Transcranial Direct Current Stimulation Enhances Muscle Strength of Non-dominant Knee in Healthy Young Males

PanPan Lu

Shenyang Sport University

Nicholas J. Hanson

Western Michigan University

Lin Wen

Graduate School of Biomedical and Health Sciences ,Hiroshima University

Feng Guo (✉ guofeng_first@163.com)

Shenyang Sport University

Research

Keywords: transcranial direct current stimulation, Surface electromyography, Rate of force development, Maximal isometric strength

Posted Date: August 13th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-795153/v1>

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

[Read Full License](#)

Version of Record: A version of this preprint was published at Frontiers in Physiology on December 20th, 2021. See the published version at <https://doi.org/10.3389/fphys.2021.788719>.

Abstract

Background: Transcranial direct current stimulation (tDCS) has been applied in training and competition, but its effects on physical performance remain largely unknown. The present study aimed to observe the effect of tDCS on muscular strength and activation of the knee in healthy subjects.

Methods: Nineteen healthy young males were subjected to 20 min real stimulation (2 mA) and sham stimulation (0 mA) on different days. The maximal voluntary contraction (MVC) of knee extensors and flexors and surface electromyography (sEMG) of the rectus femoris (RF) and biceps femoris (BF) were recorded before, immediately after, and 30 min after stimulation. MVC, rate of force development (RFD), and sEMG activity were analyzed before and after each condition. **Results:** MVC of left leg extensor and flexor was significantly higher immediately after real stimulation and 30 min after stimulation than before, and MVC of left leg flexor was significantly higher 30 min after real stimulation than that after sham stimulation ($P < 0.05$). The RFD of left leg extensor and flexor immediately after real stimulation was significantly higher than before stimulation, and the RFD of left leg extensor immediately after real stimulation and 30 min after stimulation was significantly higher than that of sham stimulation ($P < 0.05$). EMG analysis showed the root mean square amplitude (RMS) and mean power frequency (MPF) of left BF and RF were significantly higher immediately after real stimulation and 30 min after stimulation than before stimulation, and the MPF of left BF EMG was significantly higher 30 min after real stimulation than that after sham stimulation ($P < 0.05$).

Conclusions: Bilateral tDCS of the primary motor cortex can significantly improve the muscle strength and explosive force of the non-dominant knee extensor and flexor, which is manifested by the increase of the amount of motor units recruited during exercise. This effect can last until 30 min after stimulation, but there is no significant effect on the dominant knee.

Introduction

An overarching goal pursued by sport professionals and scientists is to seek safe and effective ways to improve exercise performance for athletes. Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique in that alters cortical excitability via a low-intensity (1-2 mA) direct current applied to the scalp, over various regions of the cerebral cortex [1]. It is generally accepted that anodal tDCS enhances cortical excitability by reducing the resting membrane threshold of cortical neurons, while cathodal tDCS decreases neuronal excitability [2]. Synaptic plasticity in the motor cortex (M1) is associated with muscular strength and can be modified by tDCS. Some studies have shown that this technique could effectively improve training and increase performance [3-6]. In a recent meta-analysis, it was shown that unilateral tDCS was more effective than bilateral tDCS in patients with stroke, while bilateral tDCS was more effective than unilateral tDCS to improve motor learning and motor performance in healthy subjects [7].

At present, there are few studies on the effect of tDCS on knee muscle strength, and most of these studies have mainly focused on stimulation of either the motor cortex or the prefrontal cortex rather than bilateral stimulation [8-10]. For example, Tanaka et al. found that there was a 13.2% increase in knee extensor strength in the hemiplegic side compared to a sham treatment when anodal tDCS (2 mA, 10 min) was delivered to the ipsilesional leg area of the primary motor cortex in chronic stroke patients [10].

Additionally, there are very few studies focusing on the post-stimulation effects of tDCS on knee muscle strength, which has major implications for athletes. It has been reported that 2 mA anodal tDCS delivered for 13 min while an individual is at rest has been shown to increase intracortical facilitation for up to 90 min after the stimulation [1, 11]. In addition, since anodal tDCS has been shown to increase cortical excitability, which would enhance muscle strength, it is necessary to observe modulation of recruitment of motor units during muscle contractions after tDCS.

The Halo Sport (Halo Neuroscience, San Francisco, CA, USA) is a portable neurostimulation device that consists of a headset similar to conventional headphones. It delivers variable direct current up to 2 mA over the scalp through surface electrodes, or “primers”, which induces changes in bihemispheric primary motor cortex [3]. The Halo Sport has been applied in training and competition, but its effects on physical performance remain largely unknown. However, it has been reported that tDCS with the Halo Sport is able to enhance aspects of sprint cycling ability and cognitive performance in healthy individuals [3].

The primary purpose of this present study was to examine the effects of bilateral anodal tDCS with the Halo Sport on knee muscle strength and EMG activity as well as its after-effect. It was hypothesized that Halo Sport would improve knee flexor and extensor strength and have a significant afterstimulation effect.

Materials And Methods

Subjects

Nineteen healthy male adults volunteered to participate in this study (mean age 23.3 ± 2.4 years; height 178.3 ± 6.0 cm; mass 80.7 ± 13.3 kg). None of the subjects suffered from any neurological history or psychiatric disorder, or had implanted electric devices. Subjects were informed about all aspects of the experiment and all signed written informed consent. The experiment protocol was approved by the Ethics Committee of the Shenyang Sport University and conformed to the Declaration of Helsinki.

Experimental design

This study employed a single-blinded, randomized, and sham-controlled crossover design to compare the effects of tDCS stimulation with sham stimulation over the primary motor cortex (M1) on knee strength and muscle activation. Subjects were required to visit the lab twice. The two experimental sessions were separated by at least 4-5 days, and carried out at the same time of a day to eliminate any circadian

effects on strength. On the first visit, body mass and height were measured. Subsequently, subjects completed a 15-min warm-up (10 min running and 5 min leg stretching) and then a 5-min rest period. At the end of the warm-up, before starting the experiment, subjects performed 3 maximal voluntary contractions (MVC) with each leg for knee flexors and extensors for the baseline test. For calculating the rate of force development (RFD), subjects were asked to elicit maximal force levels as quickly as possible during the MVC tests. Additionally, the EMG signals from the rectus femoris (RF) and biceps femoris (BF) were sampled during the MVC testing. Experimental testing consisted of a real tDCS or sham stimulation for 20 min under resting state, the order of which was randomized. Immediately and 30 min after intervention the MVC tests were performed again. During the second visit, the basic testing procedure was same to the first visit. Data were compared among pre-intervention (baseline test), immediately, and 30 min after intervention.

Experimental Procedures

tDCS Procedures

Subjects sat in a comfortable chair in a resting state. The Halo Sport was correctly positioned on the head. In order to ensure good electrical contact with the scalp, three primers as electrodes were soaked in normal saline (0.9% NaCl) prior to administration. The size of the electrodes affixed to the scalp was 28 cm² (6.4 × 4.4 cm²). The primers were positioned over the left and right leg regions of M1, along the Cz midline central, spanning from ear to ear, therefore lying over the critical spots of the 10/20 EEG system (i.e., from C1 to C6, with the aim to stimulate both sides of the motor cortex). The current was set at 2 mA and the stimulation duration was for 20 min. In the active stimulation, the electrical current gradually increased up to 2 mA over 30 s, and thereafter was kept at this level for 20 min. In the sham condition, the electrical current was first ramped up for 30 s, after which it was terminated. Similar stimulation settings have been tested in multiple clinical trials and have proven to be safe in humans [12, 13].

MVC test, force development rate (RFD), and evaluation of dominance of lower limb

The MVC testing was performed by a dynamometer system (HUR, Finland). Subjects were asked to sit on a bench with their back firmly fixed into the backrest and hands grasping the handles. The isometric MVC force of knee flexors and extensors was measured at a 120° knee joint angle. For the MVC test of knee extensor, subjects extended their knees against a resistance arm as soon as possible to maximal force for 5 s. This process was repeated 3 times with a rest interval of 30 s. After a 5-min rest, the MVC test of knee flexor was performed in the same method. After a 5-min rest, the MVC of the other knee was measured. The order of testing (right vs. left) was randomized. Based on the subject's MVC, the RFD was calculated according to a reference [14]. The average values of MVC and RFD for 3 times tests were selected.

Additionally, the MVC force level of knee was used to evaluate dominance of lower limb, namely the side with a larger knee force, was defined as the “dominant” lower limb and the other was the non-dominant limb [15].

Surface electromyography assessment (sEMG)

The sEMG signals of each rectus femoris (RF) and biceps femoris (BF) during MVC testing were recorded with a portable sEMG system (Shimmer3 EMG, Shimmer Company, Ireland). Two self-adhesive surface electrodes were attached on the muscle belly of the selected muscle in a bipolar configuration, while the reference electrode was placed over the skin of the tibial tuberosity. Sampling rate of the signals was set at 1,024 Hz and the measured data were converted to digital format via a 12-bit analog-to-digital (A/D) converter. Additionally, 8-450 Hz band pass filter and 49-51 Hz notch filter were employed, in an attempt to minimize the influence of power frequency signal (50 Hz). The RMS and MPF of sEMG of biceps femoris and rectus femoris during MVC were analyzed. Normalized RMS was adopted in this study, i.e., the RMS value of each stage was divided by the RMS value corresponding to the maximal value of 3 MVCs during the baseline test. All data were expressed as percentages.

Statistical analysis

SPSS 17.0 software and GraphPad Prism 8 were used for statistical analysis and drawing graphs [respectively](#). The normality of the data distribution was evaluated by Shapiro-Wilk tests. Analyses of MVC, RFD as well as sEMG activities of rectus femoris and biceps femoris during MVC tests were conducted utilizing two-way (intervention (2 levels: tDCS and sham) × time (3 levels: pre-intervention, immediately, and 30 min after intervention) repeated measures ANOVA. Also, dominance of lower limb was assessed using paired sample t-tests. All data were expressed by mean ± standard deviation (SD) and statistical significance was set *a priori* at $P < 0.05$.

Results

Adverse effects of tDCS

None of the subjects requested the stimulation be discontinued due to discomfort; all subjects completed the testing in full. Adverse effects results of different tDCS conditions were displayed in Table 1. Overall, 2 mA tDCS and sham tDCS were [similarly](#) well tolerated and no serious adverse events were reported. Adverse effects were not significantly different between 2 mA tDCS and sham application ($P > 0.05$).

Table 1 Comparison of adverse effects between experimental and sham tDCS

	Experimental (n=19)	Sham (n=19)	<i>P</i>
Headache n(%)	1(5.3)	0	1.00
Itching n(%)	6(31.6)	4(21.1)	0.71
Tingling n(%)	9(47.4)	6(31.6)	0.51
Burning n(%)	2(10.5)	0	0.49
Dizziness n(%)	1(5.3)	0	1.00

Determination of dominant lower limb

As shown Fig. 1, there was a significant difference in knee extensor and flexor strength between sides. The force of the right knee extensor was significantly greater than that of the left knee extensor (Right: 2193.2 ± 465.2 N; Left: 2042.8 ± 488.9 N; $P < 0.01$); the force of the right knee flexor was significantly larger than that of the left knee flexor (Right: 947.8 ± 270.9 N; Left: 882.2 ± 257.1 N, $P < 0.05$).

Rate of force development (RFD)

The two-way repeated measures ANOVA revealed that there was a significant interaction for the RFD of left leg extension ($F_{(2, 35)} = 3.952$, $P = 0.028$), and a significant main effect of condition was also observed ($F_{(1, 36)} = 5.220$, $P = 0.028$). The RFD of left leg extension (pre: 1409.4 ± 493.3 N·s⁻¹; immediate: 1691.7 ± 531.7 N·s⁻¹, $P < 0.01$) and flexion (pre: 751.8 ± 324.2 N·s⁻¹; immediate: 1028.8 ± 637.4 N·s⁻¹, $P < 0.05$) immediately after real stimulation was significantly greater than that before stimulation, and the RFD of left leg extension immediately after (tDCS: 1691.7 ± 531.7 N·s⁻¹; sham: 1359.8 ± 360.5 N·s⁻¹, $P < 0.05$) and 30 min after real stimulation (tDCS: 1690.8 ± 438.9 N·s⁻¹; sham: 1178.3 ± 797.1 N·s⁻¹, $P < 0.05$) was significantly greater than that in the sham group ($P < 0.05$). However, there was no significant interaction (condition $\times$ time) effect, time effect or condition effect on the RFD of right knee extensor and flexor ($P > 0.05$, Fig. 2).

Maximal voluntary contraction (MVC)

The two-way repeated measures ANOVA revealed that there was a significant interaction for the MVC of left knee extension ($F_{(2, 35)} = 9.756$, $P < 0.01$) and flexion ($F_{(2, 35)} = 4.109$, $P = 0.021$). Compared to before stimulation, the MVC force of left knee extension (pre: 2042.8 ± 488.9 N; immediate: 2219.5 ± 519.6 N; 30 min: 2111.7 ± 515.0 N, $P < 0.01$) and flexion (pre: 882.2 ± 257.1 N; immediate: 1003.7 ± 235.5 N; 30 min: 985.0 ± 292.3 N, $P < 0.05$) were significantly increased immediately after and 30 min after real stimulation. Moreover, the MVC of left leg flexion 30 min after real stimulation was significantly higher compared to sham tDCS (tDCS: 985.0 ± 292.3 N; sham: 801.1 ± 184.8 N, $P < 0.05$). On the other hand, none of the interventions had a prominent effect on right extensor and flexor ($P > 0.05$, Fig. 3).

Root mean square (RMS)

There was no significant main effect of time and the condition $\times$ time interaction were found for the RMS amplitudes of bilateral rectus femoris and biceps femoris sEMG ($P > 0.05$), whereas the main effect of condition was significant for the RMS amplitudes of left rectus femoris ($F_{(1, 36)} = 5.531, P = 0.024$) and biceps femoris ($F_{(1, 36)} = 4.320, P = 0.045$) sEMG. The RMS amplitudes of left rectus femoris (pre: 118.4 ± 46.6 ; immediate: 156.3 ± 44.0 ; 30 min: $152.1 \pm 75.3, P \leq 0.05$) and biceps femoris (pre: 82.1 ± 29.5 ; immediate: $114.2 \pm 57.0, P \leq 0.05$; 30 min: $112.1 \pm 38.4, P \leq 0.01$) sEMG immediately after and 30 min after real stimulation were significantly higher compared to before stimulation. Nevertheless, none of the interventions had a prominent effect on right rectus femoris and biceps femoris ($P > 0.05$, Fig. 4).

Mean power frequency (MPF)

The two-way repeated measures ANOVA revealed no significant main effect of time and the condition $\times$ time interaction were found for the MPF of bilateral rectus femoris and biceps femoris sEMG ($P > 0.05$), whereas the main effect of condition was significant for left biceps femoris ($F_{(1, 36)} = 5.192, P = 0.029$). The MPF values of left rectus femoris (pre: 116.2 ± 25.1 ; immediate: 130.2 ± 26.2 ; 30 min: $128.2 \pm 21.5, P \leq 0.05$) and biceps femoris (pre: 97.0 ± 16.3 ; immediate: 109.6 ± 26.3 ; 30 min: $108.2 \pm 18.1, P \leq 0.05$) sEMG were significantly higher immediately after and 30 min after real stimulation compared to before stimulation, meanwhile, the MPF of left biceps femoris sEMG 30 min after real stimulation was increased significantly compared with the sham condition (tDCS: 108.2 ± 18.1 ; sham: $94.7 \pm 12.2, P < 0.05$). No significant difference was noted in right rectus femoris and biceps femoris ($P > 0.05$, Fig. 5).

Discussion

Rate of force development (RFD)

In many sports such as basketball, boxing, weight lifting, etc., numerous technical movements require athletes to complete rapid muscle contraction in a short period of time. Explosive force, determined by strength as well as speed, is the ability of the neuromuscular system to exert maximum muscle strength with maximum acceleration in the shortest time. The rate of force development (RFD) is an important index of explosive force, which is defined as the slope of the force-time curve of muscle under the condition of dynamic and static contraction [16]. It is particularly important to seek effective strategies for athletes to increase their RFD. Athletes with a high RFD have faster muscle contraction speed, and are able to complete motor tasks more quickly, and therefore gain a greater competitive advantage.

At present, there are few studies on the enhancement of RFD through tDCS. We found that the RFD of the subjects' left leg extension and flexion increased significantly immediately after 2 mA direct current stimulation over bilateral M1 area; moreover, the RFD of left leg extension immediately after real stimulation was significantly larger compared with sham condition. Previous studies have shown that the increase of M1 cortical excitability induced by tDCS can alter the firing frequency of neurons, increase the nerve impulse to muscles, and promote the recruitment of motor units [17]. The nerve impulse is an

electrical signal sent from the central nervous system to the muscle, which is conducive to driving the recruitment of motor units and triggering the muscle to generate force [18]. Some studies have pointed out that RFD is closely related to the recruitment of nerve to motor units per unit time, the frequency of nerve impulses, and the type of muscle contraction [16]. Hence, the enhancement of RFD in this study may be relevant to the increased cortical excitability induced by tDCS. The results of the present study are also supported by other published studies. Halo Neuroscience found that 15 min of 2 mA bihemispheric tDCS administered via the Halo Sport device aggrandized vastly the RFD of non-dominant hand in healthy right-handed subjects during an isometric pinch force task [18]. Likewise, Cates et al. found the healthy right-handed subjects receiving 2 mA of anodal tDCS for 15 min exhibited **prominently** enhancement in peak rate of force development (pRFD) of non-dominant ballistic thumb during and after stimulation compared to the sham condition [19]. These results indicate that tDCS may contribute to the increases in RFD of the non-dominant limb.

In addition to the immediate effect of tDCS, the after-effect of tDCS on cortical excitability was also observed in the present study; namely, the RFD of left leg extension 30 min after tDCS intervention was significantly greater than that of the sham condition. Tanaka et al. [20] observed that following 10 min of anodal tDCS at 2 mA over the contralateral leg motor cortex, the maximal pinch force of the left leg in healthy adult subjects was transiently enhanced, and the augment effect lasted for 30 min after the end of tDCS sessions. The results of the present study are consistent with these studies, which verify that tDCS intervention has after-effects. However, our study found that the RFD improved 30 min after real stimulation, but not as significantly as in the immediate period after stimulation. A previous study found the after-effects of tDCS increasingly decreased with the prolongation of time after stimulation [21]. The duration of the post-stimulation effects was left to the duration, times as well as intensity of the stimulation [22]. It is reported that the stimulation effect is able to last for 30-60 minutes following a single tDCS session for 10-20 min [23]. Repetitive intervention more than 1 week is capable of having effect for 1-2 weeks [24], and the after-effects of prolonged tDCS stimulation can even be detected few months later [25]. Regarding current intensities, a recent study reported that the intensity of 2 mA may not be sufficient to affect neuronal circuits [26]. Vöröslkos et al. [27] proposed by testing transcranial alternating current stimulation (tACS) that because a large part of the current is lost as a result of soft tissues, skin as well as resistance of the skull, at least 4.5 mA would be required to affect the neuronal circuits. Nevertheless, there is a relative paucity of data on the effectiveness and safety of higher current intensity on exercise capacity in healthy populations at present [28, 29], therefore, the practice of applying high-intensity electrical stimulation in an attempt to obtain the gain effects needs to be carefully considered. Furthermore, as a result of the high variability among individuals, the most effective measure may be to apply individualized current intensity to the subjects [27].

We found that tDCS has the capacity to increase the recruitment of motor units by modulating the excitability of cerebral cortex as well as nerve impulses, thus increasing the rate of force development, and its after-effects can last for 30 minutes. These findings demonstrate that tDCS delivered via the Halo Sport may be a safe and effective method to facilitate explosive strength for healthy populations in daily life or in exercise training.

Maximal voluntary contraction

It is generally believed that motor unit recruitment strategy is crucial in the process of maximum force generation [30]. Previous studies have indicated that motor unit recruitment and synchronicity can be modulated by anodal tDCS [17]. As a consequence, it can be inferred that this neuromodulatory technique may contribute to the improvement of MVC force. We found that the MVC of the left flexor and extensor groups immediately after and 30 min after real stimulation increased significantly compared with before stimulation, furthermore, the MVC of the left leg flexion 30 min after tDCS intervention was **prominently** greater than the sham condition. The results of the present study are consistent with the results reported in previous studies. For instance, Washabaugh et al. found that 2 mA, 12 min of anodal tDCS vastly aggrandized the knee extensor torque and MVC ability in healthy subjects than sham stimulation, and the stimulation effect was also remarkable 25 min after stimulation [31]. A plausible explanation for the improvement in muscular strength is that tDCS-induced changes in corticospinal excitability increase the recruitment of motor units, thus leading to greater muscle strength during contraction [32].

Interestingly, the pronounced effect of the lower limb muscle strength enhancement after tDCS administration was mainly manifested in the non-dominant leg. Muscle strength of the dominant leg did show an upward trend after stimulation, but with no statistical difference compared to the sham. Asymmetric use of the dominant and non-dominant legs might elicit asymmetry of cortical excitability between the dominant and non-dominant hemisphere, namely, the excitability of the non-dominant motor cortex is lower than that of the dominant motor cortex [33]. Boggio et al. [33] investigated the effect of anodal tDCS of the dominant and non-dominant M1 on the hand motor function in healthy right-handed subjects. Their results showed that non-dominant hand (left hand) motor function was significantly improved by anodal stimulation (1 mA, 20 min), whereas neither anodal nor sham tDCS gave rise to a **prominent** change in the dominant hand motor performance. The possible reason for the lack of effects on the dominant hemisphere is that there may be a ceiling effect on the stimulation effect of tDCS on the dominant side. Since the cerebral dominant hemisphere is already optimally activated, an additional increase in excitability by anodal tDCS would not provide further behavioral benefits to these subjects [33]. Nonetheless, in a study by Vargas, 20 adolescent female soccer players underwent five MVC tests of **bilateral** knee extensors after 2 mA anodal tDCS and found significant improvement in MVC force in the dominant limb [9]. These inconsistent findings suggest that further studies are needed to confirm whether there is a ceiling effect of tDCS on the enhancement of athletic abilities. Although the effects of tDCS on the dominant limb muscle strength are controversial, it is clear from the results of this study that tDCS has the potential to augment the muscle strength of non-dominant limb. In future experimental research and actual sports training, tDCS technology can be employed to increase the non-dominant limb muscle strength of athletes, narrow the gap with the dominant limb, avoid the imbalance phenomenon, and further boost the overall exercise capacity, which would have an exceedingly practical significance for muscle strength training and the prevention of sports injury.

Muscle Activation assessment

The main mechanism of enhancing muscle strength by transcranial direct current stimulation is to regulate the nerve factors related to muscle strength. EMG is capable of reflecting the influence of nerve drive and other factors during muscle contraction. Fast-twitch (type II) muscle fibers are commonly innervated by high-threshold neurons. This muscle fiber types are usually closer to the surface, and their contractile changes are able to be well recorded via sEMG signals [34]. The changes of motor unit recruitment, in a sense, can be traced by sEMG [35]. A previous study has argued that the peak torque and EMG amplitude of biceps brachii in healthy subjects during maximum contraction can be significantly increased after 2 mA, 10 min anodal tDCS over the left M1. The author believes that the muscle activation may be related to the changes of motor unit recruitment strategies [32]. The results of the present study showed that the activation level of left biceps femoris and rectus femoris was significantly higher immediately after and 30 min after tDCS administration than before, indicating that tDCS can elevate the activation levels of non-dominant knee and recruit more motor units, so as to enhance muscle strength. A similar phenomenon was observed in a previous study by Frazer et al. [36], who found the muscle strength and EMG amplitude of the non-dominant (left) biceps brachii in healthy subjects were increased significantly after discharging 2 mA direct current applied to M1 for 20 min. Nevertheless, no significant change was noted in the activation level of the right flexor and extensor muscles after tDCS treatment, which was consistent with the results of muscle strength in this study. Kan et al. found that 2 mA of anodal tDCS for 10 min did not affect the RMS amplitude of biceps brachii sEMG in elbow endurance test of healthy male subjects. The authors summarize that tDCS intervention would not further heighten muscle function when muscle function has reached the maximum [37]. Considering that the subjects selected in this study were all right leg dominant, the muscle activation level has reached the best state in high-intensity exercise, and in this state, the ability of tDCS to increase the number of motor unit recruitment to improve the muscle activation degree is limited, resulting in no significant improvement in muscle strength performance.

There is a certain correlation between sEMG amplitude and muscle strength; generally speaking, muscle strength increases with increasing sEMG amplitude. Several studies point out, however, that the changes of sEMG amplitude and power spectrum are not only related to muscle strength, but also related to fatigue degree [38]. The time-domain EMG signal tends to increase with the enhancement of muscle strength as well as the generation of fatigue, while the frequency-domain EMG signal increases with the improvement of muscle strength, but decreases with the generation of fatigue [38]. Consequently, mean power frequency (MPF) was employed in an attempt to determine whether the increase of RMS value is caused by the augment of muscle strength. Our results showed that the MPF values of left rectus femoris and biceps femoris sEMG were significantly higher immediately after and 30 min after real stimulation compared to before stimulation, meanwhile, the MPF of left biceps femoris sEMG was increased significantly 30 min after real stimulation compared with the sham condition. Also, the corresponding MVC values immediately after and 30 min after tDCS intervention were increased, so the increase of RMS values could exclude the effects of fatigue factors. The changes of EMG amplitude are related to the number of motor unit recruitment, impulse frequency and synchrony. Therefore, tDCS was likely to

promote the recruitment of motor units, increase the level of muscle activation, and then enhance muscle strength in this study.

Limitations

Whilst the present study revealed that bihemispheric tDCS over M1 using the Halo Neurostimulation System could facilitate the strength performance and explosive force of knee joint to some extent, several limitations should be noted. First, the present research was restricted to normal healthy young male subjects. Future studies should utilize athletes as subjects; this can provide a reliable basis for tDCS technology to serve the realm of athletics better. Additionally, not including female subjects could also be considered as a limitation of the current study. In view of the gender differences in the current delivered to the skull during tDCS application, the effects of tDCS on the motor performance of different gender subjects may also be different. Hence, future research can enroll the equal number of female subjects, so as to explore the effects of tDCS technology on female subjects' muscle strength and the differences between genders. Finally, this study used a single tDCS session; repeated studies should be conducted to evaluate the long-term stimulation effect of tDCS in the future. In addition, neuroimaging techniques such as transcranial magnetic stimulation (TMS) and electroencephalography (EEG) can be utilized to explore the mechanism of tDCS improving motor performance.

Conclusions

Single transcranial direct current stimulation of bilateral primary motor cortex can significantly improve the muscle strength and explosive force of the non-dominant knee, which is manifested by the increase of the amount of motor units recruited during exercise. The effect on muscle strength can last until 30 min after stimulation, but there is no significant effect on the dominant knee.

Abbreviations

tDCS: Transcranial direct current stimulation; RFD: Rate of force development; MVC: Maximal voluntary contraction; sEMG: Surface electromyography; RMS: Root mean square amplitude; MPF: Mean power frequency; RF: Rectus femoris; BF: Biceps femoris; M1: Primary motor cortex.

Declarations

Ethics approval and consent to participate

The study was approved by the Ethics Committee of the Shenyang Sport University. Written informed consent was obtained from all individual participants included in the study.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

This study was supported by Natural Science Foundation of Liaoning Province (20180550169).

Authors' contributions

PL carried out the experiments and wrote the manuscript. NJH supervised the study and polished the manuscript. LW participated in the recording, processing and analysis of the data. FG conceived of the study and revised the manuscript. All authors read and approved the final manuscript.

Acknowledgements

Not applicable.

Author details

¹College of Human Kinesiology, Shenyang Sport University, 36 Jinqiansong East Road Sujiatun District, Shenyang, 110102, Liaoning, China. ²Department of Human Performance and Health Education, College of Human Development and Education, Western Michigan University, Kalamazoo, Michigan, USA. ³Graduate School of Biomedical and Health Sciences, Hiroshima University, 2-3 Kasumi 1-chome, Minami-ku, Hiroshima, 734-8553, Japan.

References

1. Nitsche M, Paulus W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *J Physiol.* 2000;527:633–9.
2. Nitsche M A, Nitsche M S, Klein C C, et al. Level of action of cathodal DC polarisation induced inhibition of the human motor cortex. *Clin Neurophysiol.* 2003;114(4):600-4.
3. Huang L, Deng Y, Zheng X, et al. Transcranial direct current stimulation with Halo Sport enhances repeated sprint cycling and cognitive performance. *Front Physiol.* 2019;10:118.
4. Alix-Fages C, García-Ramos A, Calderón-Nadal G, et al. Anodal transcranial direct current stimulation enhances strength training volume but not the force-velocity profile. *Eur J Appl Physiol.* 2020;120(8):1881-91.

5. Vieira L, Lattari E, Abreu M, et al. Transcranial direct current stimulation (tDCS) improves back-squat performance in intermediate resistance-training men. *Res Q Exerc Sport*. 2020;(4):1-9.
6. Grosprêtre S, Grandperrin Y, Nicolier M, et al. Effect of transcranial direct current stimulation on the psychomotor, cognitive, and motor performances of power athletes. *Sci Rep*. 2021;11: 9731.
7. Halakoo S, Ehsani F, Hosnian M, et al. The comparative effects of unilateral and bilateral transcranial direct]current stimulation on motor learning and motor performance: A systematic review of literature and meta-analysis. *J Clin Neurosci*. 2020; 72:8-14.
8. Maeda K, Yamaguchi T, Tatemoto T, et al. Transcranial direct current stimulation does not affect lower extremity muscle strength training in healthy individuals: A triple-blind, sham-controlled study. *Front Neurosci*. 2017;11: 179.
9. Vargas VZ, Baptista AF, Pereira GOC, et al. Modulation of isometric quadriceps strength in soccer players with transcranial direct current stimulation: a crossover study. *J Strength Cond Res*. 2017; 32(5):1336-41.
10. Tanaka S, Takeda K, Otaka Y, et al. Single session of transcranial direct current stimulation transiently increases knee extensor force in patients with hemiparetic stroke. *Neurorehabil Neural Repair*. 2011;25(6):565-9.
11. Stagg CJ, Nitsche MA, Physiological basis of transcranial direct current stimulation. *Neuroscientist*. 2011;17:37-53.
12. Vines BW, Cerruti C, Schlaug G. Dual-hemisphere tDCS facilitates greater improvements for healthy subjects' non-dominant hand compared to uni-hemisphere stimulation. *BMC Neurosci*. 2008; 9:103.
13. Kantak SS, Mummidisetty CK, Stinear JW. Primary motor and premotor cortex in implicit sequence learning—evidence for competition between implicit and explicit human motor memory systems. *Eur J Neurosci*. 2012;36:2710-5.
14. Molina R, Denadai B. Dissociated time course recovery between rate of force development and1peak torque after]eccentric exercise. *Clin Physiol Funct Imaging*. 2012;32(3):179-84.
15. Workman C, Fietsam A, Rudroff T. Transcranial direct current stimulation at 4 mA induces greater leg muscle fatigability in women compared to men. *Brain Sci*. 2020;10(4):244.
16. Aagaard P, Simonsen E, Andersen J, et al. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol* (1985). 2002;93(4):1318-26.
17. Dutta A, Krishnan C, Kantak S, et al. Recurrence quantification analysis of surface electromyogram supports alterations in motor unit recruitment strategies by anodal transcranial direct current stimulation. *Restor Neurol Neurosci*. 2015;33(5):663-9.
18. Neuroscience H. Bihemispheric transcranial direct current stimulation with Halo Neurostimulation System over primary motor cortex enhances rate of force development in an isometric lateral pinch force task. 2016.<https://halo-website-static-assets.s3.amazonaws.com/whitepapers/mvc.pdf>
19. Cates A, Lin R, Wingeier B. Abstract #70: Effect of tDCS over motor cortex on isometric rate of force development in healthy adults. *Brain Stimul*. 2019;12(2).

20. Tanaka S, Hanakawa T, Honda M, et al. Enhancement of pinch force in the lower leg by anodal transcranial direct current stimulation. *Exp Brain Res*. 2009;196(3):459-65.
21. Mashal N, Metzuyan-Gorelick S. New information on the effects of transcranial direct current stimulation on n-back task performance. *Exp Brain Res*. 2019;237(5): 1315-24.
22. Nitsche M, Paulus W. Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*. 2001;57(10):1899-901.
23. Ardolino G, Bossi B, Barbieri S, et al. Non-synaptic mechanisms underlie the after-effects of cathodal transcutaneous direct current stimulation of the human brain. *J Physiol*. 2005;568:653-63.
24. Butts R, Kolar M, Newman-Norlund R. Enhanced motor skill acquisition in the non-dominant upper extremity using intermittent theta burst stimulation and transcranial direct current stimulation. *Front Hum Neurosci*. 2014;8:451.
25. Reis J, Schambra H, Cohen L, et al. Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation. *Proc Natl Acad Sci U S A*. 2009;106(5):1590-5.
26. Holgado D, Zandonai T, Ciria L, et al. Transcranial direct current stimulation (tDCS) over the left prefrontal cortex does not affect time-trial self-paced cycling performance: Evidence from oscillatory brain activity and power output. *PLoS One*. 2019;14(2):e0210873.
27. Voroslakos M, Takeuchi Y, Brinyiczki K, et al. Direct effects of transcranial electric stimulation on brain circuits in rats and humans. *Nat Commun*. 2018;9(1):483.
28. Bikson M, Grossman P, Thomas C, et al. Safety of transcranial direct current stimulation: Evidence based update 2016. *Brain Stimul*. 2016;9(5):641-61.
29. Esmaeilpour Z, Marangolo P, Hampstead B, et al. Incomplete evidence that increasing current intensity of tDCS boosts outcomes. *Brain Stimul*. 2018;11(2):310-21.
30. Farina D, Negro F. Common synaptic input to motor neurons, motor unit synchronization, and force control. *Exerc Sport Sci Rev*. 2015;43(1):23-33.
31. Washabaugh E, Santos L, Claffin E, et al. Low-level intermittent quadriceps activity during transcranial direct current stimulation facilitates knee extensor force-generating capacity. *Neuroscienc*. 2016;329:93-7.
32. Krishnan C, Ranganathan R, Kanyak S, et al. Anodal transcranial direct current stimulation alters elbow flexor muscle recruitment strategies. *Brain Stimul*. 2014;7(3):443-50.
33. Boggion P, Castro L, Savagim E, et al. Enhancement of non-dominant hand motor function by anodal transcranial direct current stimulation. *Neurosci Lett*. 2006;404:232-6.
34. Williams P, Hoffman R, Clark B. Preliminary evidence that anodal transcranial direct current stimulation enhances time to task failure of a sustained submaximal contraction. *PLoS One*. 2013;8(12):e81418.
35. Zhou P, Rymer W. Factors governing the form of the relation between muscle force and the EMG: a simulation study. *J Neurophysiol*. 2004;92(5):2878-86.

36. Frazer A, Williams J, Spittle M, et al. Cross-education of muscular strength is facilitated by homeostatic plasticity. *Eur J Appl Physiol.* 2017;117(4):665-77.
37. Kan B, Dundas J, Nosaka K. Effect of transcranial direct current stimulation on elbow flexor maximal voluntary isometric strength and endurance. *Appl Physiol Nutr Metab.* 2013;38(7):734-9.
38. Luttmann A, Jger M, Laurig W. Electromyographical indication of muscular fatigue in occupational field studies. *Int J Industrial Ergonomics.* 2000;25(6):645-60.

Figures

Figure 1

Comparison of bilateral knee extensor and flexor strength Notes: *: $P \leq 0.05$, **: $P \leq 0.01$.

Figure 2

Effects of tDCS on rate of force development (N·s⁻¹) of bilateral knee flexors and extensors Notes: pre: pre-stimulation, post-0 min: 0 min after stimulation, post-30 min: 30 min after stimulation. Significant difference compared to pre-stimulation: * $P < 0.05$, ** $P \leq 0.01$, significant difference compared to sham: # $P < 0.05$.

Figure 3

Effects of tDCS on maximal voluntary contraction of bilateral knee flexors and extensors Notes: Significant difference compared to pre-stimulation: * $P < 0.05$, ** $P \leq 0.01$, significant difference compared to sham: # $P < 0.05$.

Figure 4

Effects of tDCS on RMS amplitudes (%) of bilateral rectus femoris and biceps femoris sEMG Notes: RF: rectus femoris, BF: biceps femoris. Significant difference compared to pre-stimulation: * $P < 0.05$, ** $P \leq 0.01$.

Figure 5

Effects of tDCS on MPF (Hz) of bilateral rectus femoris and biceps femoris sEMG Notes: RF: rectus femoris, BF: biceps femoris. Significant difference compared to pre-stimulation: * $P < 0.05$, significant

difference compared to sham: #P < 0.05.