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The effect of transcranial direct current stimulation on dynamic balance after an endurance exhausting activity in mental fatigue condition

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Abstract

Background: Anodal transcranial direct current stimulation (a-tDCS) is a new neuro-modulatory technique.

Aim: This study aimed to investigate the effect of a-tDCS on dynamic balance after exhaustion.

Material and Methods: Fifteen endurance-trained men voluntarily attended five separate sessions. In the first session, Maximal aerobic speed (MAS) was measured. Then, the participants were randomly assigned to four different conditions: 1. Mental fatigue (MF)+a-tDCS, 2. MF+sham (s-tDCS), 3. a-tDCS, and 4. s-tDCS. In each session, after dynamic balance measurement, the participants were exposed to the conditions and received 20 min of anodal tDCS over the dorsolateral prefrontal cortex (DLPFC). Then, the participants performed a submaximal endurance activity at 70% of MAS until exhaustion. Immediately after exhaustion, dynamic balance was measured again.

Results: After exhaustion, the dynamic balance of the right leg under the a-tDCS condition was significantly higher than the MF+s-tDCS (P= 0.008). The dynamic balance significantly decreased from pre- to post-test in MF+s-tDCS and s-tDCS conditions (P= 0.0001). In the left leg, the dynamic balance under the a-tDCS condition was significantly higher than MF+s-tDCS (P= 0.025).

Conclusions: Anodal stimulation of the DLPFC could be beneficial for the dynamic balance and may have a protective effect against the negative consequence of exhausting activity on the dynamic balance in endurance-trained men.

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1. Introduction

Non-invasive brain stimulation (NIBS) is one of the novel methods that have been used in sports in recent years. NIBS in sports, which is also known as neurodoping, includes intervention in the activity of neuronal circuits in different brain regions with the aim of inducing optimal effects on sports performance [1]. Transcranial Magnetic Stimulation (TMS) and Transcranial Direct Current Stimulation (tDCS) are among the most common techniques used in this field, which can produce the expected effects by changing the excitability of brain neurons [1, 2, 3]. In the study of Okano et al. (2015), it has been shown that tDCS can cause depolarization or hyperpolarization of the resting potential of the membrane in the stimulated areas, depending on the type of stimulation [4].

Anodal stimulation causes depolarization and increased excitability; and cathodal stimulation cause hyperpolarization and decrease the excitability of neurons in the target areas. It seems that the main mechanism of tDCS effect would be the change in the inhibitory neurotransmitter gamma-aminobutyric acid (GABA) and the efficiency of N-methyl-D-aspartate (NMDA) receptors.

Multiple studies have shown desirable effects of tDCS on many variables related to various aspects of sports performance, such as muscular strength, endurance performance, motor sensation, motor learning, cognitive performance, and muscle fatigue.

Colzato et al. (2017) demonstrated desirable effects of tDCS on endurance performance, cognitive performance, and fatigue [5]. Machado et al. (2019) showed that a-tDCS improves sports performance in cyclists [6]. In another study, Vitor-Costa et al. (2015) demonstrated that a-tDCS leads to the significant increase in time to exhaustion during high-intensity endurance activity [7].

It is also important to note that some studies have not reported such positive effects. For example, Baldari et al. (2018) reported that a-tDCS did not result in significant changes in physiological responses, perceived exertion, and sports performance in endurance runners [8].

Despite some inconsistencies in the results of research on the effectiveness of a-tDCS, a wide range of studies indicate the beneficial effects of this strategy in sports. This is not limited to scientific studies and in practical settings, this strategy has also been used effectively by professional athletes at the Olympic level [9].

On the other hand, in addition to studies that directly investigated the effect of a-tDCS on athletic performance, in recent years, studies have also been conducted on the effectiveness of a-tDCS on other factors like balance, which plays imperative role in improving athletic performance, preventing sports injuries and also bone fractures caused by falls [10]. The results of these studies have shown that a-tDCS can help improve static and dynamic balance by modifying sensory input and intervening in the process of sensory information processing in the brain [11].

Balance is a complex and multidimensional concept that relates to the control of posture and essentially refers to the ability to maintain a position, move between positions, and avoid falling when responding to an external disturbance [12]. Balance maintenance is considered a critical point for performing in sports fields and most motor skills in daily life, whereas its weakness is considered one of the most important factors in causing injuries to athletes [13, 14, 15, 16].

In recent years, the detrimental effect of mental fatigue on athletic performance has been reported in many studies. Interestingly, it has been shown that the

Dorsolateral prefrontal cortex (DLPFC) might play a critical role in mediating the effect of mental fatigue and performance. This raises the question as to whether a-tDCS could cope with the negative effects of mental fatigue.

In this regard, Nikooharf et al. (2021) showed that anodal stimulation of the DLPFC reduced the undesirable effects of mental fatigue in 50-meter swimming and improved performance [17].

Furthermore, in the latest study conducted in this field, de Sousa Fortes et al. (2022) demonstrated that anodal stimulation of the left Orbital prefrontal cortex (OPFC) region of the brain could improve maximum 3 min activity in amateur female swimmers under mental fatigue condition [18].

The results of these studies, which are the only studies conducted so far on the application of a-tDCS as an ergogenic strategy against mental fatigue, indicate that the DLPFC region can be an effective target for brain stimulation in combating mental fatigue. Previously, the desirable effects of stimulating the DLPFC region in reducing neuromuscular fatigue, reducing perceived pressure, improving decision-making, improving muscular endurance, and control have also been demonstrated [19, 20].

There is evidence that mental fatigue reduces cognitive resources and impairs balance performance, especially when balance tasks are complex. For example, when trying to walk or stand while concurrently performing a secondary cognitive task [21]. Furthermore, in the latest study conducted in this field, Jessica Pitts and Tanvi Bhatt (2023) demonstrated that mental fatigue affected both volitional and reactive balance, resulting in increased postural sway, decreased accuracy on volitional tasks, delayed responses to perturbations, and less effective balance recovery responses [22].

Therefore, considering the numerous evidence demonstrating the desirable effects of a-tDCS on physiological performance, cognitive function, decision-making, and other factors affecting sports performance, conducting studies to investigate the effect of this intervention on balance under conditions of mental fatigue caused by excessive mental activity is essential both from a theoretical and practical perspective.

Therefore, based on what has been said, the innovation of the present research is related to the investigation of the effect of a-tDCS stimulation of the DLPFC region and its impact on balance under conditions of mental fatigue caused by excessive mental activity. Accordingly, the main objective of the present study is to investigate the effect of anodal stimulation of the DLPFC region on balance before and after a submaximal endurance exercise in endurance-trained men.

2. Materials and Methods

2. 1. Participation

Fifteen healthy endurance-trained men with a mean age of 22.9±2.9 years and a mean body mass index of 22.5±1.7 kg/m^2 participated voluntarily in this study. The sample size was determined using GPower software version 3.1 with a statistical power of 80%, effect size of 35%, and a significance level of 0.05, considering the desired statistical test (F values in repeated measures ANOVA with 1 group and 3 measurement stages) [23, 24].

Inclusion criteria were: 1. Male endurance-trained individuals with at least one year of regular training experience, 2. Age range of 18 to 30 years, 3. Body mass index of 18.5 to 24.9 kg/m^2, 4. Obtaining a certificate of no medical restriction for participating in exercise programs from a physician, 5. Right-handedness, 6. No color blindness or color vision disorders.

Exclusion criteria were: 1. Any chronic disease, 2. History of seizures, epilepsy, or other neurological disorders, 3. Presence of implantable devices or pacemakers in the body, 4. Tobacco and alcohol consumption.

Withdrawal criteria were: 1. Voluntary withdrawal of participants from the study, 2. Incidence of acute illnesses and musculoskeletal injuries during the implementation phase of the study, 3. Failure to attend any of the scheduled sessions in the study.

2. 3. Procedure

In order to conduct the study, after selecting the participants based on the inclusion criteria, an informed consent form was read and signed by the participants. Then, the participants attended a familiarization session to become acquainted with the study procedures. In addition, in the same session, anthropometric characteristics of the participants were measured. In the familiarization session, the participants were also familiarized with the method of brain stimulation. To examine the absence of any abnormal reaction to brain stimulation, they received short doses (for 5 min) of electrical brain stimulation experimentally. If there was any abnormal reaction (skin burning, dizziness, nausea, etc.) up to 48 hours after the session, the participant was excluded from the study. After the familiarization session, the participants' maximal aerobic speed (MAS) was measured using the progressive treadmill test. Then, each participant attended the laboratory four times in total to receive interventions. Participants were randomly assigned in a counterbalanced-crossover design for the order of receiving interventions, with a one-week interval between each session.

In these four sessions, the participants first performed the Y Balance Test (YBT) at the laboratory. Then, they completed an incongruent Stroop task for 30 min to induce MF or watching emotionally neutral documentaries as control situation. After that, the a-tDCS or s-tDCS were conducted for 20 min followed by running on a treadmill at an intensity equivalent to 70% of MAS.

After completing the endurance activity, YBT was immediately performed again and the results were recorded. In order to prevent the effect of circadian rhythm on participants' performance, each participant performed their four measurements at a specific time of day. Additionally, a food recall form was completed by the participants 48 hours before their first session in the laboratory, and the information was used to standardize the participants' nutrition in subsequent sessions. In each session, the participants were present in the laboratory two hours after consuming a standardized meal.

2. 3. 1. Incremental running test (measure the maximal aerobic speed (MAS)

To measure the maximal aerobic speed (MAS), an incremental running test on a treadmill was used. First, the participants warmed up for 3 min at a speed of 6 km per hour on a treadmill with a 1% incline. After the warm-up, the incremental test started at a speed of 8 km/h on a treadmill with a 1% incline, and the running speed was increased by 1 km every 3 min. Verbal encouragement was provided throughout the test to elicit maximal effort from the participants [25].

To determine the attainment of the predefined criteria for reaching maximal effort, the following indicators were considered: reaching a heart rate greater than 100% of the predicted maximal heart rate for endurance athletes (calculated as age × 0.7-206) and ratings of perceived exertion (RPE) equal to or greater than 19 on the Borg 20-6 scale. The time and speed at the completion of the last stage were recorded for calculating MAS [25].

Participants were instructed to abstain from consuming food or engaging in heavy exercise, alcohol, and caffeine consumption for 2 hours and 24 hours before the test, respectively. The MAS was calculated using the following formula [25].

MAS= Vcomplete + (Inc × t/T)
MAS= Maximal aerobic speed
Vcomplete= Speed at the completion of the last stage in the incremental test
Inc= Speed increment from one stage to the next
t= Time elapsed during an incomplete stage
T= Time required and expected to complete a full stage

2. 3. 2. Endurance exhausting activity

The endurance activity used in the present study involved running at a speed equivalent to 70% of the MAS until exhaustion. To achieve this, after conducting an incremental test and calculating MAS in the initial session, the value equivalent to 70% of MAS was determined for each participant. This speed was then used in the following four sessions of the experiment when participants were present. To perform the submaximal endurance activity, participants warmed up on a treadmill according to the standard procedure and then performed the endurance activity at a speed of 70% of MAS until exhaustion. Inability to maintain the prescribed speed (70% of MAS) accompanied by reaching a heart rate higher than 100% of the predicted maximum heart rate based on age and RPE values equal to or greater than 19 on the Borg scale were considered indicators of reaching exhaustion. The duration of the activity at the moment of exhaustion was recorded [25].

2. 3. 3. Inducing mental fatigue

To induce MF, the modified incongruent version of the Stroop test was used for a duration of 30 min. For the test, the participant sat on a comfortable chair in a calm environment in front of a computer screen. In this version of the Stroop test, four words (yellow, blue, green, and red) were displayed in incongruent colors (e.g., the word "red" written in blue). The words appeared randomly on the monitor with a time interval of 1.5 sec. On the keyboard, there were four buttons corresponding to four colors (blue, yellow, red, and green) used in the test. The test was conducted as follows: when the words "blue", "yellow", "red", or "green" appeared on the screen, the participant had to press the button corresponding to the color of the word (not the word being displayed). For example, if the word "blue" was displayed in green, the participant would press the green button. There was one exception to these conditions: if any of the words were displayed in red, in that particular case, the participant would press the button corresponding to the word itself, not the displayed color. For example, if the word "blue" was shown in red, the participant would press the blue button. Prior to the main test, 20 practice trials were conducted to familiarize the participants with the test procedure. The participants were instructed to prioritize accuracy and response speed. After each response, visual feedback indicating the correctness or incorrectness of the response was presented on the monitor [26, 27].

2. 3. 4. Transcranial Direct Current Stimulation (tDCS)

In order to precisely stimulate the target area in the current study (left DLFPC region), the international 20-10 brain mapping system and a specialized EEG cap were used. The image of the international

20-10 brain mapping system is presented in Figure 1.

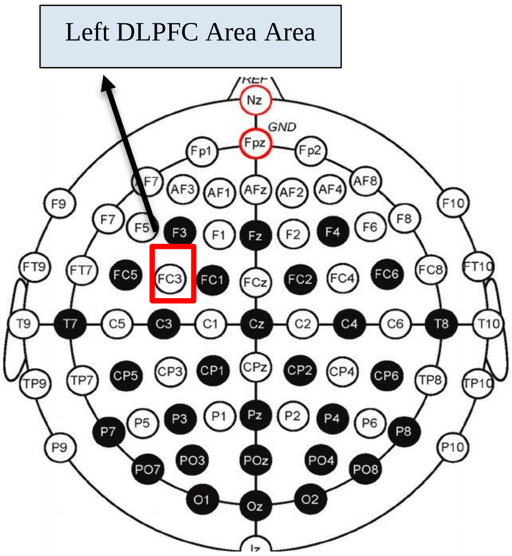

Figure 1. International brain mapping system 20-10 and the left DLPFC region

Participants were instructed to refrain from consuming caffeine and alcohol within 48 hours prior to their laboratory visit. After arriving at the laboratory and performing cognitive tests, participants sat on a comfortable chair that had been prearranged in the designated area. Subsequently, the target area for electrode placement was marked using the specialized EEG cap, and the electrodes were installed in the marked regions. For the stimulation of the left DLFPC region, the anodal electrode was placed in the F3 area and the cathodal electrode was placed in the AF8 area. The electrode placement for the sham stimulation was similar to that of the active stimulation [28]. After electrode placement, participants received 20 min of anodal electrical stimulation with an intensity of 2 milliamperes while seated and without any verbal communication.

It should be noted that the current study was conducted as a double-blind study. The participants and the primary investigator were unaware of the type of stimulation received in each session, and this information was only available to an external person outside the research team until the end of the study. To conceal the order of stimulation received from the primary investigator, all stages related to determining the random order of stimulation for each participant were carried out by the same individual outside the research team.

Furthermore, to conceal the type of stimulation from the participants, the tDCS device was hidden from their view by a cover, and the primary investigator was absent from the laboratory during the installation of the electrodes, the 20 min stimulation period, and the removal of the electrodes.

2. 3. 5. Y balance test (YBT)

The YBT was used to measure the dynamic balance of the participants' left and right legs. Prior to performing the balance test, the actual length of the lower limb was measured in the supine position. For this purpose, the distance from the anterior superior iliac spine to the medial malleolus was considered as the standard length of the lower limb. In the YBT, the maximum reach distance of the left and right legs was recorded in three predetermined directions: 1. anterior direction, 2. posteromedial direction, and 3. posterolateral direction (Figure 2) to determine the dynamic balance of the left and right legs.

To perform the YBT, after providing necessary instructions on how to perform the test, the participants were allowed to perform six practice movements for each direction. Then, after an adequate rest period around 3 min, the participants were asked to perform the YBT in the following order:

1. Right leg at the center point of the directions, 3 attempts with the left leg for maximum reach in the anterior direction.

2. Left leg at the center point of the

directions, 3 attempts with the right leg for maximum reach in the anterior direction.

3. Right leg at the center point of the directions, 3 attempts with the left leg for maximum reach in the posteromedial direction.

4. Left leg at the center point of the directions, 3 attempts with the right leg for maximum reach in the posteromedial direction.

5. Right leg at the center point of the directions, 3 attempts with the left leg for maximum reach in the posterolateral direction.

6. Left leg at the center point of the directions, 3 attempts with the right leg for maximum reach in the posterolateral direction.

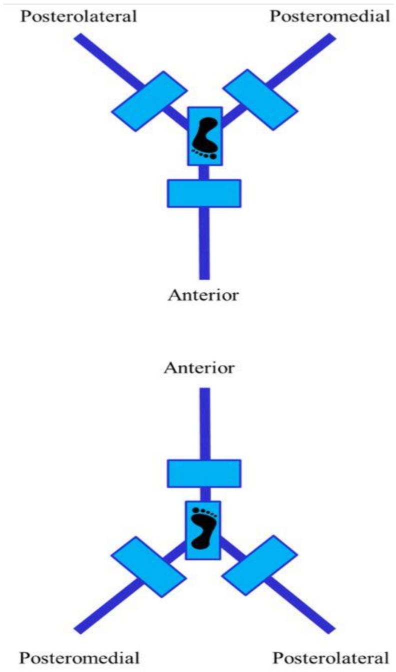

Figure 2. A YBT excursion in operation

In each attempt, the dynamic balance of the leg is assessed at the center point of the measured directions. The best reach distance achieved in the three attempts performed in each direction is recorded as the balance score. Sufficient rest periods are provided between attempts in different directions. The dynamic balance score of each leg is calculated using the following formula [29]:

$$\text{Composite Score} = \frac{(\text{Anterior} + \text{Posteriomedial} + \text{Posterolateral})}{(3 \times \text{Limb Length})} \times 100$$

2. 4. Statistic

The Shapiro-Wilk test was used to check the normality of each data set. Since the assumption of normality was met in all the data set, two-way repeated measures of ANOVA (4*2 factorial design including four conditions and two time points) were used for statistical analysis. When the interaction effect between condition and time was not significant, we reported the main effect of condition and time; and, if there was a significant interaction effect between condition and time, the simple main effect of condition and time was analyzed separately using one-way repeated measures of ANOVA and paired-sample t-test, respectively. The bonferroni post hoc test was used for pairwise comparisons when required. The Mauchly’s sphericity test was used and when the assumption of sphericity was not met, the Greenhouse-Geisser correction was applied. The Partial η^2 measure of the effect size was reported. In all statistical tests, a significance level of 0.05 was considered. Statistical analysis was done using SPSS version 23 software.

3. Results

The overall results of the study are presented in Table1.

3. 1. Right Leg

The results of the present study showed a significant ‘condition × time’ interaction effect ($F_{(3,45)} = 4.78$, $p = 0.006$, $\eta^2_p = 0.242$) on the dynamic balance of the right leg. Based on significant interaction effect, simple main effect of condition was analyzed using one-way repeated measures ANOVA and the results demonstrated that there was no significant difference in the dynamic balance of the right leg among four experimental conditions at pre-test ($F_{(1.7,25.8)}= 1.3$, $p= 0.26$, $\eta^2_p = 0.084$) while a significant difference was observed at post-test ($F_{(3,45)}= 3.98$, $p= 0.013$, $\eta^2_p = 0.21$). Pairwise comparisons revealed that the dynamic balance of the right leg under the a-tDCS condition was significantly higher than that of the MF+s-tDCS at post-test ($P= 0.008$, $d= 0.5$, $\Delta= +4.9\%$). There were no significant differences among other conditions ($P> 0.05$). Moreover, analyzing simple main effect of time using paired sample t-test showed that the dynamic balance significantly decreased from pre-test to post-intervention in MF+s-tDCS and s-tDCS conditions ($t_{(15)}= 5.56$, $P= 0.0001$; $t_{(15)}= 2.4$, $P= 0.029$; respectively). No significant changes were observed in other conditions ($P> 0.05$).

3. 2. Left Leg

Our results showed that there was no significant 'condition × time' interaction effect on the dynamic balance of the left leg ($F_{(1.7,25.9)}= 1.73$, $P= 0.17$, $\eta^2_p = 0.104$). Since there was no significant interaction effect, the main effect of condition and time was reported. The results demonstrated a significant main effect of condition on the dynamic balance of the left leg ($F_{(3,42)}= 3.75$, $P= 0.018$, $\eta^2_p = 0.211$). Pairwise comparisons indicated that the dynamic balance of the left leg under a-tDCS condition was significantly higher than the dynamic balance under MF+s-tDCS condition ($P= 0.025$, $d= 1.6$, $\Delta= +3.8\%$). There were no significant differences among other conditions ($P> 0.05$). Analyzing simple main effect of time showed that there were no significant changes in the dynamic balance of the left leg from pre-test to post-intervention ($P> 0.05$).

Table1. The mean±standard deviation values of the dynamic balance in the right and left leg

	Right Leg		**Left Leg**	
	Pre	**Post**	**Pre**	**Post**
MF + a-tDCS	105.2±10.1	104.1±9.3	104.2±7.0	104.1±8.6
MF + s-tDCS	103.8±9.4	101.1±9.2$^{\&}$	106±13.4	100.6±7.8
a-tDCS	105.8±9.8	106.1±10.5*	106.6±9.3	107.1±9.1*
s-tDCS	102.9±8.9	101.9±9.5$^{\&}$	104.8±8.2	103.7±8.6

Pre: Before the endurance exhausting activity, Post: After the endurance exhausting activity, MF: Mental Fatigue, a-tDCS: Anodal transcranial direct current stimulation, s-tDCS: Sham situation, * Significantly higher than MF+s-tDCS situation. $^{\&}$ Significantly lower than pre situation.

4. Discussion

In the present study, the effect of anodal stimulation of the left DLPFC region on the dynamic balance of the left and right leg after performing an exhausting endurance activity under mental fatigue condition was investigated. The results of the present study showed that in the condition of a-tDCS of the DLPFC region, the dynamic balance of both the right and left legs was significantly better than the condition of MF+s-tDCS. In addition, the results showed that the dynamic balance of the right leg in s-tDCS conditions (irrespective of MF) attenuated after the endurance exhausting activity. In other words, a-tDCS had a protective effect against the negative effect of exhausting activity on the dynamic balance of the right leg.

The results of studies conducted in the field of balance show that static, dynamic balance is affected by adjustments caused by external (sensory information like neuromuscular and mental fatigue) and internal factors (information processing by the central nervous system), and changes in these adjustment factors can cause changes in static and dynamic balance [10].

These factors, particularly in special conditions (such as mental fatigue) are mainly based on receiving sensory information, processing this information in the relevant areas of the nervous system, and finally creating the necessary movement schema and implementing it. Therefore, in summary, it can be said that maintaining balance, especially dynamic balance, is constantly based on receiving information, analyzing and processing that information, and creating an appropriate response. Therefore, any disturbance in sensory information processing as well as performing motor actions can lead to disturbances in maintaining balance [30].

Different areas in the brain are responsible for processing sensory information received from the environment as well as sensory information coming from other areas of the nervous system. Among them, the role of the prefrontal cortex (PFC) region and especially the DLPFC region is of particular importance. According to Robertson and Marino (2016), DLPFC is an important region for processing and integrating sensory information and also mediating motor areas such as primary motor cortex in a top-down manner, leading to appropriate motor responses by the CNS [31].

In the present study, it seems that the anodal stimulation of the left DLPFC area, by increasing the activity of neurons in this area, has been able to overcome the negative effects of mental fatigue on dynamic balance. In this context, Wittenberg et al. (2017) considered mechanical, cognitive, and sensory challenges the most important factors in maintaining balance, especially dynamic balance [30].

It seems that the participants in the current research have faced all three challenges by performing endurance activity under mental fatigue condition, but in the condition of a-tDCS stimulation, the adjustments made to this area were able to overcome the negative effects caused by these challenges.

In line with our study, Manor et al. (2016) showed that anodal stimulation of the DLPFC area could have a positive effect on the postural control of healthy older adults [32]. Moreover, Zhou et al. (2015) reported a beneficial effect of a-tDCS of the DLPFC area on the standing postural sway in older adults [33]. Both the above studies researched older people. However, a more recent study on 18-30-year-old endurance-trained men showed a favorable effect of a-tDCS of the DLPFC area on the dynamic balance of these athletes under hypoxic conditions [29].

There are also conflicting results, as a recent review reports no effect of a-tDCS on the static balance in multiple sclerosis patients. However, the stimulation area was the primary motor cortex (M1) area instead of DLPFC [34]. It is interesting that in the study of Etemadi et al. (2022), only stimulation of the DLPFC, and not the M1, had a beneficial effect on the balance [29]. Another study also investigated the effect of M1 stimulation on the balance task of healthy elderly people and found no effect of a-tDCS on the whole body dynamic balance [35]. To our knowledge, there is no other published study regarding the effect of a-tDCS on the DLPFC area and it is a novel and interesting field for future studies.

5. Conclusions

According to the results, it can be concluded that the implementation of an endurance-exhausting activity can cause a decrease in dynamic balance. However, anodal stimulation of the DLPFC area could have a protective effect against this negative effect. In overall, anodal stimulation of the left DLPFC area has a potential ergogenic aid on dynamic balance in endurance-trained men.

Conflict of interest

The authors declared no conflicts of interest.

Authors' contributions

All authors contributed to the original idea, study design. All authors have read and agreed to the published version of the manuscript. Conceptualization, TV, AE; Methodology, TV, AE; Investigation, AA, TV, AE; Writing- Original Draft, AA; Writing- Review & Editing, TV, AE; Supervision, TV, AE.

Ethical considerations

The authors have completely considered ethical issues, including informed consent, plagiarism, data fabrication, misconduct, and/or falsification, double publication and/or redundancy, submission, etc. The current research has the ethics code number (IR.RAZI.REC.1401.24) from the ethics committee in biomedical research of Razi University. Also, the present study has a clinical trial code number (IRCT20220724055538N1) registered in the Clinical Trial Center of Iran.

Data availability

The dataset generated and analyzed during the current study is available from the corresponding author on reasonable request.

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