Original article (short paper)

Motor cortex tDCS does not improve strength performance in healthy subjects

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Abstract—The influence of transcranial direct current stimulation (tDCS) upon maximal strength performance in exercises recruiting large muscle mass has not been established in healthy populations. The purpose of this study was to investigate whether anodal tDCS was able to increase the performance during maximal strength exercise (MSEX) in healthy subjects. Fourteen volunteers (age: 26 ± 4 yrs) performed two MSEX after anodal or sham tDCS (2mA; 20min prior MSEX), involving knee extensors and flexors in concentric isokinetic muscle actions of the dominant limb (3 sets of 10 repetitions). The electrical muscle activity (sEMG) of four recruited muscles was recorded during MSEX. Anodal tDCS was not able to improve force production (i.e., total work and peak torque), fatigue resistance, or electromyographic activity during MSEX when compared to sham condition. In conclusion, anodal tDCS applied upon the contralateral motor cortex was not capable of increasing the strength performance of knee extensors and flexors in young healthy subjects.

Keywords: neuroscience, tDCS, neuromodulation, fatigue and motor rehabilitation

Resumo—"ETCC sobre o córtex motor não aumenta o desempenho de força em sujeitos saudáveis." A influência da estimulação transcraniana por corrente contínua (ETCC) sobre o desempenho da força muscular em exercícios que recrutam grandes massas musculares ainda não foi estabelecido em populações saudáveis. O objetivo desse estudo foi investigar se a ETCC anódica seria capaz de aumentar o desempenho durante exercício máximo de força (EMF) em sujeitos saudáveis. Catorze voluntários (idade: 26 ± 4 anos) executaram dois EMF com aplicação prévia da ETCC anódica ou placebo (2mA; 20 mim), envolvendo músculos flexores e extensores do joelho dominante em ação concêntrica isocinética (3 séries de 10 repetições). A atividade elétrica muscular (sEMG) de quatro músculos recrutados foi registrada durante o EMF. A ETCC anódica não foi capaz de melhorar a produção de força (trabalho total e pico de torque), resistência à fadiga ou atividade eletromiográfica durante o EMF, quando comparada à condição placebo. Em conclusão, a ETCC anódica aplicada sobre o córtex motor contralateral não foi capaz de aumentar o desempenho de força de flexores e extensores de joelho em jovens saudáveis.

Palavras-chave: neurociência, ETCC, neuromodulação, fadiga e reabilitação motora

Resumen—"tDCS en motor corteza no aumenta el rendimiento de fuerza en sujetos sanos." La influencia de estimulación transcraneal de corriente directa (tDCS) en ejercicios de fuerza muscular de rendimiento que reclutan grandes masas musculares no se ha establecido en la población sana. El objetivo de este estudio fue investigar si la ETCC anódica podría mejorar el rendimiento durante el ejercicio máximo de la fuerza (EMF) en sujetos sanos. Catorce voluntarios (26 ± 4 años de edad) realizaron dos EMF con la aplicación previa de ETCC anódica y placebo (2 mA, 20 i) la participación de los flexores y extensores de la rodilla dominante en acción concéntrica (3 series de 10 repeticiones). La actividad eléctrica muscular (sEMG) en cuatro músculos reclutados se registró durante el EMF. La ETCC anódica no fue capaz de mejorar la potencia de salida (trabajo total y pico de torque), la resistencia a la fatiga o la actividad electromiográfica durante el EMF, cuando comparada con la condición placebo. Por lo tanto, la ETCC anódica aplicada a la corteza motora contralateral no fue capaz de aumentar el rendimiento de la fuerza de flexores y extensores de la rodilla en jóvenes sanos.

Palabras claves: neurociencia, tDCS, neuromodulación, la fatiga y la rehabilitación motora

Introduction

Transcranial direct current stimulation (tDCS) is a non-invasive technique that can be used to alter cortical activity and has been widely used in the treatment of several neurological disorders (Nitsche *et al*., 2008; Nitsche & Paulus, 2011). A continuous weak electric current is applied to the brain via 2 electrodes that are placed on the subject's scalp. Anodal tDCS has been shown to induce changes in the cell membrane resting potential, favoring depolarization and increasing spontaneous neuronal firing rate, whereas opposite effects are provoked by cathodal tDCS (Nitsche & Paulus, 2000). These changes in neuronal excitability may persist for an hour or more if applied for 9 min or longer using 0,3-2mA of the current intensity (Nitsche & Paulus, 2001). Although tDCS stimulates only the cortical area directly beneath the electrode, it can modulate areas not directly beneath the electrode, via cortical networks (Lang *et al*., 2005).

It has been shown that tDCS can modulate motor learning and performance (Cogiamanian, Marceglia, Ardolino, Barbieri, & Priori, 2007; Kaminski *et al*., 2013) and help treating symptoms of diseases associated with motor impairments as Parkinson´s disease (Boggio *et al*., 2007). We have recently demonstrated that tDCS applied over the temporal or prefrontal cortex can induce changes in cardiac autonomic modulation at rest in athletes (Montenegro *et al*., 2011), as well as to increase peak cycling performance (Okano *et al*., 2013), and energy expenditure during post-exercise recovery (Montenegro, Okano, Cunha, Fontes, & Farinatti Pde, 2013).

Some previous research suggested that tDCS may also improve performance in specific tasks involving voluntary muscle contraction (Cogiamanian *et al*., 2007; Reis & Fritsch, 2011; Tanaka, Hanakawa, Honda, & Watanabe, 2009; Tanaka *et al*., 2011; Williams, Hoffman, & Clark, 2013), due to an increase of motor cortical excitability and consequent enhancement of motor drive from the cortex to spinal motor pool. This would lead to additional recruitment of motor units and attenuation of supraspinal fatigue related to muscle pain. Moreover, the effects of a single tDCS session were reported to induce improvements of hand function, size of motor evoked potential, force production, and fatigue resistance in healthy subjects (Boggio *et al*., 2006b; Cogiamanian *et al*., 2007; Jeffery, Norton, Roy, & Gorassini, 2007; Tanaka *et al*., 2009) and stroke patients (Gandiga, Hummel, & Cohen, 2006; Hendy, Teo, & Kidgell, 2014; Hummel *et al*., 2005; Hummel & Cohen, 2005; Tanaka *et al*., 2011). However, there are controversial results reporting no additional increasing in maximal voluntary force during specific tasks involving elbow flexion (Lampropoulou & Nowicky, 2013) or wrist extension (Hendy & Kidgell, 2013).

So, it is feasible to think that anodal tDCS effect would be more likely to occur in patients with diseases characterized by hypo-excitability of motor areas, than in healthy populations. This premise is in line with recent studies reporting no strength gains following anodal tDCS in healthy subjects (Hendy & Kidgell, 2013; Kan, Dundas, & Nosaka, 2013; Lampropoulou & Nowicky, 2013). This could be, at least in part, explained by the hypothesis that in healthy subjects there would be a ceiling effect of tDCS upon the cortex excitability. In a few words, the capacity of motor neuronal stimulation from external electrical sources to increase the motor unit recruitment would be limited in healthy subjects compared to those with motor impairment (Hendy & Kidgell, 2013) and when reached no further improvement of force production would be possible. Another possibility is that acute effects induced by tDCS would not be the same within maximal and submaximal strength exercise, or would not be enough to significantly increase training intensity and volume, hence not changing dose-response relationships in long term training. In other words, the tDCS effects would either not be observed on tasks performed with maximal intensity or would not influence chronic effects of long term resistance training in healthy individuals. Future research is warranted to ratify theses hypothesis and to verify these possibilities.

Most studies investigated the tDCS effects within submaximal exercise and have demonstrated beneficial effects on strength performance after anodal tDCS. However, we could find only three studies about tDCS effects on maximal strength, but focusing on dynamic exercise of small muscle groups (i.e. right wrist extensors) or isometric exercise in elbow flexors (Hendy & Kidgell, 2013; Kan *et al*., 2013; Lampropoulou & Nowicky, 2013). No previous research investigated the influence of tDCS on maximal strength performance in exercises recruiting large muscle groups, acutely or chronically. This is an important issue to determine whether favorable tDCS effects can be expected in tasks requiring maximal force, or only within exercises demanding submaximal strength, particularly in healthy individuals.

Therefore, the after-effects of the anodal and sham tDCS over the left motor cortex (M1) in the right-dominant leg were evaluated and compared, including the average peak torque, total work, percentage of work fatigue, and quadriceps muscle electrical activity. It has been hypothesized that anodal tDCS would not be able to improve the performance of maximal strength exercises in a cohort of healthy young subjects.

Methods

Experimental approach to the problem

Subjects were all college students that volunteered for the study. Each participant visited the laboratory twice. On the first visit anthropometric measurements were taken. Subsequently, subjects initially laid in a calm environment for 10 min and then either anodal [2mA during 20min] or sham tDCS was applied. Immediately after the tDCS, subjects remained at rest for additional 10 min and a maximal isokinetic strength test was performed. The same procedures were repeated in the second visit, with the other stimulation (anodal or sham condition) being applied. The first and second visits were separated by 48-72 h and the type of stimulation was defined in a randomized counter-balanced design (Please see Figure 1). The evaluators who applied the maximal isokinetic strength test did not know whether the data corresponded to the anodal tDCS or sham condition. All measures in each visit were performed in the

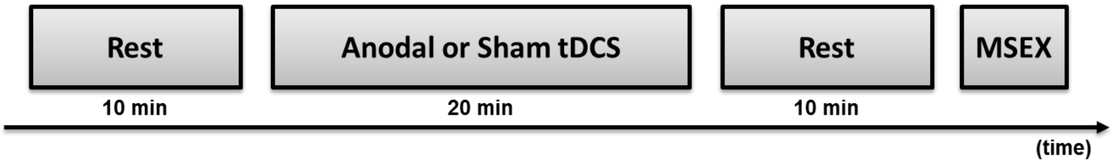


Figure 1. Study design overview. tDCS = Transcranial direct current stimulation; MSEX = Maximal strength exercise.

morning [i.e., 8:00h to 11:00h a.m.] to avoid circadian effects on strength. The ambient temperature ranged from 21°C to 23°C and relative humidity ranged from 55% to 70%. The subjects received the information to keep their food diet routine normally prior to perform the visits but were discouraged to consume ergogenic beverages like coffee.

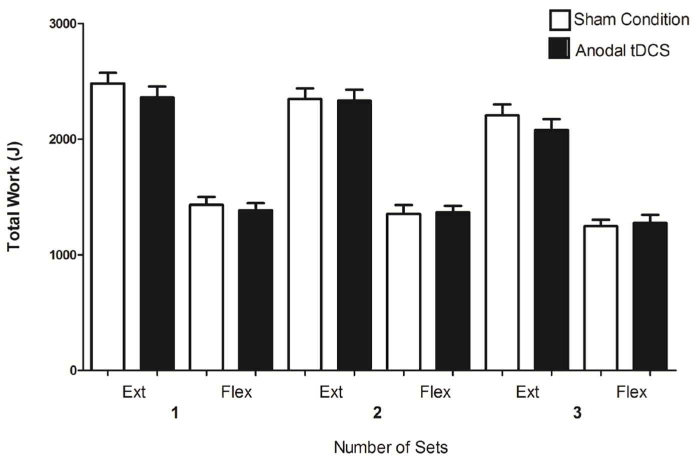
Subjects

Fourteen healthy right-dominant men participated in the present study (*n* = 14; mean ± SD, age: 26 ± 4 yrs; height: 177.1 ± 6.0 cm; weight: 77.8 ± 17.9 kg; body mass index: 24.7 ± 4.8 kg/m^2). All participants had previous experience in strength training for more than six months. Exclusion criteria were: a) presence of cardiovascular, metabolic, or neurological disease; b) smoking or use of ergogenic substances; c) cardiovascular, respiratory, muscle, neurological, or skeletal problems that could preclude exercise performance. Before inclusion in the study all procedures of the experimental protocol were explained to the participants, who subsequently provided written informed consent. The study was approved by the institutional ethics committee (process number: UFAL017262/2009-09), and complied with the ethical standards of the World Medical Association (Declaration of Helsinki).

Procedures

Maximal strength exercise (MSEX)

The MSEX was performed in a Biodex™ System 4 PRO isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA) involving both knee extensors and flexors muscles only in concentric muscle action of the dominant limb. The range of motion varied between 0° to 90° with execution speed fixed in 60°.s^{-1}. Subjects were verbally encouraged to perform maximal effort during 3 sets of 10 repetitions with 120 s intervals between sets and 48- to-72 h between sessions. The average of peak torque and total work per sets were measured as indicators of force production, whereas work fatigue percentage was adopted as an index of fatigue-resistance capacity. The work fatigue index was defined by the work percentage difference between the first and last third of 10 repetitions in each set. All tests were considered as valid only when the coefficient of variation (CV) between sets was lower than 15% as described elsewhere (Pincivero, Lephart, & Karunakara, 1997).



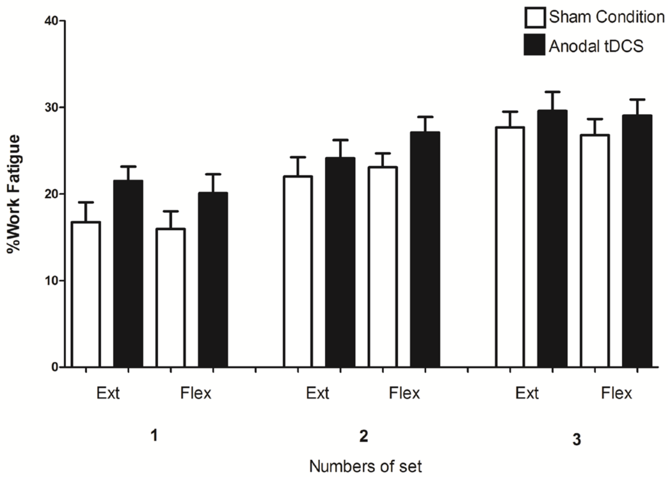


Figure 2. Mean ± SD values of total work (left side) and work fatigue percentage (right side) within maximal isokinetic strength exercise after sham and anodal tDCS (*n*=14). 2-way ANOVA with repeated measures did not detected significant differences between anodal and sham tDCS for total work *(P* = .32) and work fatigue percentage (*P* = .67). tDCS = Transcranial direct current stimulation. Ext = Extension muscular phase; Flex = Flexion muscular phase.

Surface electromyography assessment (sEMG)

The surface electromyographic activity of vastus medius (RM), rectus femoris (RF), biceps femoris (BF), and semitendinosus (ST) during MSEX was evaluated in a subgroup of 6 volunteers. The bipolar configuration and technique of electrode placement followed the standards recommended by SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles, 2011). The reference electrode was attached on the skin over the tibial tuberosity.

Data acquisition was performed using an electromyograph Noraxon™ (Myosystem 1400A, Scottsdale, Arizona, USA) with sampling frequency of 2000 Hz. Peak values were averaged to normalize the EMG signals as previously described (Halaki & Ginn, 2012). Signals were bandpass filtered within a range of 20 to 500 Hz. Signal analyzes were made in the time domain, using the root mean square of muscle activity (RMS). Data were normalized by the peak of RMS signal (percentage of root mean square - % RMS).

Transcranial direct current stimulation (tDCS)

The electric current was applied using a pair of sponges soaked on saline solution (140 mMols of NaCl dissolved in Milli-Q water) involving both electrodes ($35cm^2$) (Dundas, Thickbroom, & Mastaglia, 2007; Nitsche & Paulus, 2000). The electrodes (anodal and reference) were connected to a constant current stimulation device with three power batteries (9V) with maximal output of 10mA (Eldith DC-Stimulator, NeuroConn, Ilmenau, Germany).

For the anodal left motor cortex tDCS, since all subjects in this study were right-leg dominant, the anode was placed over M1 area according to the international EEG 10-20 system (Klem, Luders, Jasper, & Elger, 1999). The reference electrode was placed over the supraorbital contralateral area (Fp2) and fixed by elastic bands. The electrodes were placed in the same position of the anodal stimulation to perform the sham condition. However, the stimulator was turned off after 30 s as described elsewhere (Gandiga *et al*., 2006; Montenegro *et al*., 2011; Montenegro *et al*., 2013; Montenegro *et al*., 2012; Okano *et al*., 2013). For both anodal tDCS and sham condition the stimuli were applied at rest before MSEX.

Statistical analyses

Data normality was confirmed by the Kolmogorov–Smirnov test. Therefore the effects of different stimulation (anodal *vs*. sham condition) on performance variables (i.e., torque, total work, percentage of work fatigue, and RMS) during the successive sets of MSEX were compared by 2-way ANOVA with repeated measures followed by Tukey *post hoc* verification in the event of significant F ratios. Two-tailed statistical significance was accepted as $P \leq .05$ and data were expressed as mean ± standard deviation. All statistical analyses were performed using Statistica 7.0 software (Statsoft™, Tulsa, OK, USA).

Results

Figure 2 shows data obtained for total work and % work fatigue during maximal dynamic strength exercise in both sham and anodal tDCS. No significant main effect of tDCS was found in average total work (knee extension: $F = 0.47$; $P = .49$, and knee flexion: $F = 0.05$; $P = .82$) and % fatigue (knee extension: $F = 0.008$; $P = .92$, and knee flexion: $F = 0.02$; $P = .87$). Interactions between sets and tDCS conditions were not significant for average total work (knee extension: $F = 1.38$; $P = .26$, and flexion: $F = 0.70$; $P = .49$) and % fatigue (knee extension: $F = 0.34$; $P = .71$, and knee flexion: $F = 1.15$; $P = .32$) as well. However, significant main effects were found with regard to the number of sets for both total work (knee extension: $F = 27.66$; $P < .001$, and knee flexion: $F = 16.70$; $P = < .001$) and % fatigue (knee extension: $F = 33.46$; $P = < .001$, and knee flexion: $F = 15.75$; $P < .001$).

Figure 3 exhibits individual and mean values of muscle torque in each set for knee extension and flexion exercises. The anodal tDCS was not able to modify the power output versus sham condition in any of the exercises and sets ($P > .05$).

Figure 4 depicts the %RMS obtained by surface electromyographic of the vastus medius (VM), rectus femoris (RF), biceps femoris (BF), and semitendinosus (ST) muscles, during MSEX in both sham and anodal tDCS. No significant main effects were detected for tDCS on muscle activities (VM: $F = 0.91$, $P = .36$; RF: $F = 0.50$, $P = .49$; BF: $F = 0.10$, $P = .75$, and ST: $F = 0.05$, $P = .81$) and sets (VM: $F = 0.95$, $P = .40$; RF: $F = 0.49$, $P = .61$; BF: $F = 1.07$, $P = .36$, and ST: $F = 0.05$, $P = .94$). Significant interactions were detected between sets and tDCS conditions for VM and RF (VM: $F = 3.81$, $P = .039$; RF: $F = 3.63$, $P = .04$), but not for BF and ST (BF: $F = 0.82$, $P = .45$, and ST: $F = 0.33$, $P = .72$.

Discussion

The main purpose of the present study was to investigate the potential effects of 20 min of anodal tDCS applied over the left motor cortex, upon the maximal isokinetic strength performance in healthy young men. Our findings indicated that anodal tDCS was not able to increase neither force production, nor fatigue resistance during maximal isokinetic exercise when compared to sham condition. These findings were reinforced by the electrical muscle activity evaluation, showing that 20 min of anodal tDCS applied prior to maximal strength exercise did not modify the muscle activity during knee flexion and extension actions.

Previous studies demonstrated that tDCS over the motor cortex may improve the motor performance in stroke patients (Gandiga *et al*., 2006; Hummel *et al*., 2005; Hummel & Cohen, 2005; Tanaka *et al*., 2011). Hummel *et al*. (2006) reported an increase of maximal finger pinch force in paretic hand muscles. More recently, Tanaka *et al*. (2011) reported an increase in isometric force production in patients with hemiparetic stroke after anodal tDCS applied on the lower limb motor cortex area. Some previous research (Boggio *et al*., 2006b; Cogiamanian *et al*., 2007; Kan *et al*., 2013; Tanaka *et al*., 2009; Williams *et al*., 2013)

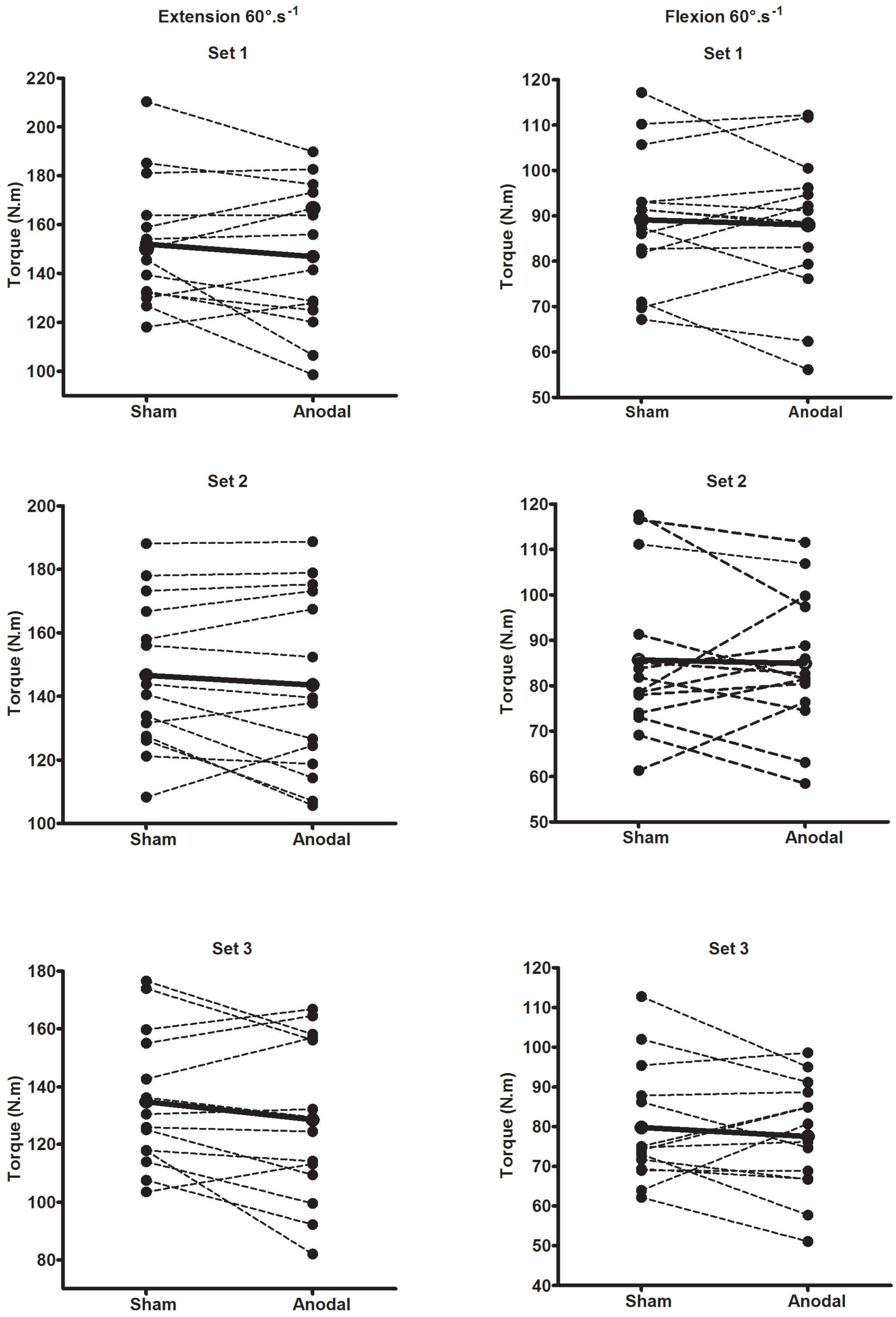


Figure 3. Individual (dashed lines) and mean (solid line) values of muscle torque per sets within knee extension and flexion after anodal tDCS and sham condition (n=14). 2-way ANOVA with repeated measures did not detected significant differences between anodal and sham tDCS for muscle torque per sets [$F(5,78) = 1.16$; $P = .33$]. tDCS = Transcranial direct current stimulation.

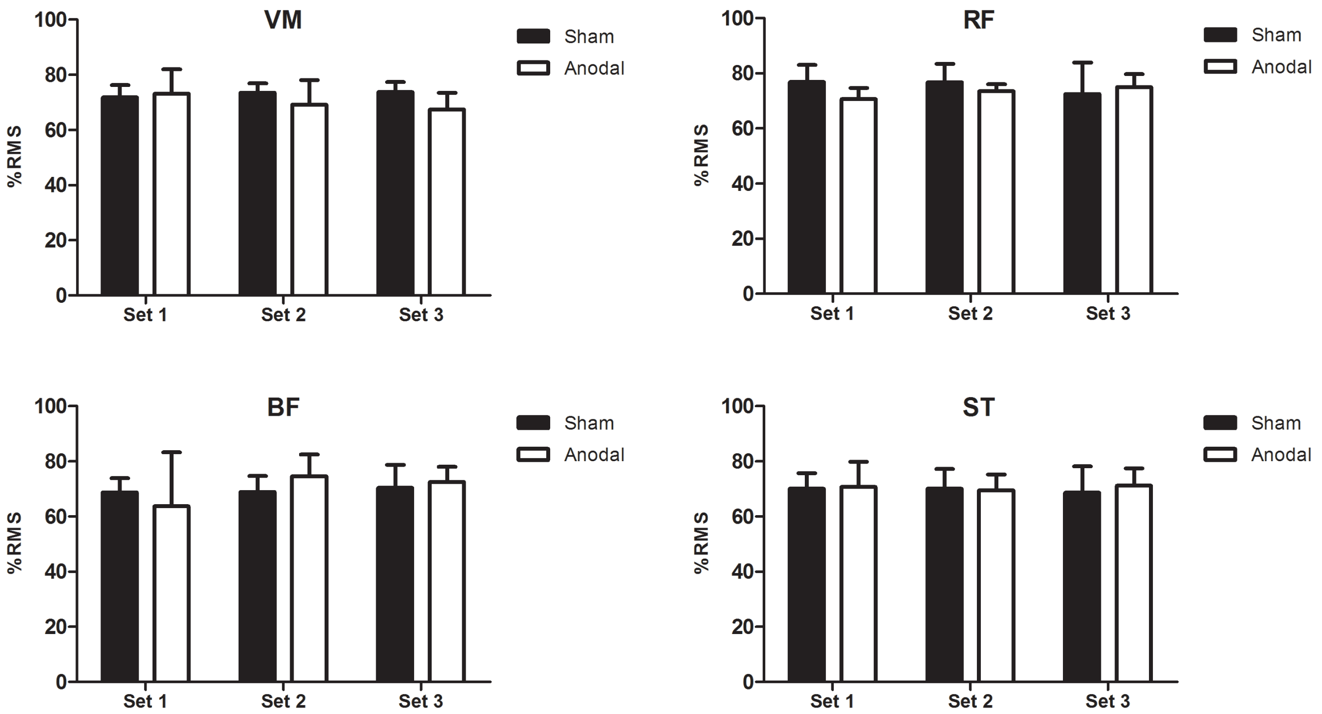


Figure 4. Mean±SD values of %RMS obtained by surface electromyography assessment for the vastus medialis (VM), rectus femoris (RF), biceps femoris (BF) and semitendinosus (ST) within maximal isokinetic strength exercise after sham and anodal tDCS (n=6). 2-way ANOVA with repeated measures did not detected significant differences between anodal and sham tDCS for %RMS (P = .64). %RMS = root means square percentage. tDCS = Transcranial direct current stimulation

with healthy subjects also suggested that anodal tDCS would be effective to improve muscle performance assessed by low-intensity exercises or very specific tests, for example the Jebsen-Taylor Hand Function Test (Boggio *et al*., 2006a), elbow flexors isometric force with 20-35% of maximal volitional contraction (Cogiamanian *et al*., 2007; Kan *et al*., 2013; Williams *et al*., 2013), or maximal pinch force of toes (Tanaka *et al*., 2009). To the best of our knowledge, this is the first study to investigate the effect of anodal tDCS applied to the motor cortex on the maximal performance of larger muscle groups, as found in the lower limbs. Since the physical performance was not influenced by the anodal tDCS, it is reasonable to suggest that the effectiveness of such stimulation may depend on the type of contraction demand (i.e., isometric *vs.* dynamic) or muscle mass recruited (large *vs.* small muscle groups), which can influence the magnitude of motor cortex requirements. In fact, such factors might help explaining the controversial results found on the tDCS effects on physical performance. Additional research is warranted to ratify the present findings and to verify these possibilities.

Interestingly, Boggio *et al*. (2006b) showed a significant increase of motor performance in the non-dominant hand after anodal, but not sham tDCS, over the contralateral primary motor cortex. In addition, anodal and sham tDCS applied on the dominant primary motor cortex did not result in significant hand motor function improvement. The authors suggested that the under-use of one of the hands would lead to functional changes in the non-dominant motor cortex, which could contribute to the decreased dexterity of this hand (Armstrong & Oldham, 1999; Ozcan, Tulum, Pinar, & Baskurt, 2004). On the other hand, the optimal activation of the dominant cerebral hemisphere could explain the lack of tDCS effects on the dominant hand. In brief, an additional increase in neuronal excitability by external sources (i.e anodal tDCS) would not result in additional benefits in the function of the dominant hand. This premise is in line with a previous study showing that the dominant compared to non-dominant motor cortex exhibits lower motor threshold, higher motor evoked potential (De Gennaro *et al*., 2004), and shorter silent period (Priori *et al*., 1999). Our results seem to concur with these findings, since all subjects in this study were right-leg dominant – actually, this was the reason why the anodal tDCS was applied over the contralateral motor cortex.

This was also observed by Hendy and Kidgell (2013), who showed that the chronic effect of anodal tDCS over the left M1, in combination with strength training of wrist extensors did not induce voluntary dynamic strength gains when compared to high intensity strength training. In addition, Kan *et al*. (2013) reported that 10-min anodal tDCS at 2 mA did not affect the maximal voluntary isometric contraction of the elbow flexors, nor the time to contraction failure in young healthy men, which has been attributed to a probable ceiling-like effect of tDCS. Lampropoulus *et al*. (2013) also failed to detect significant differences between anodal and sham tDCS with regard to acute effects on maximum voluntary force, perception of effort, or electrical muscle activity during elbow flexion.

Our findings reinforce these data, since no change in voluntary muscular drive could be detected during knee flexion and extension exercises. Therefore, it is feasible to speculate that: (i) subjects exhibiting cortical hypo-activation, particularly in the dominant motor cortex (i.e. stroke patients) would be more responsive to anodal tDCS compared to healthy subjects; and (ii) in healthy subjects the increase of neuronal excitability induced by tDCS would be most likely to increase the performance of submaximal than maximal dynamic or isometric exercises.

Available evidence suggests that the ipsilateral motor cortex might also contribute to force production, sending efferent commands to activated muscles. Hence there would be a complementary modulation of muscle force, concomitant to contralateral motor cortex activation (Dai, Liu, Sahgal, Brown, & Yue, 2001; Shibuya, 2011; Shibuya, Sadamoto, Sato, Moriyama, & Iwadate, 2008; Ward & Frackowiak, 2003). In such case, anodal tDCS applied over the ipsilateral motor cortex could be an interesting strategy to optimize muscle performance in healthy subjects, as previously demonstrated (Boggio *et al*., 2006b). Another possible strategy to optimize the leg muscle performance would be to amplify the electrical current density (μA/cm^3) under the active electrodes (McCreery, Agnew, Yuen, & Bullara, 1990) or to increase the duration of tDCS stimulus, in order to promote more effective changes in the corticomotor excitation, responsible to recruit motor units of major muscles groups in the lower limbs (Bastani & Jaberzadeh, 2012). Finally, the anodal tDCS could be applied during (and not prior to) the exercise performed until fatigue, since there is preliminary evidence demonstrating that anodal tDCS would be effective to bolster the capacity to exercise under such conditions (Williams *et al*., 2013). Again further research is necessary to elucidate these points.

The main limitation of this study was the fact that specific cortical areas activated by tDCS were not controlled. Unfortunately it was not possible to use image production techniques such as fMRI to control for the actually stimulated areas. Such control would allow a better understanding of the mechanisms underlying the observed effects on muscle performance during maximal exercise. However, it is worthy to notice that a previous study has shown that 2mA of bi-cephalic tDCS applied during 10 min over the leg area of the primary motor cortex was able to increase the leg corticospinal tract excitability for at least 60 min (Jeffery *et al*., 2007). Therefore, it is highly probable that the bi-cephalic anodal tDCS presently applied has indeed activated the targeted cortical areas.

In conclusion, anodal tDCS was not able to increase the performance during maximal isokinetic strength exercise in healthy young individuals. These results may suggest that this technique would not be effective to improve maximal strength production in healthy subjects or during activities demanding maximal strength.

In practical terms, despite the fact that some evidence suggested that tDCS might be effective to improve physical performance and attenuate effort perception during submaximal exercise in healthy and unhealthy subjects, our data suggest that this would not be true during maximal strength exercise. This information is original as has evident application within sports and rehabilitation sets. In brief, our findings indicate that tDCS should not be considered to increase the performance of tasks or exercises demanding maximal strength. Further research applying alternative tDCS protocols, with different electrodes positioning for contralateral or ipsilateral motor cortex stimulation, or increased electrical current density and time should be tested to investigate the potential effects of electrical stimulation to improve strength performance in healthy populations.

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