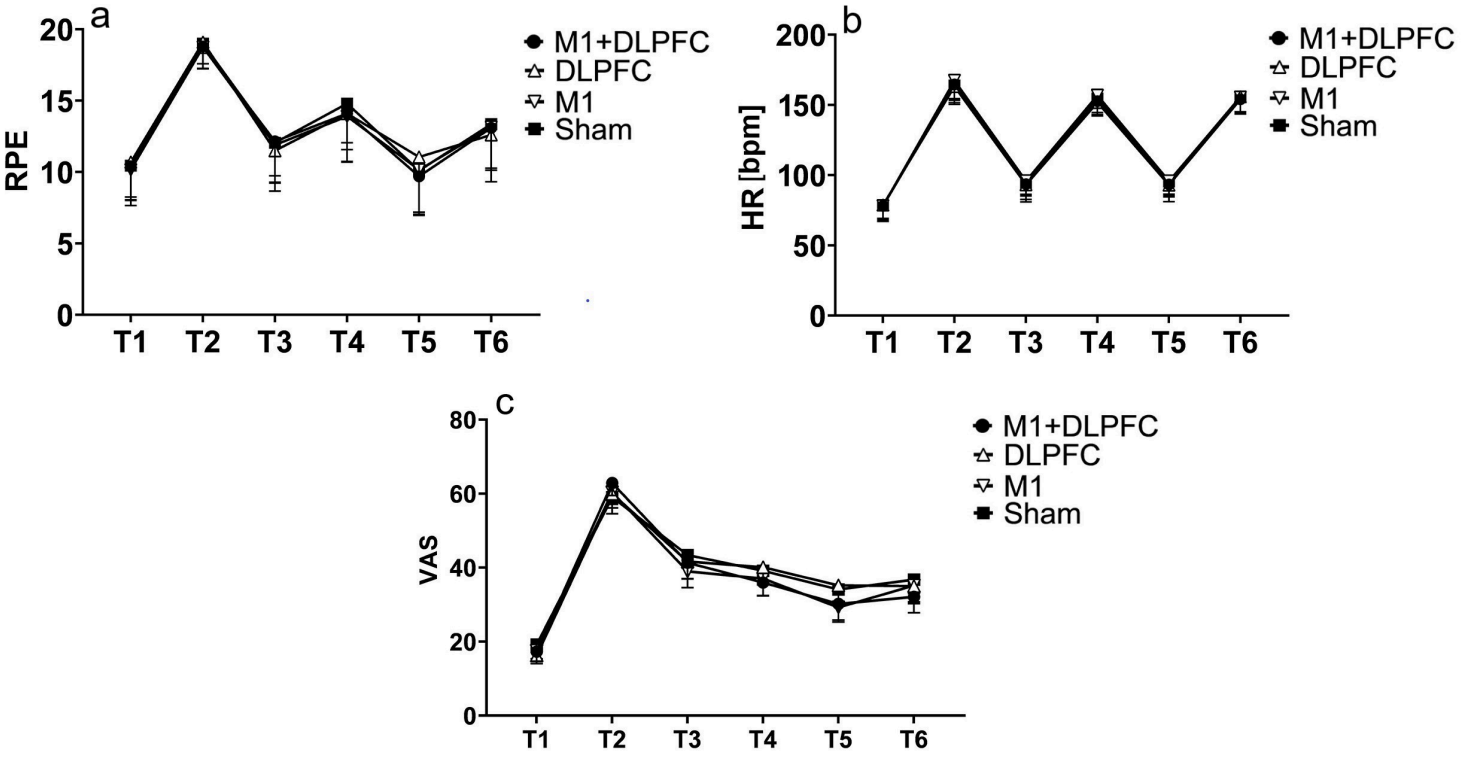


Figure 2

Results of the psycho-physiological parameters. RPE (panel a), HR (panel b), and VAS (panel c) values at the start (T1), after the fatigue intervention (T2), after the tDCS intervention (T3), after post 1 (T4), after a 20 min rest (T5), and after post 2 (T6). No significant differences in RPE, HR or VAS were observed among sessions at all time points. Error bars represent standard error (SEM).

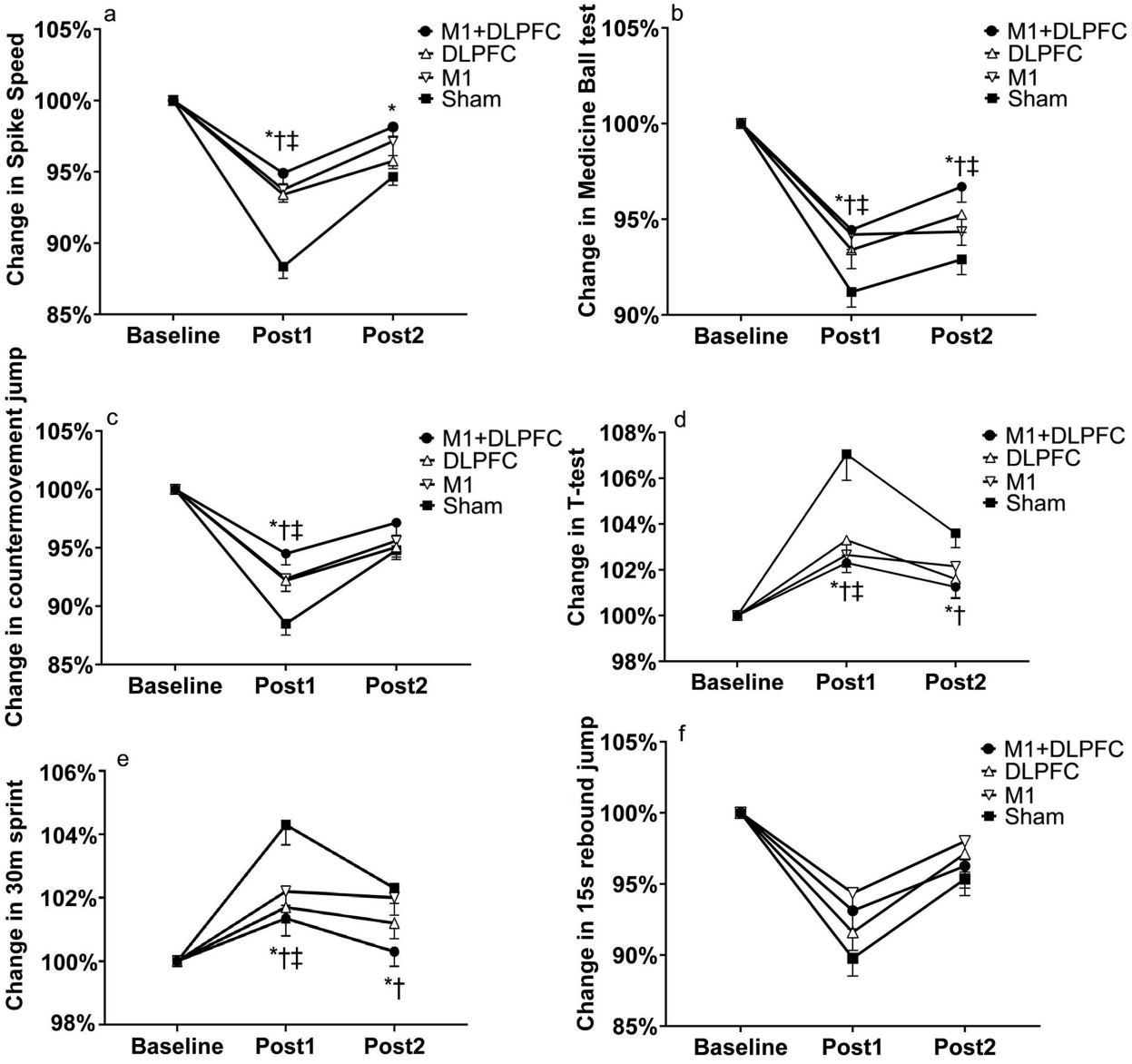


Figure 3

Group data from the spike test (panel a), medicine ball test (panel b), countermovement jump (panel c), T-test (panel d), 30-m sprint (panel e) and 15-s rebound jump (panel f). The level of significance was set at $p < 0.05$, and error bars represent the standard error of the mean. *, significant difference between M1 + DLPFC session and sham session; †, significant difference between DLPFC and sham session; ‡, significant difference between M1 session and sham session.