EFFECTS OF FOUR WEEKS OF HIGH-DEFINITION TRANSCRANIAL DIRECT CURRENT STIMULATION AND FOOT CORE EXERCISE ON FOOT SENSORIMOTOR FUNCTION

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Objective: This study aimed to examine the effects of four weeks of high-definition transcranial direct current stimulation (HD-tDCS) and foot core exercise (FCE) on the foot sensorimotor function (i.e., toe flexor strength and passive ankle kinesthesia). Methods: Thirty-six participants were randomly assigned into three groups: HD-tDCS, FCE, and control group. A total of 12 training sessions was performed over 4 weeks (i.e., three sessions per week) in the laboratory. The participants in the HD-tDCS group performed HD-tDCS and the FCE group completed short foot exercise, towel curls, toe spread and squeeze, and balance board training. Foot muscle strength and passive ankle kinesthesia were assessed at baseline and post-intervention. Results: Compared with the control group, HD-tDCS induced a greater decrease in percent change in the passive kinesthesia thresholds of dorsiflexion (−9.32%), inversion (−25.15%), and eversion (−21.46%). A significantly higher increase in percent change in metatarsophalangeal joint flexor strength was existed in HD-tDCS group (13.77%) and a significantly greater increase in percent change in toe flexor strength was observed in the FCE group (13.13%). Conclusion: Four weeks of high-definition transcranial direct current stimulation (HD-tDCS) can improve foot sensorimotor function and foot core exercise can only strengthen toe flexor muscles.

KEYWORDS: high-definition transcranial direct current stimulation, foot core exercise, foot sensorimotor function.

INTRODUCTION: The foot core system consists of a complex foot structure, including active, passive, and neural subsystems, which provides stability and flexibility to cope with changing foot demands(McKeon et al., 2015). The diminished sensorimotor function of the foot and ankle has been linked to poor functional performance and is also associated with loading-related injuries(Ridge et al., 2019). Thus, it is critical to strengthen the foot sensorimotor function to address the foot-related conditions.
The main method of strengthening the foot core system is foot core exercise (FCE), which is traditionally described as intrinsic foot muscle flexion exercises such as towel curls, toe-spread-out exercises, and short foot exercise. The previous studies demonstrated that foot core exercise can improve ankle-foot functional performance by certainly activating the plantar intrinsic muscles (Mulligan and Cook, 2013; Hashimoto and Sakuraba, 2014).
Currently, transcranial direct current stimulation (tDCS) induced a weak electric direct current applied to the scalp to modulate cortical excitability to improve physical performance (Nitsche and Paulus, 2001). Our previous systematic review has shown that tDCS can ultimately influence the neural circuitry responsible for the neuromechanical regulation of the foot and ankle and then improve their muscle strength and somatosensory function (Xiao et al., 2020). As with other physical training, such positive effects induced by tDCS may be accumulated in multiple-session interventions to improve performance by re-shaping neuroplasticity(Nitsche et al., 2005), especially HD-tDCS. However, this issue has not yet been examined.
Therefore, the purpose of this study was to examine the effects of FCE and HD-tDCS on foot sensorimotor function. It was hypothesized that four weeks of FCE and HD-tDCS intervention would both result in greater foot muscle strength and somatosensory function compared with the control group.

METHODS: Thirty-six healthy young adults without the habit of regular exercise were recruited from a university community via advertisements and randomly assigned to three groups (Table

1) using a Microsoft Excel random number table. The inclusion criteria were as follows: the ability to stand or walk without any personal assistance and no history of lower extremity injuries in the past 6 months. The exclusion criteria were as follows: skin allergies, any contraindications to the use of tDCS (e.g., metal-implanted devices in the brain), and participation in tDCS or FCE training program.

Table 1. Participant demographics

Groups	Year (yrs)	Height (cm)	Weight (kg)
HD-tDCS group (*n* = 12)	21.9 ± 2.1	174.9 ± 6.1	69.8 ± 7.6
FCE group (*n* = 12)	22.7 ± 2.0	173.5 ± 7.1	69.3 ± 13.1
Control group (*n* = 12)	23.5 ± 1.5	177.5 ± 6.1	75.2 ± 7.1
p	0.135	0.272	0.256

A total of 12 training sessions was performed over 4 weeks (i.e., three sessions per week) in the laboratory. Foot muscle strength and passive ankle kinesthesia were assessed at baseline and post-intervention. The participants in the HD-tDCS group performed a 4 × 1 ring-type HD-tDCS with a current intensity of 2 mA for 20 minutes. The anode electrode was placed over the Cz and was surrounded by four return electrodes (i.e., C3, C4, Fz, and Pz) on based on 10/20 electroencephalogram (EEG) brain templates. For the FCE group, the training in this study consisted of short foot exercise, towel curls, toe spread and squeeze, and balance board training, with a goal to strengthen intrinsic and extrinsic foot muscles and the functionalities of the foot and ankle. Participants in the control group did not receive any intervention.
The passive kinesthesia threshold of the ankle joint was assessed using an ankle proprioception tester (KP-11, Toshimi, Shandong, China) (Sun et al., 2015). Specifically, each participant sat on an adjustable seat with eyes closed, and the dominant foot was placed on the bottom of the foot pedal. The platform was randomly activated to drive the participant's ankle in plantarflexion, dorsiflexion, inversion, and eversion. After the trigger and the direction of foot movement were confirmed, the participants pressed the stop button immediately. The research personnel then recorded the angular displacement (i.e., the passive kinesthesia thresholds of the ankle joint). Metatarsophalangeal joint (MPJ) flexor strength was measured using an MPJ flexor strength testing system customized and validated by the team (Zhang et al., 2019; Xiao et al., 2020). Toe flexor strength was measured in a sitting position by using a toe grip dynamometer (T.K.K.3361, Niigata, Japan).
We calculated training effects for percent change from baseline to post-intervention during the groups. SPSS 22.0 (SPSS Inc., Chicago, IL, USA) was used to complete the statistical analysis. Shapiro–Wilk test was used to examine if the outcomes were normally distributed and Levene's test was used to check homoscedasticity. For normal distributed and homoscedastic data, a one-way ANOVA was used to examine if percent changes in each outcome between baseline to post-intervention were significantly different among groups and a Bonferroni post-hoc test was performed for further multiple comparisons. However, if the outcomes were not normally distributed, therefore non-parametric test (Kruskal-Wallis test) was implemented and Dunn's multiple comparison test was the post-hoc test. The significance level was set to $p < 0.05$ for all the analyses.

RESULTS: The ANOVA showed a significant difference in the percent changes in the passive kinesthesia thresholds of dorsiflexion ($F_{(2, 33)} = 3.634$, $p = 0.037$, $\eta_p^2 = 0.181$) and inversion ($F_{(2, 33)} = 12.197$, $p < 0.001$, $\eta_p^2 = 0.425$). Also, a significant difference was observed for the percent changes in the passive kinesthesia threshold of eversion (H = 7.788, $p = 0.020$). Post-hoc tests showed that compared with FCE group, a greater decrease in the percent change in the passive kinesthesia threshold of dorsiflexion in HD-tDCS group was observed (t = 2.522, $p = 0.050$, Cohen's $d = 0.965$). HD-tDCS induced a greater decrease in percent change in the passive kinesthesia threshold of inversion compared with FCE (t = 3.519, $p = 0.004$, Cohen's $d = 1.30$) and control group (t = 4.761, $p < 0.001$, Cohen's $d = 2.04$). Besides, compared with

the control group, a greater decrease in the percent change in the passive kinesthesia threshold of eversion in HD-tDCS group was observed (p = 0.016, Figure 1).
Significant differences in the percent changes in MPJ flexor strength ($F_{(2, 33)}$ = 4.517, p = 0.018, η_p^2 = 0.215) and toe flexor strength ($F_{(2, 33)}$ = 3.342, p = 0.044, η_p^2 = 0.172) were observed. Post-hoc tests showed that compared with the control group, a significantly higher percent change in MPJ flexor strength was existed in HD-tDCS group (t = 3.143, p = 0.020, Cohen's d = 1.28) and a significantly greater percent change in toe flexor strength was observed in FCE group (t = 2.828, p = 0.040, Cohen's d = 1.16, Figure 1).

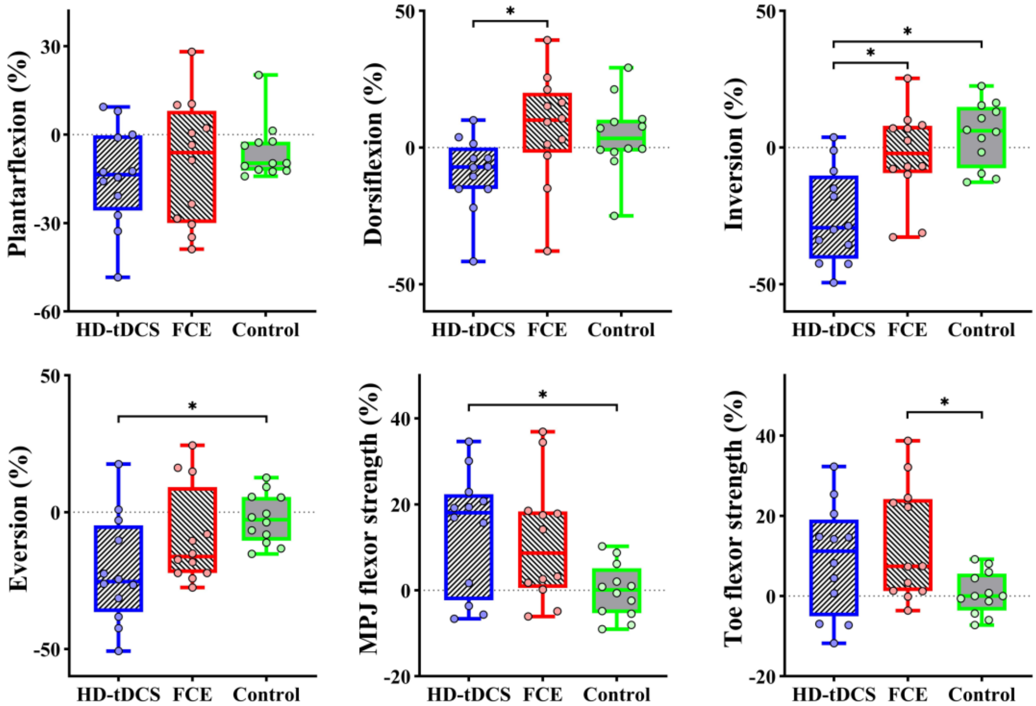

Figure 1: Differences in the percent changes in passive ankle kinesthesia thresholds and foot muscle strength among groups. HD-tDCS: high-definition transcranial direct current stimulation; MPJ: metatarsophalangeal joint; FCE: foot core exercise; *p < 0.05.

DISCUSSION: This study aimed to investigate the effects of FCE and HD-tDCS on foot sensorimotor function (i.e., toe flexor strength and passive ankle kinesthesia). The results showed that compared with FCE and control groups, HD-tDCS could significantly decrease the passive kinesthesia thresholds of ankle dorsiflexion, inversion, and eversion. HD-tDCS improved MPJ flexor strength and FCE enhanced toe flexor strength.
In this study, the results suggested that HD-tDCS could improve the sensory perception of the ankle. The previous study showed that tDCS could decrease the vibrotactile threshold of the foot sole when standing and the tactile threshold of the left center of the distal pulp of the hallux, indicating that tDCS could enhance ankle-foot somatosensory function (Zhou et al., 2018; Yamamoto et al., 2020). Evidence from MRI showed that tDCS increased activation of the left posterior paracentral lobule (including S1) in response to relatively large and easily-perceivable pressure stimuli applied to the right foot sole (Wang et al., 2015). Based upon the above evidence and our results, it contends that HD-tDCS applied over the sensorimotor cortex lowers the ankle passive kinesthesia thresholds by activating the somatosensory cortical network within the brain. However, such a significant decrease in ankle passive kinesthesia was not observed in FCE. A possible factor is that the healthy young adults were recruited in this study, which may exist individual differences due to small sample size.
Consistent with the hypothesis, the results showed that four weeks of HD-tDCS and FCE can enhance intrinsic foot muscle strength. Generally, anodal tDCS alters the resting membrane potential of the targeted neurons to increase cortical excitability and these effects can persist

for up to 1.5 h following about 10 min of conventional tDCS, while about 6 h after receiving more focal HD-tDCS(Kuo et al., 2013). Moreover, this lasting effect induced by a-tDCS may continuously reduce short interval intracortical inhibition (SICI), assisting in the production of voluntary force output by modulating descending the excitatory drive, thereby improving muscle strength(Weier et al., 2012). Different from HD-tDCS, FCE directly acted on strengthening muscles. The specificity of exercise (e.g., short foot exercise, towel curls) included in the FCE protocol likely activate various flexor muscle activity. Towel curls tend to recruit the flexor hallucis and digitorum longus and short foot exercise targets the plantar intrinsic muscles of the foot. Thus, more than four weeks of intrinsic foot muscle strengthening can improve and activate the intrinsic foot muscle (e.g., abductor hallucis, flexor digitorum brevis, and flexor hallucis brevis) (Fraser and Hertel, 2019).

CONCLUSION: Four weeks of high-definition transcranial direct current stimulation (HD-tDCS) can improve foot sensorimotor function and foot core exercise can only strengthen toe flexor muscles.

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