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Bi-hemispheric anodal transcranial direct current stimulation worsens taekwondo-related performance

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ABSTRACT

Transcranial Direct Current Stimulation (tDCS) is a neuromodulatory technique that has been used as an ergogenic aid in exercise/sports performance. However, little is known about its effects on highly-trained subjects, as athletes. The present study aimed to verify the effects of bi-hemispheric anodal tDCS (a-tDCS) on the performance of taekwondo athletes. Additionally, we investigated the persistence of the effects of the a-tDCS one hour after it. Nineteen Taekwondo athletes received active or sham bi-hemispheric a-tDCS over the primary motor cortex (M1). a-tDCS was delivered at 1.5 mA for 15 min. Athletes performed Countermovement Jumps (CMJ) and the Frequency Speed of Kick Test (FSKT) immediately (Mo1) and one hour after stimulation (Mo2). The athletes also reported their session-rating of perceived exertion (session-RPE). The total number of kicks (TK) was higher in sham than in the active a-tDCS condition ($p < 0.01$). In addition, TK was higher at Mo2 than at Mo1 ($p < 0.05$). Similarly, the session-RPE was higher in the a-tDCS condition ($p < 0.05$) and was greater one-hour post-stimulation ($p < 0.01$). No differences were found for CMJ performance ($p > 0.05$). Thus, bi-hemispheric a-tDCS worsens performance of taekwondo athletes, and the effect remains present even 1 h after the stimulation.

1. Introduction

Transcranial direct current stimulation (tDCS) is a low-cost non-invasive brain stimulation technique that is used to modulate cortical excitability, producing facilitatory, under the anodal electrode, or inhibitory effects, under the cathodal electrode (Nitsche et al., 2003; Nitsche and Paulus, 2001; Thair, Holloway, Newport, & Smith, 2017). The acute neuromodulatory effects of tDCS are mainly attributed to subthreshold changes in the resting membrane potential (Stagg & Nitsche, 2011; Yavari, Nitsche, & Ekhtiari, 2017). If applied for enough time, tDCS effects can persist for up to 90 min (Nitsche & Paulus, 2001) and the neuroplastic after-effects are related to long-term potentiation-like mechanisms (Liebetanz, Nitsche, Tergau, & Paulus, 2002; Stagg & Nitsche, 2011). Although not a consensus, the enhancement of motor cortical excitability by tDCS delivered over the M1 has been found to improve motor performance in healthy subjects (e.g., Boggio et al., 2006; Vargas et al., 2018).

More recently, interest in the use of tDCS to enhance exercise/sports performance has increased (for more details see Angius, Hopker, & Mauger, 2017; Banissy and Muggleton, 2013; Edwards et al., 2017). For instance, several studies have investigated the effects of tDCS on maximal dynamic strength (e.g. Frazer, Williams, Spittles, & Kidgell, 2017; Hendy, Teo, & Kidgell, 2015), maximal isometric strength (e.g. Giboin & Gruber, 2018; Vargas et al., 2018), muscle endurance (e.g. Flood, Waddington, Keegan, Thompson, & Cathcart, 2017; Maeda et al., 2017), aerobic performance (e.g. Angius, Hopker, Marcora, & Mauger, 2015; Angius et al., 2018), and other physical capacities, such as flexibility (e.g. Mizuno & Aramaki, 2017) and muscle power (e.g. Lattari et al., 2017), in particular, by stimulating the M1 area.

A possible explanation for the beneficial effects of anodal tDCS stimulation of the M1 area in exercise/sports performance can be related to the fact that changes in cortical excitability or on the cortico-spinal pathway may increase M1 output inducing an increase in the neural drive, which denotes the magnitude of efferent neural output to motor units, generating an increase in the rate of force development (Gabriel, Kamen, & Frost, 2006; Gandevia, 2001; Gandevia, Allen, Butler, & Taylor, 1996; Lattari et al., 2017); and the prominent role of the M1 brain area in supraspinal fatigue, that is related to the failure to generate output from the M1 (Angius et al., 2017; Gandevia, 2001). Supraspinal fatigue, which is accompanied by changes in motor cortex excitability, together with peripheral mechanisms, participates in muscle fatigue (Angius et al., 2017; Gandevia, 2001). For this reason, interventions that increase M1 excitability might increase the output from M1, consequently delaying the development of supraspinal fatigue and improving exercise/sports performance. Additionally, in short maximal efforts, studies have demonstrated that the voluntary activation is actually sub-maximal, suggesting that even though the muscles retain potential capacity, the central nervous system fails to generate the maximal evocable force (Gandevia, 2001; Gandevia et al., 1996). Therefore, the performance in such tasks could also be improved by an increase in the output from M1.

Although some results have demonstrated the beneficial effects of anodal stimulation of the M1 (e.g. Angius et al., 2018; Lattari et al., 2017), other studies have failed to demonstrate such effects (e.g. Angius et al., 2015; Hendy & Kidgell, 2013). The inconsistency of the effects of tDCS can be explained by several factors, as montages adopted (areas of stimulation or inhibition), intensity and duration of the stimulation, electrodes size, and the interval between the stimulation and the task to be performed (Angius et al., 2018; Colzato, Nitsche, & Kibele, 2017; Lattari et al., 2017). Moreover, another possible factor that could explain the controversial results could be the level of performance of the subject. In addition, few studies have investigated bilateral (Pixa & Pollok, 2018) and lower limbs tasks (e.g. Maeda et al., 2017; Tanaka, Hanakawa, Honda, & Watanabe, 2009). More specifically, tasks that involve simultaneous coordination of right and left lower limbs (as often used in the sports) are even scarce.

In this kind of task, an electrode montage that involves placing the anodal electrode over the main target area and the cathodal electrode over the contralateral area may induce a decreased excitability in the area over which the cathode was positioned, that may, therefore, nullify or negate the positive effects of the anodal stimulation (Angius, Pageaux, Hopker, Marcora, & Mauger, 2016). For this reason, it seems that a bi-hemispheric montage in which anodal electrodes are placed over the main target area (e.g. right and left M1 target area) and the cathodal electrodes placed in the extracephalic area (e.g. shoulders) might be more appropriate (Angius et al., 2018; Angius et al., 2016) for tasks that involve simultaneous coordination of right and left lower limbs.

Thus, based on the idea tDCS may increase the output from M1, therefore inducing an increase in neural drive (Gabriel et al., 2006; Lattari et al., 2017), delaying the development of supraspinal fatigue (Angius et al., 2017; Gandevia, 2001), and consequently contributing to the increase in motor performance, we addressed the question of whether the anodal tDCS of M1 enhances the motor performance of taekwondo athletes. In this way, we assessed the effects of bi-hemispheric anodal stimulation with electrodes positioned over M1 (C3 and C4 according to the International 10–20 EEG system) on the performance of the Countermovement Jump (CMJ) and the Frequency Speed of Kick Test (FSKT). The choice of the CMJ and FSKT is based on the fact that these tasks try to replicate some characteristics, as sequence of the most used technical kicks (*bandal tchagui*), physical and physiological demands, observed during taekwondo matches and training sessions (Goulart et al., 2016; Santos & Franchini, 2018; Santos, Valenzuela, & Franchini, 2015). Therefore, the primary aim of the present study was to verify the effects of bi-hemispheric anodal stimulation of M1 on the CMJ and FSKT performance of taekwondo athletes. The secondary aim was to investigate if the effect of bi-hemispheric a-tDCS was maintained after one hour of the stimulation. We hypothesized that bi-hemispheric anodal stimulation of M1 would improve the CMJ and FSKT performance of Taekwondo athletes as compared with the sham condition and that the effects of the stimulation would remain detectable even one hour after the stimulation.

2. Methods

2.1. Participants

Nineteen black belt Taekwondo athletes (12 men, 7 women; mean ± SD, age: 19 ± 3 years; body mass: 60.7 ± 6.9 kg; height: 171.7 ± 6.9 cm; body fat: 13 ± 8%; practice time: 8.9 ± 5.0 years; level: international/national) volunteered to participate in this study. The athletes participated in approximately seven taekwondo-specific training sessions and three strength-training sessions weekly. The athletes reported to be free from mental disorders and injuries in the lower body and were not engaged in any rapid acute weight loss strategy during the study period. The participants were informed about the procedures and possible risks before signing the written informed consent. The research was approved by the local Research Ethics Committee (approval number: 79302817.0.0000.5149), in accordance with the Declaration of Helsinki.

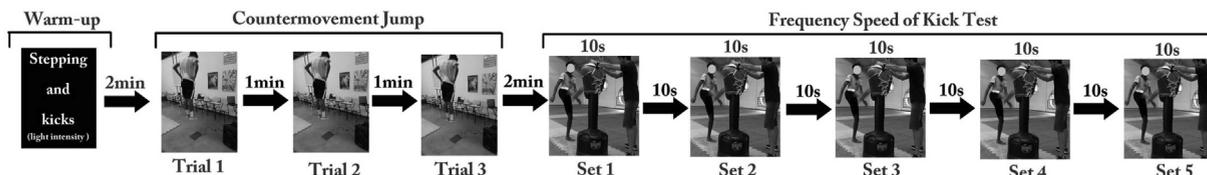## Procedures of the experimental sessions
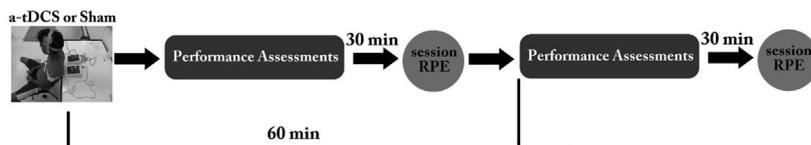
Performance Assessments

Fig. 1. Procedures of the experimental sessions. a-tDCS, anodal transcranial direct current stimulation; session-RPE, session rating of perceived exertion; CMJ, countermovement jump; FSKT, frequency speed of kick test; min = minute; s = seconds.

2.2. Experimental protocol

The participants visited the laboratory on three different occasions, one preliminary visit and two experimental visits. Although the athletes selected in the present study frequently used the FSKT and CMJ in their training routine, the preliminary visit was directed to the characterization of the subjects and their familiarization with the study protocols. The athletes answered a questionnaire about their competitive level and training routines and had their body mass, height, and body skinfolds measured. For familiarization, the athletes performed 10 CMJ with 1-minute recovery between jumps and then performed the FSKT.

Before the beginning of the stimulation, the subjects should report their rating of perceived recovery (RPR). The RPR scale proposed by Laurent et al. (2011) was used to control for a possible influence of the recovery status on the performance outcomes between experimental sessions.

For the experimental sessions, as previously conducted by other authors (e.g. Angius et al., 2017, 2016; Valenzuela et al., 2019; Vargas et al., 2018), athletes were randomly assigned in a single-blind and counterbalanced order to either the anodal (a-tDCS) or the sham condition. In each session, the subjects executed performance assessments composed by CMJs and the FSKT immediately and 1 h after the stimulation. Additionally, the subjects should report their session rating of perceived exertion (session-RPE) 30 min after the performance assessment. The experimental sessions were performed at the same time of the day and were interspaced by at least 48 h. The subjects were instructed to avoid caffeine and alcohol consumption and strenuous exercise for 48 h before each visit. The procedures performed are illustrated in Fig. 1.

2.3. Transcranial direct current stimulation

The present study adopted a bi-hemispheric extracephalic montage similar to the one used by Angius et al. (2018). For the anodal condition (a-tDCS) the electrodes were positioned to target the M1 bilaterally [points C3 and C4 according to the international 10–20 EEG system (Angius et al., 2017; Angius et al., 2016; Klem, Luders, Jasper, & Elger, 1999; Valenzuela et al., 2019; Vargas et al., 2018), while the cathodal electrodes were placed on the ipsilateral shoulders]. The stimulation intensity was set at 1.5 mA and was delivered for 15 min using rubber electrodes (anodes: 35 cm^2, cathodes: 25 cm^2) covered with sponges soaked in saline solution (NaCl 0.9%). The current was ramped up and down for 30 s. For the sham condition, the same montage was used, but the current was turned off after 30 s. Two tDCS equipment (Soterix Medical Inc., 1300A) were used to deliver the stimulation. The participants reported itching and tingling sensation under the electrodes during tDCS but did not report any adverse effects.

2.4. Performance assessments

The performance assessments were conducted at two moments: immediately (Moment 1) and 1 h after (Moment 2) the cessation of the stimulation. The subjects started by warming-up and then performed the CMJs and the FSKT (Fig. 1).

2.4.1. Warm-up

The subjects performed 5 min of warm-up consisting of 2 min of stepping and moving according to the taekwondo-specific techniques and 3 min of low-intensity taekwondo kicks.

2.4.1.1. Countermovement Jump.
Two minutes after the warm-up the subjects performed 3 CMJs with 1-minute rest between them. The participants were instructed to jump as high as possible and to maintain their hands on the waist and knees extended during the

aerial phase. The jumps were performed in a contact platform (Hidrofit, Minas Gerais, Brazil). The highest jump height of the three trials was considered for analysis. The subjects rested for 2 min and then proceeded to the FSKT.

2.4.2. Frequency Speed of Kick Test (FSKT)

The FSKT 90 s duration was performed as described previously (Santos & Franchini, 2016, 2018). After a sound signal, the athletes had to perform the maximal number of kicks, alternating right and left legs. The technique used was the *bandal tchagui*. The test consists of 5 sets of 10 s with 10 s of rest between sets, performed in a kicking dummy (Boomboxe, São Paulo, Brazil) equipped with a taekwondo body protector (Protector, Daedo). The performance was determined by the number of kicks in each set ($FSKT_{1-5}$), the total number of kicks (sum of the number of kicks in all sets - $FSKT_{total}$) and the kick decrement index (KDI). The KDI indicated the performance decrease throughout the test and was calculated according to the equation 1 (Santos & Franchini, 2016, 2018).

$$KDI\,(\%) = \left[1 - \frac{FSKTset1 + FSKTset2 + FSKTset3 + FSKTset4 + FSKTset5}{bestFSKTsetxnumberofsets} \right] \times 100$$

where: FSKT is the number of kicks performed; set1-5 refers to the number of the set performed (e.g. set1 = first set); the number of sets = 5.

2.4.3. Session – Rating of Perceived Exertion (session-RPE)

The CR-10 RPE-scale proposed by Foster et al. (2001) was used to evaluate the athletes' perceived exertion. The subjects had to report their session-RPE 30 min after the FSKT execution in each moment. Athletes were oriented to consider the whole session performed.

2.5. Statistical analysis

The distribution of each variable was examined using the Shapiro Wilk test. When the assumptions of normality were not assumed, median, interquartile range and non-parametric statistical test were used. On the other hand, when normality assumptions were assumed, mean, standard error and parametric statistical test were used.

For analysis of RPR, the Wilcoxon test was used. For the CMJ, $FSKT_{total}$, KDI, and session-RPE two-way repeated measures ANOVA [2 conditions (anodal tDCS and Sham) versus 2 moments (immediate and one hour later)] was used. The sphericity assumption was tested using the Mauchly's test, and the Greenhouse-Geisser correction was used when the sphericity assumption was violated. For the $FSKT_{1-5}$, three-way repeated measures ANOVA [2 conditions (anodal tDCS and Sham) versus 5 sets ($FSKT_{1-5}$) versus 2 moments (immediate and one hour later)] was used and Bonferroni post-hoc tests were performed in sets comparisons.

As suggested by Field (2009), The equation to convert a z-score into the "r" effect size (classified by small: 0.10 to 0.30; moderate: 0.30 to 0.50; and large: 0.5 or larger) was used for effect size calculation in Wilcoxon test. Similar to other studies (e.g. Suppiah, Low, & Chia, 2016), partial eta-squared (ηp^2) was used as a measure of effect size on the repeated measures ANOVA analysis and classified using the following scale (small: 0.01; moderate: 0.09; large: 0.25). All analyses were conducted using α = 5%.

3. Results

There were no significant differences [z = 1.412, p = .158; ES = 0.32 (medium)] in athletes' RPR between conditions [Median of RPR in tDCS condition = 9 (interquartile range = 2) and Median of RPR in Sham condition = 10 (interquartile range = 2)].

Regarding CMJ height (Fig. 2), there were no significant effects of conditions [$F_{(1,18)}$ = 0.126; p = .726; ηp^2 = 0.007 (small)], moments [$F_{(1,18)}$ = 0.518; p = .481; ηp^2 = 0.028 (small)] or interaction between moment and condition [$F_{(1,18)}$ = 0.352; p = .560; ηp^2 = 0.019 (small)].

The total number of kicks during the FSKT (Fig. 3a) was affected by condition [$F_{(1,18)}$ = 11.687; p = .003; ηp^2 = 0.394 (large)]
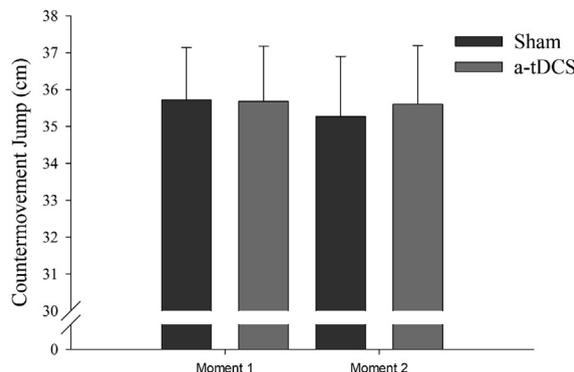

Fig. 2. CMJ measure in moments (immediate and one hour later) and conditions (a-tDCS and Sham).
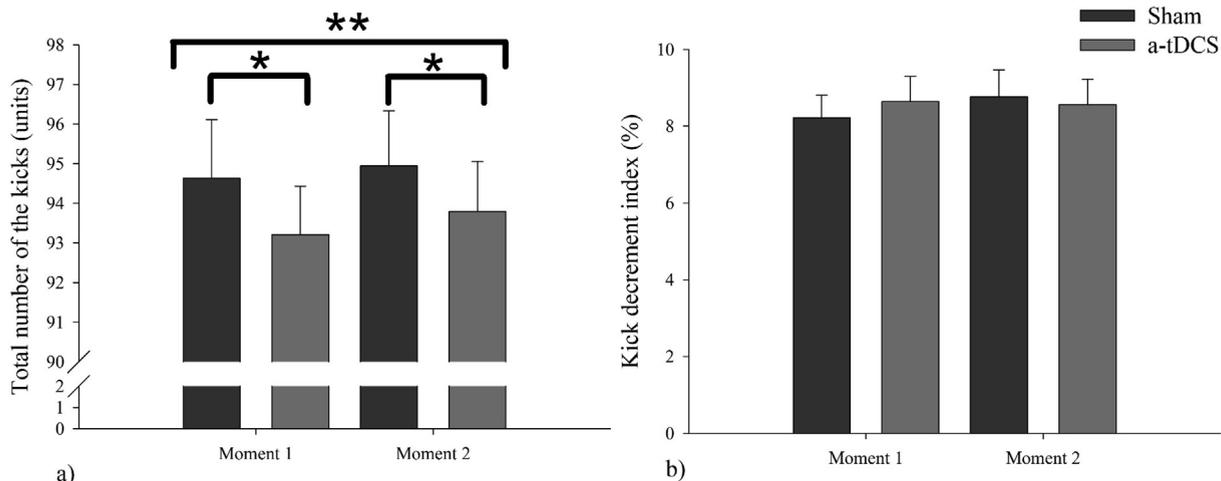
Fig. 3. FSKT measures [a) Total Number of Kicks and b) kick decrement index] in moments (immediate and one hour later) and conditions (a-tDCS and Sham). Significant differences in conditions (*) and moments (**).

and moments [$F(1,18) = 4.738$; $p = .043$; $\eta p^2 = 0.208$ (moderate)], but there was no interaction between moment and condition [$F(1,18) = 0.170$; $p = .685$; $\eta p^2 = 0.009$ (small)](Fig. 3a). The total number of kicks was higher one hour after stimulation than immediately after stimulation, regardless of the condition. In addition, the a-tDCS condition resulted in lower number of kicks than sham condition.

There was no significant differences between conditions [$F(1,18) = 0.056$; $p = .816$; $\eta p^2 = 0.003$ (small)], moments [$F(1,18) = 0.192$; $p = .667$; $\eta p^2 = 0.011$ (small)], or interaction between moment and condition [$F(1,18) = 0.677$; $p = .421$; $\eta p^2 = 0.036$ (small)] for the kick decrement index (Fig. 3b).

Regarding the number of kicks in each set (Fig. 4), there were significant main effects of conditions [$F(1,18) = 11.687$; $p = .003$; $\eta p^2 = 0.394$ (large effect)], moment [$F(1,18) = 4.738$; $p = .043$; $\eta p^2 = 0.208$ (moderate)], and sets [$F(1.57,28.240) = 137.216$; $p < .001$; $\eta p^2 = 0.884$ (large)]. The number of kicks was lower at a-tDCS condition than sham condition, and the moment 2 exhibited higher number of kicks than moment 1. In addition, the athletes exhibited higher number of kicks in the preceding sets ($FSKT_1 > FSKT_{2-5}$; $FSKT_2 > FSKT_{3-5}$; $FSKT_3 > FSKT_{4-5}$; $FSKT_4 > FSKT_5$) ($p < 0.01$, all comparisons). No interactions between condition and sets [$F(2.69, 48.43) = 0.493$; $p = .669$; $\eta p^2 = 0.027$ (small)], condition and moments [$F(1,18) = 0.170$; $p = .685$; $\eta p^2 = 0.009$ (small)], moment and sets [$F(2.60,46.826) = 2.552$; $p = .075$; $\eta p^2 = 0.124$ (moderate)] or condition, moment and sets [$F(4,72) = 1.700$; $p = .159$; $\eta p^2 = 0.086$ (small)] were found (Fig. 5).

Effects of condition [$F(1,18) = 4.461$; $p = .049$; $\eta p^2 = 0.199$ (moderate)] and moment [$F(1,18) = 8.652$; $p = .009$; $\eta p^2 = 0.325$ (large)] were detected, but no interaction between moment and condition [$F(1,18) = 0.001$; $p = .999$; $\eta p^2 = 0.001$ (small)] was found for the session-RPE. The athletes reported higher session-RPE at moment 2 than at moment 1, regardless of the condition. In addition, the a-tDCS condition resulted in higher session-RPE than sham.
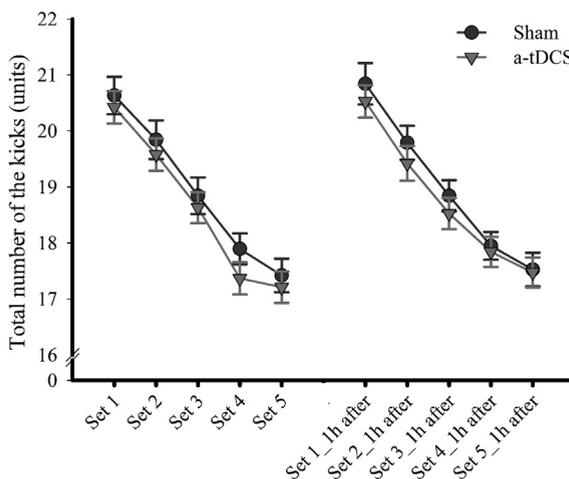

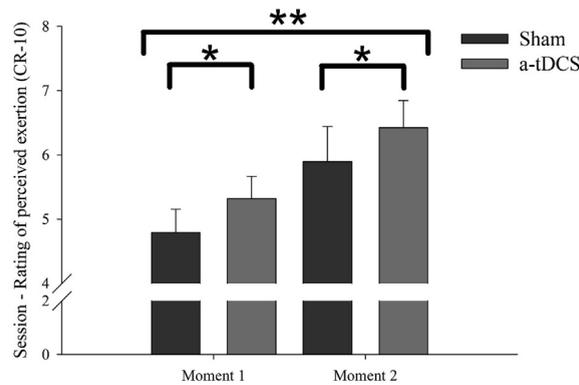**Fig. 4.** FSKT measures – number of kicks in each set.

Fig. 5. session-RPE 30 min after the FSKT execution in each moment (immediate and one hour later) and conditions (a-tDCS and Sham). Significant differences between conditions (*) and moments (**).

4. Discussion

To the best of our knowledge, this is the first study assessing the effects of the bi-hemispheric anodal stimulation on the performance of the CMJ and the FSKT of taekwondo athletes. We hypothesized that the M1 anodal bi-hemispheric condition would enhance the performance of the CMJ and FSKT of taekwondo athletes when compared with the sham condition and that the effects of anodal bi-hemispheric condition would remain present even 1 h after the stimulation. Therefore, the results of the present study only confirmed our secondary hypothesis.

A possible beneficial effect of M1 anodal bi-hemispheric stimulation on FSKT and CMJ performance would be related to the prominent role of the M1 brain area in the development of supraspinal fatigue (Angius et al., 2017; Gandevia, 2001). The bi-hemispheric a-tDCS of M1 would increase local excitability, increasing its output and delaying the development of the supraspinal fatigue. Further, the increased M1 output could also enhance the central nervous system's ability to generate force during maximal efforts (Gandevia, 2001; Gandevia et al., 1996). However, our results showed that M1 anodal bi-hemispheric condition worsened the performance of the taekwondo athletes on FSKT.

A recent study of Furuya, Klaus, Nitsche, Paulus, and Altenmüller (2014) also found a deleterious effect of a-tDCS. The authors delivered 2 mA to the M1 of subjects for 15 min and found a decrease in the finger performance of expert pianists but not in the performance of non-musicians. The interesting explanation of Furuya et al. (2014) lies in the fact that playing the piano requires many varying patterns of movement coordination across joints and muscles that may require an elaborate motor cortex organization. Their results suggested that, in tDCS studies, it is important to consider the subject's level of expertise on the task.

Motor skill acquisition is characterized by the cognitive, associative, and autonomous stages (Fitts & Posner, 1967), that are accompanied by neuroplasticity with cortical and subcortical interactions (Karni et al., 1998; Puttemans, Wenderoth, & Swinnen, 2005). In the cognitive stage of the motor skill acquisition, an enlarged M1 activation as a result of practice has been observed previously and may be the result of the building of a specific motor representation, such as the establishment of the spatiotemporal ordering of muscle commands (Karni et al., 1998; Puttemans et al., 2005). Contrarily, in the autonomous stage, subjects accumulate a considerable amount of practice (e.g. athletes) and exhibit decreases in the M1 activation (Karni et al., 1998; Puttemans et al., 2005). In this sense, neuroimaging studies (e.g. Naito & Hirose, 2014) have reported a lower cortical activation in skilled players when compared to non-skilled players, which suggest selective recruitment of specific motor neurons. Indeed, a study with other striking combat sport athletes (i.e. karate athletes) indicated that elite karate athletes were characterized by a reduced cortical activation during simple voluntary hand movements (Del Percio et al., 2010), which has been denominated "neural efficiency" (Del Percio et al., 2010; Del Percio et al., 2008). Therefore, the facilitation of motor cortex excitability in athletes (well-trained subjects) may disrupt neuromuscular recruitment, causing unwanted facilitation of motor neurons innervating muscles expected to be suppressed (Furuya et al., 2014).

Our results suggest that taekwondo athletes may present a different functional architecture, that means how a certain change in structure (architecture) could generate a certain change in a brain function, and a lower activation of the motor cortex compared to less skilled subjects, a characteristic previously reported in athletes (for more details, see Jäncke, Koeneke, Hoppe, Rominger, & Hänggi, 2009; Naito & Hirose, 2014; Yarrow, Brown, & Krakauer, 2009). Additionally, for the execution of a complex task in which coordination is important to perform a greater number of kicks in the target, an elaborate cortex motor organization is required. Thus, athletes' motor cortex might be disturbed more easily than the motor cortex of non-athletes, containing relatively less specialized motor programs (Furuya et al., 2014). As hypothesized by Furuya et al. (Furuya et al., 2014), "It is also possible that the relation between training and motor cortical excitability forms an inverse U-shape…". In addition, another interesting result found by us shows that the session-RPE was significantly higher in bi-hemispheric anodal condition than in sham condition. A plausible explanation can be related to the disruption of the neuromuscular recruitment. The unwanted facilitation of motor neurons innervating muscles to be suppressed could have led to increased energy expenditure and consequently to a greater perception of effort.

Different from our hypothesis, bi-hemispheric anodal stimulation did not change the performance of the trained taekwondo

athletes in the CMJ. A recent study conducted by Lattari et al. (2017) showed that CMJ performance was improved by anodal tDCS stimulation [2 mA during 20 min with the anodal electrode placed over the Cz (according to the 10–20 EEG system) and the cathode electrode placed on right orbitofrontal cortex] in subjects with advanced weight-training experience. Even though the different results can be attributed to the different stimulation protocols adopted, it is important to note the differences in the subjects' characteristics. Differently from the subjects investigated by Lattari et al. (2017), our volunteers are often exposed to CMJ in the control of the training load and in the constant evaluations in which they are submitted and probably are better trained at the task.

As we found deleterious effects of the bi-hemispheric anodal condition when compared with the sham condition in the FSKT$_{total}$ but not in the CMJ, it seems plausible to speculate that the complexity of the task, coupled with the practitioner's experience, also appears to be an important covariant in the interpretation of tDCS-related outcomes. The definition of the term task complexity (Hausmann, Kirk, & Corballis, 2004) used by us is related to the intrinsic (e.g. multi-joint actions) and extrinsic task demands (spatial complexity of the action). Therefore, we are assuming that FSKT is a more complex task than CMJ because both intrinsic and extrinsic demands are higher in the FKST. As the CMJ is a less complex task with lower coordination demand, it seems that the a-tDCS is not able to impair its execution. In addition, as we were not able to detect a deleterious effect of a-tDCS on the isolated sets of the FSKT (lack of interaction between condition and sets), it seems that the duration of the task also influences the effects of the a-tDCS on the performance of athletes. Therefore, in short duration tasks such as the CMJ and the sets of the FSKT, there is not enough time to develop substantial supraspinal fatigue, and/or the deleterious effects caused by the disruption of the neuromuscular system may not be detectable.

Edwards et al. (2017) presented some concerns regarding the expansion of direct-to-consumer usage of tDCS, especially in athletes. The present study may have practical implications, in particular regarding the potential use of tDCS for ergogenic purposes. Unlike other neurostimulation techniques (e.g., rTMS), tDCS devices are relatively small and easy to use, and therefore its use by people unaware of its potential effects has been reported (Antal et al., 2017). Even though some studies have pointed to a possible benefit of tDCS (Frazer et al., 2017; Hendy et al., 2015; Lattari et al., 2017; Vargas et al., 2018), it seems to be still early to assume its beneficial effects in all contexts. More studies need to be conducted, especially with athletes, because some additional questions remain unclear. Moreover, it would be interesting that more investigations were carried out investigating the tDCS effects on the performance of beginners in complex tasks using the lower limbs. However, it is important to point out that complex tasks, related to the intrinsic and extrinsic task demands (Hausmann et al., 2004), as a taekwondo kick task involving simultaneous coordination of right and left lower limbs requires a considerable amount of practice to stabilize performance (Swinnen, 2002). Thus, controlling the learning effects would be another point to be considered.

In addition, it is also important to note the existence of publication bias in favor of positive results. Studies that found no effect of a treatment or with findings that are opposite to the expected effect are less likely to be published (Mlinarić, Horvat, & Šupak Smolčić, 2017; Sedgwick, 2015). Apart from possibly wasting other researchers' time and effort, not reporting negative results compromises the validity of meta-analysis and ultimately the ability to draw conclusions about a specific treatment (DeVito & Goldacre, 2019; Mlinarić et al., 2017).

However, although our results have demonstrated the deleterious effect of the stimulation on the execution of field tasks in athletes, other montages seem to be beneficial for this group. For example, Okano et al., 2015 investigated the effects of 20 min of anodal tDCS over the left temporal cortex of trained cyclists during an incremental cycling test and found statistically significant effects in peak power output during incremental cycling test, heart rate and perception of effort at a submaximal workload.

In the end, the present study presented some limitations. We did not measure cortical excitability changes and our suggested explanation of the deleterious effects of a-tDCS remains hypothetical. Additionally, we cannot rule out the possibility that the current stimulation affected the primary motor cortex adjacent areas. For instance, Hampstead, Brown, and Hartley (2014), using the combination of neuroimaging techniques (more specifically, fMRI) associated with tDCS, found that other areas were also stimulated. Thus, it is important to consider that without the use of neuroimaging (e.g. fMRI) to monitor the real effect of the tDCS, the current may flow to areas that are not necessarily predicted by the researcher. Thus, the results here reported may be attributed to the modulation of neuronal activation not only of the primary motor cortices but also of the other adjacent areas that we cannot predict..

5. Conclusions

Our results showed that M1 anodal bi-hemispheric condition worsened the performance of the taekwondo athletes on FSKT and the session-RPE and the effect remained present even 1 h after the stimulation, but had no influence on CMJ.

Declaration of Competing Interest

We confirm that there are no potential conflicts of interest.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.06.003.

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