Transcranial Direct Current Stimulation to Assist Experienced Pistol Shooters in Gaining Even-Better Performance Scores

Article *in* The Cerebellum · February 2019

DOI: 10.1007/s12311-018-0967-9

5 authors, including:

Ali mohammad Kamali
Shiraz University of Medical Sciences

Mohammad Nami
Shiraz University of Medical Sciences

Seyedeh-Saeedeh Yahyavi

Alireza Mohammadi

The Cerebellum
https://doi.org/10.1007/s12311-018-0967-9

ORIGINAL PAPER

Transcranial Direct Current Stimulation to Assist Experienced Pistol Shooters in Gaining Even-Better Performance Scores

Ali-Mohammad Kamali [1,2,3,4] • Mohammad Nami [1,2,3,6] • Seyedeh-Saeedeh Yahyavi [1,2,3,4] • Zahra Kheradmand Saadi [2,3,5] • Alireza Mohammadi [7]

Abstract
Recently, brain stimulation has been considered as a promising method for the empowerment of athletes' performance. This study recruited 16 pistol shooters who were randomly assigned to two arms, including the control receiving no intervention and the experimental group receiving either sham or real transcranial direct current stimulation (tDCS), i.e., anodal stimulation and cathodal suppression over the cerebellar and dorsolateral prefrontal cortex (dlPFC) regions, respectively. Our outcome measures were the score and latency to shooting, as well as number of errors and task time in the dynamic tremor and mirror-tracing tasks. Our findings suggested that tDCS vs. sham improves the average shooting score in pistol shooters by 2.3% ± 0.65 (mean ± SEM, $p = 0.018$). Furthermore, the bullet hole distance from the Air Pistol Target center was found to be significantly shorter in the experimental (tDCS) group ($p = 0.02$). In the control group, no significant difference was noted between the shooting scores of shooters over the consecutive two sessions. In terms of latency to shooting, no significant difference was noted within groups between both sessions. However, for the dynamic tremor task outcome, there were significantly less errors after real tDCS than after sham stimulation. In addition, the results of the mirror-tracing task in the tDCS group showed significant differences between the sham and real-tDCS sessions favoring the real-tDCS session ($p = 0.001$). Therefore, concurrent suppression of dlPFC and stimulation of cerebellum through tDCS may increase shooting scores in experienced pistol shooters.

Keywords tDCS · Pistol shooters · Cerebellum · dlPFC

Introduction

Motor learning, motor control, and their coding mechanisms in the brain play a critical role in the accuracy of performance in pistol-shooting athletes. Although the number of studies on noninvasive brain stimulation through neuromodulation is increasing, none has investigated the effects of transcranial direct current stimulation (tDCS) as a noninvasive brain stimulation approach on the performance of professional pistol shooters. Brain stimulation through tDCS transfers a weak

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12311-018-0967-9) contains supplementary material, which is available to authorized users.

✉ Alireza Mohammadi
ar.mohammadi@bmsu.ac.ir

1 Department of Neuroscience, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran

2 DANA Brain Health Institute, Iranian Neuroscience Society-Fars Branch, Shiraz, Iran

3 Neuroscience Laboratory, NSL (Brain, Cognition and Behavior), Department of Neuroscience, School of Advanced Medical Sciences and Technologies, Shiraz University of Medical Sciences, Shiraz, Iran

4 Student Research Committee, Shiraz University of Medical Sciences, Shiraz, Iran

5 Department of Foreign Languages and Linguistics, Shiraz University, Shiraz, Iran

6 Academy of Health, Senses Cultural Foundation, Sacramento, CA, USA

7 Neuroscience Research Center, Baqiyatallah University of Medical Sciences, Tehran, Iran

Published online: 23 July 2018

electrical current, which is reported to change the frequency and dynamics of the brain [1]. An emerging body of evidence has reported that tDCS may induce notable changes in cerebellar cortical excitability [2].

Shooting, done through rifle or pistol is a competitive sport in terms of shooting latency, accuracy, and stability. Hand tremors and slight movements, though hard to be recognized, play key roles in shooting results. It has been reported that a deviation of 0.03 degrees in targeting can lead to losing a 5-cm target 10 m away [3]. One of the defining variables to affect shooting results is the intensity of physiological tremor, which is insignificant in individuals. The condition is rarely visible and may be heightened by intense emotion, physical fatigue, hypoglycemia, hyperthyroidism, heavy metal poisoning, stimulants, alcohol withdrawal, or fever [4]. Alcohol is shown to decrease this tremor by influencing the thalamus or cerebellum [5].

Although cerebellar stimulation has received increasing attention recently, the effects of cerebellar stimulation for athletes have not been explored, and it is still unknown whether the anodal stimulation of the cerebellum with all its complex networks involved in motor activity, balance and muscle tones [6], can lead to improved performance in shooters.

The highest density of neurons in the cerebellum across the brain is considered a key feature of this structure [7]. It has been postulated that both motor functions and cognition may benefit from cerebellar stimulation [8]. Furthermore, the cognitive and emotion-related areas of the cortex are known to be affected by cerebellum trough cortico-ponto-cerebellar and cerebello-thalamo-cortical networks [9]. In other words, the cerebello-cerebro-cerebellar connections are reciprocally connecting the cerebellum with the cerebrum through the thalamus (cerebello-thalamo-cortical) and vice versa through the pons (cortico-ponto-cerebellar) [10, 11].

It is speculated that anodal stimulation of the cerebellum can decrease tremor in patients suffering from ataxia [12]. As reported by Galea et al., anodal tDCS over the cerebellum potentially results in less errors and faster adaptation to the visuomotor transformation [13]. Moreover, anodal cerebellar tDCS can enhance implicit learning, which is of high importance in the acquisition of motor and cognitive skills [14].

In support of the effectiveness of stimulation, a study showed that cerebellar tDCS can improve cerebellum-dependent locomotor learning [15]. Generally, anodal cerebellar tDCS may potentially result in enhanced cognitive and motor functions, while cathodal tDCS inhibits the same [13, 16, 17]. On the other hand, studies have shown that cathodal tDCS over the left dorsolateral prefrontal cortex (dlPFC) can increase scores in the golf putting task [18]. Likely, cathodal tDCS over the left dlPFC would inhibit verbal working memory, which would result in reduction in verbal-analytical functions supporting the implicit motor learning control [18]. It should be noted that tDCS primarily impacts the excitability of the neurons and only impacts the neuronal firing frequency by increasing the synchronization in already existing networks [19].

As already outlined, the cerebellum plays a key role in motor coordination and balance, which are central functions in the case of shooting [20]. The existing evidence on modulating the cerebellum and dlPFC with consequent effects on motor learning and physiological tremor [16, 18] prompted us to hypothesize that the concurrent anodal cerebellar and cathodal dlPFC tDCS would enhance the performance of experienced pistol shooters.

Method

Participants

Through announcement in various shooting clubs in Fars province, 17 right-handed participants (9 males, 8 females; aging 26 to 33 years, with 2 to 3 years of experience in pistol shooting) were included in the study; however, one of them (1 male) did not receive intervention due to hand injury. Demographic information of the participants is demonstrated in Table 1.

Handedness was documented in our demographic questionnaire based on the subjects' self-report. This study was approved by the Ethics Committee of Baghiatallah University of Medical Sciences (proposal code: 96-06-001639). Informed written consent was obtained from the participants for the research procedure. All participants were healthy individuals with no history of neurocognitive disorders, doping, or alcohol and drug use. Subjects were asked to ensure enough sleep the nights before the tests and refrain from drinking tea, coffee, or any type of energy drinks on the day of experiment.

Data were acquired over two sessions with the interval of 48 h. During the interval, participants had no shooting training. The participants whose fatigue severity based on the visual analogue scale (VAS) [a continuous single-item fatigue scale ranging from 0 (no fatigue) to 10 (severe fatigue)] was below 2.5 could take part in the study; otherwise, the experiment session had to be rescheduled. Participants were randomly assigned to two parallel arms, i.e., an experimental group and a control group. The experimental group, also known as the tDCS group, received either sham or real tDCS in two different sessions. The control group received no intervention during the two study sessions.

Experimental Design

Through a double-blinded, controlled randomized investigation, the tDCS group received 2 mA of sham and real tDCS for 20 min in sessions 1 and 2, respectively. After tDCS, the participants fired ten shots as shooting tasks, then performed

Table 1 Demographic information of participants

	tDCS group ($n = 8$)	Control group ($n = 8$)
Male/female	4/4	4/4
Mean age in years	28.3 ± 2.5	29.5 ± 3.5
Mean years of training in shooting	2.3 ± 0.4	2.6 ± 0.5
Mean years of formal education	16 ± 2	15 ± 3

the mirror-tracing and dynamic tremor task (also known as vertical upside down V) with the intervals of 3-min rest after each experiment. In the control group, athletes received no intervention, and instead of stimulation, rested for 20 min with the same position as the tDCS group, and then followed the same procedure as the tDCS group individuals regarding the quality of tasks and rest. The study design is illustrated in Fig. 1.

There were two issues to address, i.e., the carry-on learning effect, which might have possibly enhanced the shooting score and the sham effect of the tDCS intervention. To clarify the first issue, a separate control arm was added, and for the second issue, data from the sham and true tDCS were comparatively analyzed. As such, the experiment sessions were minimized to two in each group without baseline assessment in tDCS arm.

tDCS

In this study, a tDCS device (TCT Research Limited, Hong Kong) was used to transfer a 2-mA electrical current for 20 min, following 30 s of ramp-up and 30 s of ramp-down. The anode electrode (35 cm^2) was placed over the right cerebellar area (CB2), 1 and 3 cm below and lateral to the inion, respectively [21, 22]. The cathode electrode (16 cm^2) [21] was placed over the left dlPFC (Fig. 2). The saline-soaked sponges (NaCl 150 mM) were placed underneath the electrodes over the scalp.

In the sham-tDCS session, electrical current was delivered for 30 s to induce a stimulation sensation. Right after the initial ramp-up, the current was switched off (despite the countdown running and the indicator light on the device screen throughout the session) for 20 min. In the real-tDCS session, the electrical current was delivered for 20 min. No stimulation was delivered to the control group during these two sessions.

Shooting Task

While standing, the pistol shooters had ten shots to the Air Pistol Target (4.5-mm caliber Air Pistol) placed 10 m down the route. Each of the participant's scores were recorded based on the International Shooting Sport Federation (Available from: ISSF—http://www.issf-sports.org/) criteria. In addition, the distance between each shot and the Air Pistol Target center was measured carefully using the ImageJ software [23]. In order to keep the shooting time, the duration of each participant's ten shots was recorded (shooting latency), and the maximum allowed time for ten shots was 12 min and 30 s (Fig. 3). The distance between the shooter's location on the fire line and the target's center was 10 ± 1 m. The shooting room had enough and adequate light with the controlled condition remained constant for all participants.

In order to specify shooting scores accurately, the scores were recorded based on the International Shooting Sport Federation criteria, and each shot's distance from the Air Pistol Target center was recorded through the ImageJ software. To rule out the effect of training per se on shooters' performance, data were obtained from the control group.

Mirror-tracing Task

A mirror-tracing task is a visual and motor task applied for learning different motor skills [24]. The mirror-tracing task was submitted to all subjects using the apparatus developed by Sina Psychology, Tehran, Iran. The subjects were required to move a metal-tip pencil with the right hand to trace the diagram of a star while looking at the reflection of the star in a mirror. The metal-tip pencil was attached to a digital timer and error recorder, which recorded the task time and the number of errors if the pencil tip touched the star borders or come out of the star pattern. The distance between each two lines of the star is 6 mm.

Before performing the task, the participants were trained how to do the task and were required to trace the pattern quickly and carefully. Task time and the number of errors as indicators of motor learning were recorded. This task was performed three times, and the task time plus number of errors were recorded [24].

Dynamic Tremor Task

The main purpose of this test is to evaluate skill and coordination [25]. The device (Sina psychology, Tehran, Iran) consisted of a vertical upside down metal "V" and a metal pin. Each arm of the metal "v" is 22 cm, and the distance between the two arms at the narrow and wide ends are 2 and 12 mm, respectively. The metal pin was connected electrically to the metal "v," through which the device could record every contact of the pin with the metal "v" as an error. With the same posture as shooting, (fully extended arms), participants grasped the pin and moved it through the metal "v" trying not to touch the edges of "v" (Instrument L. Hole Type Steadiness Tester 2009. Available from: www.lafayetteinstrument.com) [26]. Similar to the mirror-tracing task, a metal-tip pencil was attached to a digital timer and error

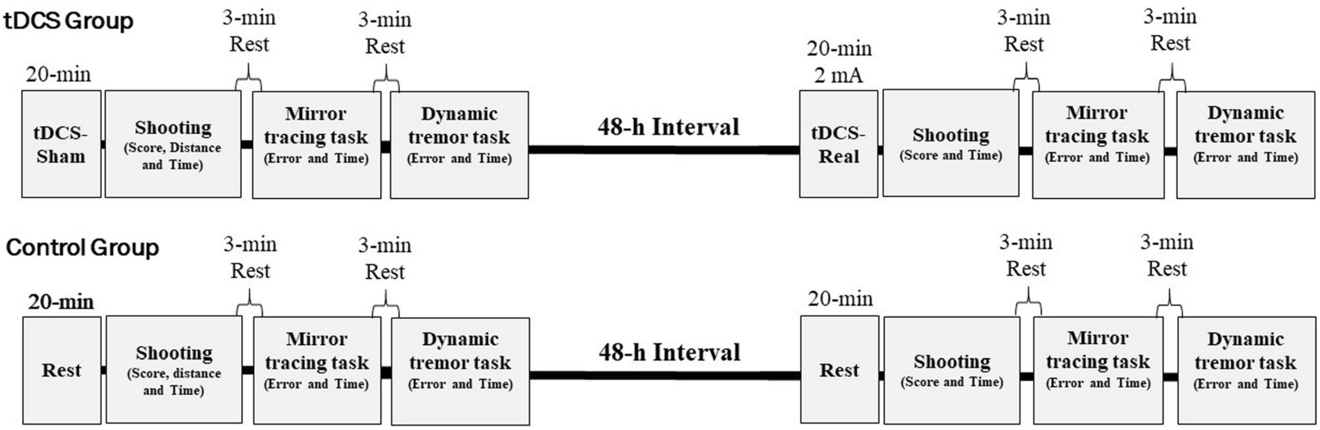

Fig. 1 The study's procedures for the tDCS and control groups. The tDCS group received sham tDCS for 20 min in the first session. Then, they performed shooting tasks for which the time of shooting and the bullet hole distance from the Air Pistol Target were recorded. With the intervals of 3-min rest, the mirror-tracing task and dynamic tremor task were performed and the task times and the number of errors were recorded. After 48 h, the tDCS group received real tDCS for 20 min in session two, and the rest of the procedure was similar to the first session. The control group received no brain stimulation, and instead rested for 20 min with similar position of the tDCS group. Later, they followed the same procedure as in the tDCS group

recorder, which recorded the task time and the number of errors if the pencil tip touched the borders.

Before performing the task, the participants received training on the task performance. This task was performed three times, and the task time plus number of errors were recorded [25].

Data Analysis

A CONSORT (Moher) diagram was applied to summarize the flow of participants and the rates of eligibility, allocation,

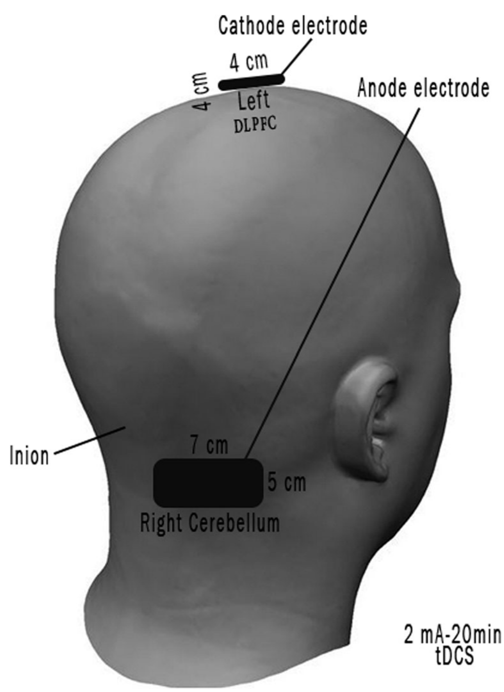

Fig. 2 TDCS montages for shooters. Two milliamperes of cathodal tDCS in the left DLPFC (F3) and anodal tDCS in the right cerebellum (CB2) for 20 min. Electrodes' size is described in the figure

follow-up, and analysis through the research (Supplementary Fig. 1). To analyze the differences between sessions 1 and 2, a series of paired sample t tests were run for the data possessing normality of distribution and homogeneity of variance. The differences between the sham- and real-tDCS sessions were evaluated based on the mean ± SEM (standard error of mean), for a set of parameters, including 1—performance score and time in shooting task, 2—number of errors and task time in the mirror-tracing task, and 3—number of errors and task time in the dynamic tremor task.

The p values below 0.05 were considered statistically significant. For the data lacking normal distribution, Wilcoxon test was applied. Similar to the t tests, the p value was set at 0.05. The SPSS statistical package (Version 22.0.0, Copyright©IBM, 2015) was used for data analyses.

Results

As described in the method section, each and every subject underwent a VAS assessment for possible fatigue before each experiment session was initiated. In case of the VAS score of more than 2.5, the session had to be rescheduled. Rescheduling the experiment session due to fatigue happened in only two instances. The subsequent session was scheduled for 48 h later as per our study protocol.

Scores, Bullet Hole Distance from Air Pistol Target Center and Shooting Latency

According to the findings, there was a statistically significant difference between the tDCS group's performance in sessions 1 (sham) and 2 (real). The real tDCS vs. sham could improve mean scores by 2.3% ± 0.65 (mean ± SEM, $p = 0.018$)

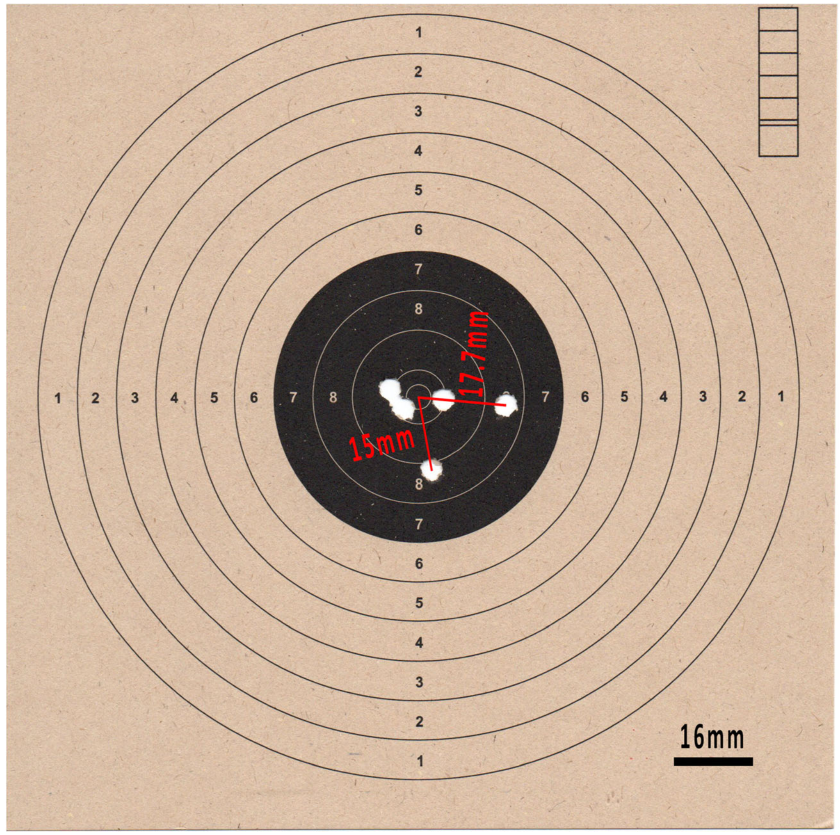

Fig. 3 Representation of each shooter's five shots to the Air Pistol Target and the distance between bullet hole and Air Pistol Target center measured by the ImageJ software

(Fig. 4). Moreover, the average distance of each shooter's ten bullet holes from the Air Pistol Target center in the tDCS group revealed a significant difference ($p = 0.02$). However, brain stimulation did not significantly affect shooting time (latency) in the tDCS group ($p = 0.23$). With respect to the control group, there were no significant differences between shooting scores ($p = 0.65$) and latency ($p = 0.95$) in sessions 1 and 2 (Fig. 4).

Mirror-tracing Task (Motor Learning)

Regarding the mirror-tracing task applied for motor learning assessment, there was no significant difference in terms of number of errors in the control group, while the results in the tDCS group showed significant differences between the sham- and real-tDCS sessions ($p = 0.001$). In addition, statistically significant differences in the task time for both tDCS ($p = 0.008$) and control ($p = 0.01$) groups are shown (Fig. 5).

Physiological Tremor

The results of the dynamic tremor task used for physiological tremor evaluation showed a significantly decreased number of errors in the real- vs. sham-tDCS sessions ($p = 0.03$), suggesting decreased physiological tremor following brain stimulation. There was however no significant difference in the task time. Neither the number of errors nor the task time were statistically different in the control group upon sessions 1 and 2 (Fig. 6).

Discussion

Brain stimulation in shooters is a new trend ultimately aiming to modulate neurofunctional networks to improve shooters' performance. Although tDCS stimulates the cortex under the electrodes, it can affect underlying subcortical areas through synaptic relationships between neurons [27]. To our best knowledge, no study has yet addressed the effects of tDCS in shooters. Most of the tDCS studies done on athletes have assessed their endurance [28, 29]. To investigate the effects of brain stimulation on the performance of pistol shooters, this study applied anodal and cathodal tDCS over right cerebellum and left dlPFC, respectively.

The findings revealed that simultaneous dlPFC inhibition and cerebellum excitation resulted in an improved mean shooting score in experienced pistol shooters by 2.3%. Nevertheless, no significant effect was documented for the average shooting time (latency). Furthermore, tDCS decreased the number of errors in the dynamic tremor task as well as the mirror-tracing task, probably supporting the relationship between the potentially decreased physiological

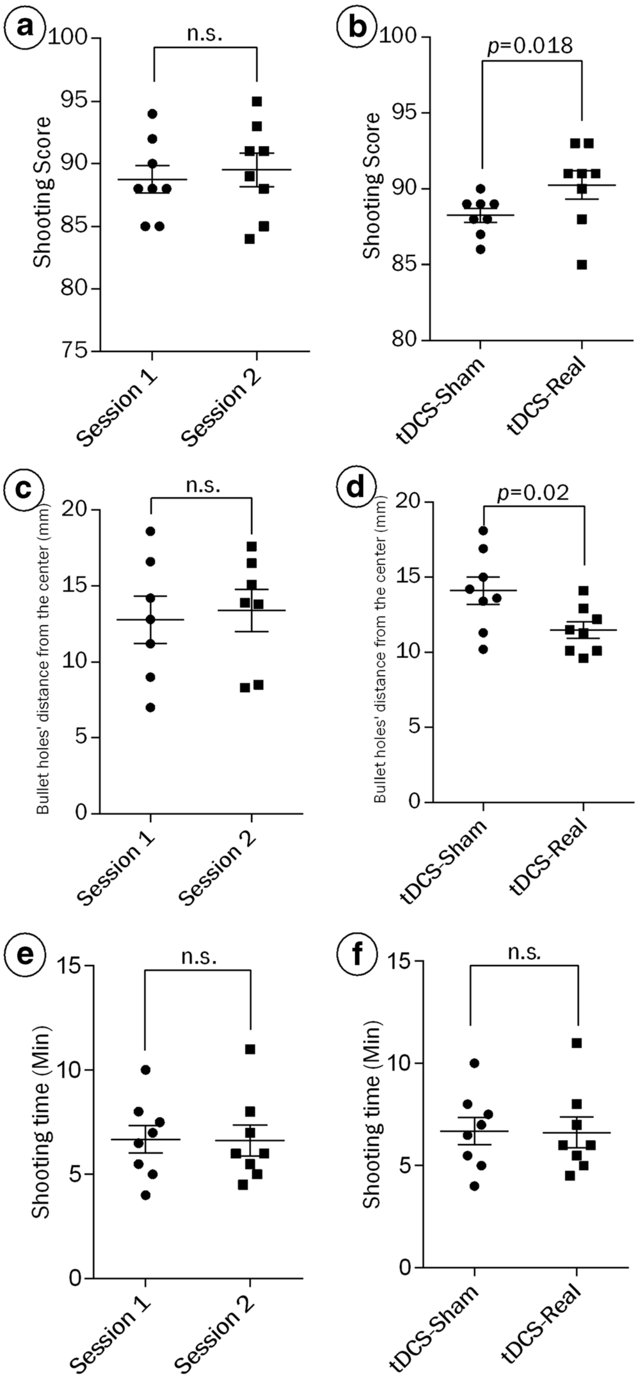

Fig. 4 Dot plots illustrating the average of each shooter's ten shots in terms of score, distance from Air Pistol Target center, and shooting latency in the control and tDCS groups in two shooting sessions with the interval of 48 h. Panel **a** indicates no significant difference between the control group's two shooting scores in two sessions ($p < 0.05$). Panel **b** shows that TDCS resulted in significant differences between the tDCS group's two shooting scores in two sessions ($p < 0.05$). Panel **c** illustrates no significant difference between each individual's ten shots average bullet hole distance from the Air Pistol Target center in the control group in two sessions ($p < 0.05$). Panel **d** shows a significant difference between each individual's tenshot average bullet hole distance from the Air Pistol Target center in the tDCS group in sessions 1 and 2 ($p < 0.05$). Panels **e**, **f** demonstrate that shooting latency was insignificant both in the control and tDCS groups ($p < 0.05$). The lines over each dot plot represent mean ± SEM. The statistical test applied was paired *t* test. To analyze the data lacking normal distribution, Wilcoxon test was employed. The *p* values below 0.05 were considered statistically significant. n. s., non-significant

tremor and enhancement in shooting performance. As such, we have documented that increased motor learning might have affected shooting scores.

It has already been shown that dlPFC inhibition can suppress verbal working memory resulting in a decreased explicit verbal-analytical motor learning and increased implicit motor learning [18]. Additionally, reports have demonstrated the enhancement of motor and cognitive performance following anodal cerebellar tDCS [14]. The tDCS-induced improvement of muscle-nerve coordination in patients suffering from ataxia also warrants the role of anodal cerebellar tDCS in improving motor performance [12].

The cerebellum plays an important role in balance and motor coordination [30]. Our findings suggest that in addition to increasing the mean shooting score, tDCS may significantly improve physiological tremor and nerve-muscle coordination.

According to the results, significant differences between sessions 1 and 2 were seen for the task time in the mirror-tracing tasks in the tDCS group. In the control group, there was no significant difference between sessions 1 and 2 in terms of the number of errors, while, the shooting latency showed a significant difference.

The decreased number of errors in the mirror-tracing task was congruent with an improved shooting performance score in the tDCS group (from session 1 to session 2). However, this was not observed in the control arm. Results revealed no significant difference between their scores in two sessions indicating that one session had no effect on their performance. The time spent on the mirror-tracing task decreased also in the control group; thus, the explanation cannot be sought in the effects of tDCS.

Our findings were in accordance with the studies, which reported the effectiveness of tDCS on peak power of trained cyclists [29] and threat detection of athletes in simulated combat situations [31]. Moreover, in line with [32], our study showed that tDCS can enhance motor learning and performance in athletes. On the other hand, anodal dlPFC turned out to be effective in improving cognitive and behavioral [33] performance of athletes. However, our results could not be compared with these studies, since our study did not evaluate the effects of cathodal dlPFC tDCS on cognition and behavior.

This study might have paved the path towards designing brain stimulation protocols in shooters. The present results may appeal to the interest of strategists in military forces, Olympics, and world championships. While this study examined the effects of dlPFC inhibition and cerebellum excitation,

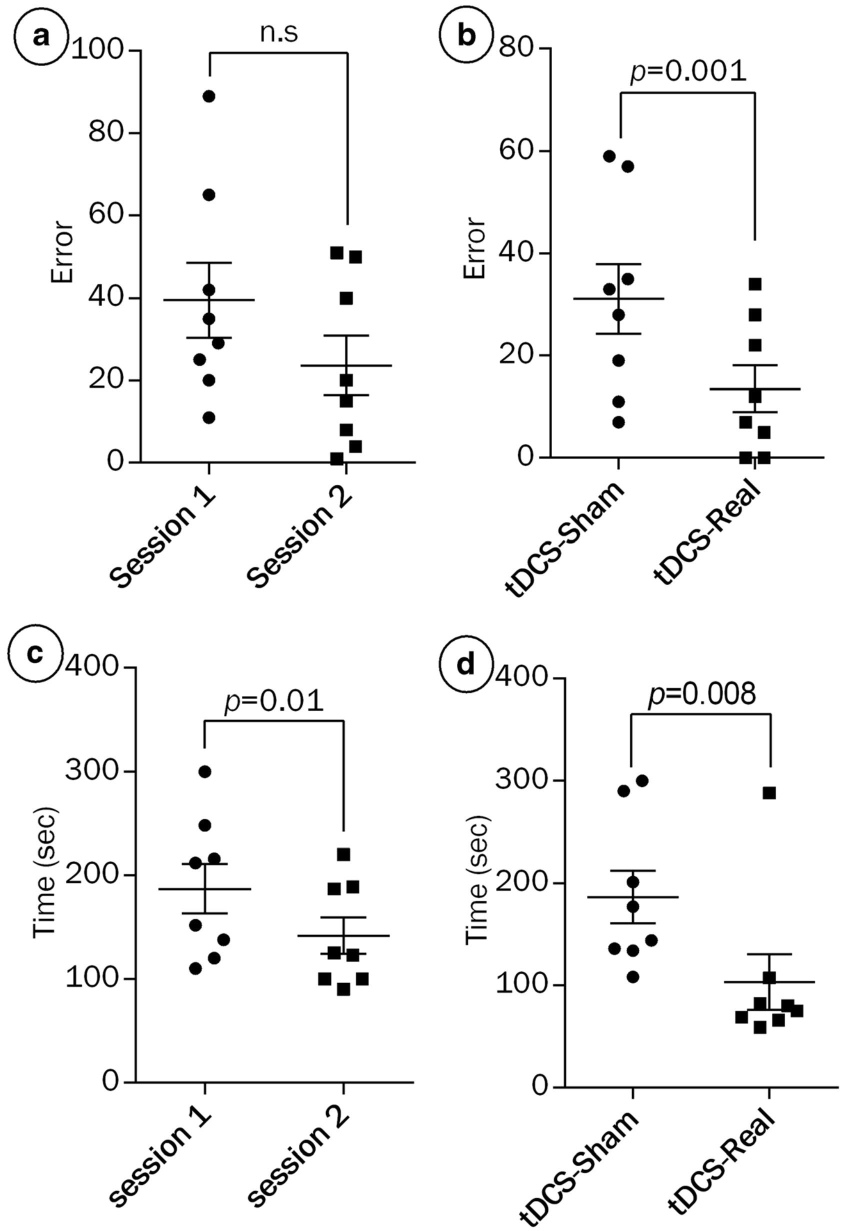

Fig. 5 Dot plots demonstrating the average of each shooter's task time and number of errors in the mirror-tracing task in two sessions with the interval of 48 h in the tDCS and control groups. Panel **a** indicates no significant difference between the number of errors in sessions 1 and 2 in the control group ($p < 0.05$). Panel **b** demonstrates the tDCS' significant effect on the number of errors in two sessions in the tDCS vs. sham group ($p < 0.05$). Panels **c**, **d** show significant difference between the latency to task performance between the tDCS and control groups ($p < 0.05$). The lines over each dot plot represent mean ± SEM. The statistical test used was paired *t* test. For the data lacking normal distribution, Wilcoxon test was employed. The *p* values below 0.05 are considered statistically significant

more investigations need to be done to address each area separately to optimize the stimulation parameters.

Though the current investigation studied pistol shooters, other research may address the effects of stimulation on other types of shooting, such as rifle shooting, shotgun shooting, and running target shooting. Moreover, the effects of stimulation on novice shooters can be another line of research.

The present research was subject to some shortcomings, including a limited sample size. In addition, instruments to assess muscular activity and oxygen usage could be of help in future research. Also, the quantitative electroencephalography (qEEG) included study may yield a more comprehensive understanding on the effects of tDCS in cortical networks and brain functional connectivity and cortical level.

Based on the existing evidence that cathodal suppression of the dlPFC has improved motor control and game performance in golf players [18], and anodal stimulation of the cerebellum has improved the upper limb tremor [12]; this study hypothesized that the concurrent anodal and cathodal stimulation and suppression of dlPFC and the cerebellum, respectively, may result in an additive or synergistic effect.

There is a possibility to observe any parallel untoward effects when applying tDCS. Meanwhile, the focus of this study was to measure the motor control capacity in professional shooters following tDCS intervention. To arrive at the very best protocol in terms of the efficacy and long-term safety to even possibly apply this to shooters in real practice, further investigations need to be pursued.

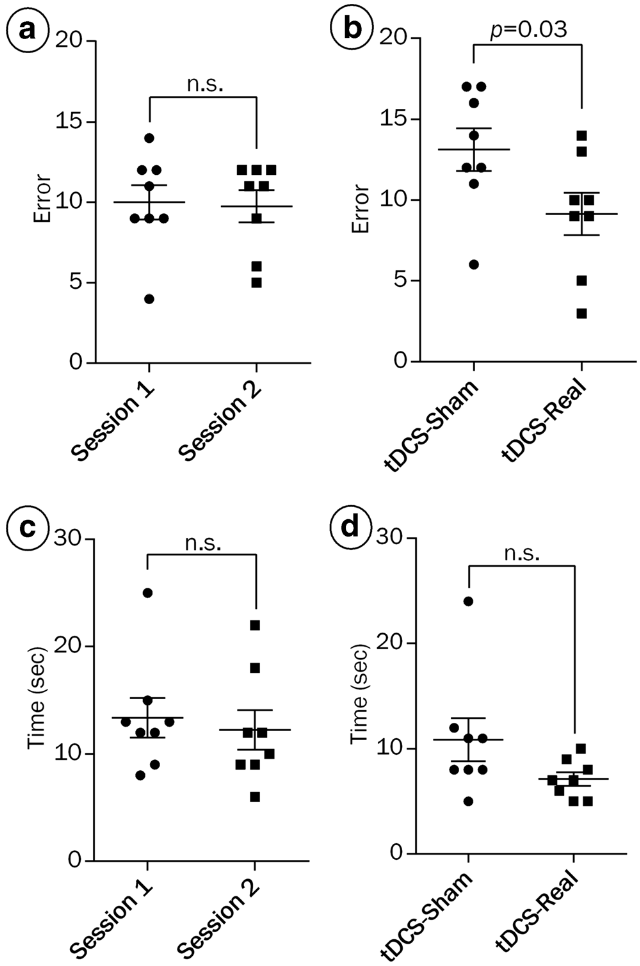

Fig. 6 Dot plots representing the average of each shooter's task time and number of errors in the dynamic tremor task in two sessions with the interval of 48 h in the tDCS and control groups. Panel **a** indicates no significant difference between the number of errors in sessions 1 and 2 in the control group ($p < 0.05$). Panel **b** shows a significant difference between the number of errors in sessions 1 and 2 in the tDCS group ($p < 0.05$). Panels **c**, **d** show no significant difference in tDCS and control groups ($p < 0.05$). The lines over each dot-plot represent mean ± SEM. The statistical test used was paired t test. For the data lacking normal distribution, Wilcoxon test was employed. The p values below 0.05 were considered statistically significant

Here, we could just demonstrate that our applied tDCS montage resulted in a significant change in pistol shooters' performance. The question whether at what level each approach (i.e., the dlPFC cathodal suppression or cerebellar anodal stimulation alone or in combination) leaves a differential impact needs to be investigated in further randomized studies.

Conclusion

Taken together, it can be stated that the concurrent right cerebellar and left dlPFC tDCS (anodal and cathodal, respectively) may increase the mean shooting scores potentially in relation to the decreased physiological tremor. Such an impact has also been in relation to increased motor learning reflected in decreased number of errors in the mirror-tracing task.

Funding Information This work was supported by the grant received from DANA Brain Health Institute; Iranian Neuroscience Society, Fars Chapter, Shiraz, Iran.

Compliance with Ethical Standards

This study was approved by the Ethics Committee of Baghiatallah University of Medical Sciences (proposal code: 96-06-001639).

Conflict of Interest The authors declare that they have no conflict of interest.

Statement of Informed Consent Informed written consent was obtained from the participants for the research procedure.

References

1. Dayan E, Censor N, Buch ER, Sandrini M, Cohen LG. Noninvasive brain stimulation: from physiology to network dynamics and back. Nat Neurosci. 2013;16(7):838–44.
2. Ferrucci R, Cortese F, Priori A. Cerebellar tDCS: how to do it. Cerebellum. 2015;14(1):27–30.
3. Lakie M. The influence of muscle tremor on shooting performance. Exp Physiol. 2010;95(3):441–50.
4. Elble, R.J., *Tremor*, in *Neuro-Geriatrics*. 2017, Springer. p. 311–326.
5. Boecker H, Wills AJ, Ceballos-Baumann A, Samuel M, Thompson PD, Findley LJ, et al. The effect of ethanol on alcohol-responsive essential tremor: a positron emission tomography study. Ann Neurol. 1996;39(5):650–8.
6. Llinàs R, Negrello MN. Cerebellum. Scholarpedia. 2015;10(1):4606.
7. Herculano-Houzel S. The human brain in numbers: a linearly scaled-up primate brain. Front Hum Neurosci. 2009;3:31.
8. Buckner RL. The cerebellum and cognitive function: 25 years of insight from anatomy and neuroimaging. Neuron. 2013;80(3):807–15.
9. Phillips JR, et al. The cerebellum and psychiatric disorders. Front Public Health. 2015;3:66.
10. Tröster A, et al. Neuropsychological deficits in essential tremor: an expression of cerebello-thalamo-cortical pathophysiology? Eur J Neurol. 2002;9(2):143–51.
11. Brodal, P. and J.G. Bjaalie, Salient anatomic features of the cortico-ponto-cerebellar pathway in *Progress in brain research*. 1997, Elsevier. p. 227–249.
12. Grimaldi G, et al. Marked reduction of cerebellar deficits in upper limbs following transcranial cerebello-cerebral DC stimulation: tremor reduction and re-programming of the timing of antagonist commands. Front Syst Neurosci. 2014;8:9.
13. Galea JM, Vazquez A, Pasricha N, de Xivry JJ, Celnik P. Dissociating the roles of the cerebellum and motor cortex during adaptive learning: the motor cortex retains what the cerebellum learns. Cereb Cortex. 2010;21(8):1761–70.
14. Ferrucci R, Brunoni AR, Parazzini M, Vergari M, Rossi E, Fumagalli M, et al. Modulating human procedural learning by cerebellar transcranial direct current stimulation. Cerebellum. 2013;12(4):485–92.

15. Jayaram G, Tang B, Pallegadda R, Vasudevan EVL, Celnik P, Bastian A. Modulating locomotor adaptation with cerebellar stimulation. J Neurophysiol. 2012;107(11):2950–7.
16. Shah B, Nguyen TT, Madhavan S. Polarity independent effects of cerebellar tDCS on short term ankle visuomotor learning. Brain Stimulation: Basic, Translational, and Clinical Research in Neuromodulation. 2013;6(6):966–8.
17. Bradnam LV, et al. Anodal transcranial direct current stimulation to the cerebellum improves handwriting and cyclic drawing kinematics in focal hand dystonia. Front Hum Neurosci. 2015;9:286.
18. Zhu FF, Yeung AY, Poolton JM, Lee TMC, Leung GKK, Masters RSW. Cathodal transcranial direct current stimulation over left dorsolateral prefrontal cortex area promotes implicit motor learning in a golf putting task. Brain Stimulation: Basic, Translational, and Clinical Research in Neuromodulation. 2015;8(4):784–6.
19. Nitsche MA, Paulus W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J Physiol. 2000;527(3):633–9.
20. Paulin MG. The role of the cerebellum in motor control and perception. Brain Behav Evol. 1993;41(1):39–50.
21. Nitsche MA, Cohen LG, Wassermann EM, Priori A, Lang N, Antal A, et al. Transcranial direct current stimulation: state of the art 2008. Brain Stimulation: Basic, Translational, and Clinical Research in Neuromodulation. 2008;1(3):206–23.
22. Steiner KM, Enders A, Thier W, Batsikadze G, Ludolph N, Ilg W, et al. Cerebellar tDCS does not improve learning in a complex whole body dynamic balance task in young healthy subjects. PLoS One. 2016;11(9):e0163598.
23. Schneider CA, Rasband WS, Eliceiri KW. NIH Image to ImageJ: 25 years of image analysis. Nat Methods. 2012;9(7):671–5.
24. Julius MS, Adi-Japha E. A developmental perspective in learning the mirror-drawing task. Front Hum Neurosci. 2016;10:83.
25. Laporte W. The influence of a gymnastic pause upon recovery following post office work. Ergonomics. 1966;9(6):501–6.
26. Louis ED, Yousefzadeh E, Barnes LF, Yu Q, Pullman SL, Wendt KJ. Validation of a portable instrument for assessing tremor severity in epidemiologic field studies. Mov Disord. 2000;15(1):95–102.
27. Keeser D, Meindl T, Bor J, Palm U, Pogarell O, Mulert C, et al. Prefrontal transcranial direct current stimulation changes connectivity of resting-state networks during fMRI. J Neurosci. 2011;31(43):15284–93.
28. Vitor-Costa M, Okuno NM, Bortolotti H, Bertollo M, Boggio PS, Fregni F, et al. Improving cycling performance: transcranial direct current stimulation increases time to exhaustion in cycling. PLoS One. 2015;10(12):e0144916.
29. Okano, A.H., et al., Brain stimulation modulates the autonomic nervous system, rating of perceived exertion and performance during maximal exercise. Br J Sports Med, 2013 p. bjsports-2012-091658.
30. Morton SM, Bastian AJ. Cerebellar control of balance and locomotion. Neuroscientist. 2004;10(3):247–59.
31. Clark VP, Coffman BA, Mayer AR, Weisend MP, Lane TDR, Calhoun VD, et al. TDCS guided using fMRI significantly accelerates learning to identify concealed objects. Neuroimage. 2012;59(1):117–28.
32. Reis J, Schambra HM, Cohen LG, Buch ER, Fritsch B, Zarahn E, et al. Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation. Proc Natl Acad Sci. 2009;106(5):1590–5.
33. Borducchi DM, et al. Transcranial direct current stimulation effects on athletes' cognitive performance: an exploratory proof of concept trial. Front Psychol. 2016;7:183.