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ORIGINAL ARTICLE

Anodal transcranial direct current stimulation enhances strength training volume but not the force–velocity profile

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Abstract

Purpose This study aimed to explore the acute effect of transcranial direct current stimulation (tDCS) on the force–velocity relationship, strength training volume, movement velocity, and ratings of perceived exertion.

Methods Fourteen healthy men (age 22.8 ± 3.0 years) were randomly stimulated over the dorsolateral prefrontal cortex with either ANODAL, CATHODAL or SHAM tDCS for 15 min at 2 mA. The one-repetition maximum (1RM) and force–velocity relationship parameters were evaluated during the bench press exercise before and after receiving the tDCS. Subsequently, participants completed a resistance training session consisting of sets of five repetitions with 1 min of inter-set rest against the 75%1RM until failure.

Results No significant changes were observed in the 1RM or in the force–velocity relationship parameters ($p \geq 0.377$). The number of repetitions was higher for the ANODAL compared to the CATHODAL ($p = 0.025$; ES = 0.37) and SHAM ($p = 0.009$; ES = 0.47) conditions. The reductions of movement velocity across sets were lower for the ANODAL than for the CATHODAL and SHAM condition ($p = 0.014$). RPE values were lower for the ANODAL compared to the CATHODAL ($p = 0.119$; ES = 0.33) and SHAM ($p = 0.150$; ES = 0.44) conditions. No significant differences between the CATHODAL and SHAM conditions were observed for any variable.

Conclusion The application of ANODAL tDCS before a resistance training session increased training volume, enabled the maintenance of higher movement velocities, and reduced RPE values. These results suggest that tDCS could be an effective method to enhance resistance-training performance.

Keywords Non-invasive brain stimulation · Bench press · Performance · Movement velocity · Ratings of perceived exertion

Abbreviations

a.u.	Arbitrary units
BP	Bench press
DLPC	Dorsolateral prefrontal cortex
F–V	Force–velocity relationship
F_0	Regression parameter (*F*-intercept) depicting maximum force
L–V	Load velocity relationship
M1	Primary motor cortex
PFC	Prefrontal cortex
P_{max}	Regression parameter $[(F_0 \cdot V_0)/4]$ depicting maximum power
RPE	Rating of perceived exertion
tDCS	Transcranial direct current stimulation
V_0	Regression parameter (*V*-intercept) depicting maximum velocity
1RM	One repetition maximum

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Introduction

One of the most important challenges for sport professionals and scientists is to identify safe and effective methods to enhance sports performance (Savulescu et al. 2004). Transcranial direct current stimulation (tDCS) is one of the techniques currently being investigated due to its potential ergogenic effect on physical performance (Angius et al. 2017). This painless technique consists of applying a constant and weak electrical current to the brain through two or more electrodes placed over the scalp (Nitsche and Paulus 2000). The ergogenic effect of tDCS could be mediated by the changes induced in the resting membrane potential of the stimulated neural cells (Stagg and Nitsche 2011). The resting membrane potential may be decreased (excitatory effect) or increased (inhibitory effect) depending on the polarity of the electrodes; the anodal electrode promotes an excitatory effect and the cathodal electrode an inhibitory effect (Nitsche and Paulus 2000; Nitsche et al. 2003). It has been shown that the effect of the application of tDCS during 15 min could last up to 90 min (Nitsche and Paulus 2001; Nitsche et al. 2003). The long-lasting effect of tDCS is of relevance, because it opens the possibility of using this technique as a part of the warm-up to subsequently increase physical performance.

Previous studies have investigated the effect of tDCS on endurance (Muthalib et al. 2013; Kan et al. 2013; Angius et al. 2015, 2016, 2018; Flood et al. 2017; Lattari et al. 2018a) and strength performance (Kan et al. 2013; Okano et al. 2015; Washabaugh et al. 2016; Frazer et al. 2016; Angius et al. 2016, 2018; Flood et al. 2017; Hazime et al. 2017; Vargas et al. 2018). A recent review conducted by Angius et al. (2017) concluded that the application of ANODAL tDCS could be associated with a reduction in supraspinal fatigue and rating of perceived exertion. In addition, several studies have reported improvements in endurance performance (e.g., time to task failure) after the application of ANODAL tDCS (Williams et al. 2013; Okano et al. 2015; Angius et al. 2016, 2018; Lattari et al. 2018a; Alix-Fages et al. 2019), although others did not find significant effects (Muthalib et al. 2013; Kan et al. 2013; Angius et al. 2015; Flood et al. 2017). The effects of ANODAL tDCS on the maximal capacities of the muscles to produce force and power remain inconclusive with a comparable number of studies showing non-significant (Kan et al. 2013; Washabaugh et al. 2016; Flood et al. 2017; Alix-Fages et al. 2019) or positive effects (Frazer et al. 2016; Lattari et al. 2017; Hazime et al. 2017; Vargas et al. 2018). For its part, CATHODAL tDCS does not seem to affect performance neither during endurance-oriented nor strength-oriented activities compared to a placebo condition (SHAM) (Lattari et al. 2016, 2017, 2018b; Angius et al. 2018).

The studies that have explored the ergogenic effects of tDCS in endurance tasks used cycling tests going until the failure or exhaustion with a fixed individual percentage of the maximum power (Angius et al. 2015, 2018; Lattari et al. 2018a, b, c) or a time to task failure with a submaximal percentage of the maximum voluntary contraction (Muthalib et al. 2013; Kan et al. 2013; Angius et al. 2016; Flood et al. 2017) and to investigate the effects in strength performance they measured maximum voluntary contractions (Kan et al. 2013; Okano et al. 2015; Washabaugh et al. 2016; Frazer et al. 2016; Angius et al. 2016, 2018; Flood et al. 2017; Hazime et al. 2017; Vargas et al. 2018). The discrepancies of the literature about the ergogenic effects of tDCS could be explained by the differences in the tasks performed and in the tDCS configuration used, being this brain stimulation applied targeting different cortical areas, using different intensities and different times of application in the different studies (Angius et al. 2017).

The training volume (e.g., number of repetitions) is known to play a crucial role in the adaptations induced by resistance training with higher training volumes being associated with greater gains in muscle hypertrophy and strength (Krieger 2010; Radaelli et al. 2015; Ralston et al. 2017; Schoenfeld et al. 2017) until getting to the point of ceiling effect (Hackett et al. 2018; Heaselgrave et al. 2018; Barbalho et al. 2019). In this regard, the study of Lattari et al. (2018b) revealed an increase in the number of repetitions during a single set of the leg press exercise performed until muscular failure after the application of ANODAL tDCS, suggesting that tDCS may be an effective tool to increase resistance training volume. Given that resistance training sessions typically consists of multiple sets of the same exercise (Schoenfeld et al. 2017), it seems important to examine the effect of tDCS on the total volume of a resistance training session consisting of multiple sets of the same exercise. An acute increase in the volume of resistance training sessions after the application of tDCS should encourage further research on the use of tDCS to promote longer-term adaptation.

Although stimulating the motor cortex with tDCS has demonstrated to induce higher ergogenic effects on time to task failure tests performance (Alix-Fages et al. 2019), it is known that the activity of the prefrontal cortex increases when the activity of the motor cortex is reduced due to fatigue (Menotti et al. 2014), and this could explain the higher strength performance when the DLPFC is stimulated (Lattari et al. 2018a). For example, previous studies have reported an increase in the number of repetitions performed after stimulating the DLPFC during a single set performed with the leg press (Lattari et al. 2018b) and elbow flexion (Lattari et al. 2016) exercises. However, the effect of targeting the DLPFC on the training volume during a typical resistance training session consisting of multiple sets has never been explored.

The main goal of this study was to explore the effect of tDCS on the total number of repetitions performed during a resistance training session with the bench press exercise. The force–velocity (*F–V*) relationship, movement velocity, and ratings of perceived exertion during the training session were also recorded to elucidate whether the changes in the number of repetitions after tDCS are associated with changes in those parameters. It was hypothesized that the ANODAL tDCS would not significantly affect any parameter of the *F–V* relationship, but it would increase bench press training volume, enable the maintenance of higher movement velocities, and reduce RPE values.

Methods

Participants

Fourteen healthy men [age = 22.8 ± 3.0 years, body mass = 81.7 ± 6.7 kg, height = 180 ± 5.66 cm, bench press 1-repetion maximum (1RM) normalised to body mass = 1.4 ± 0.1 kg] volunteered to participate in this study. All participants were recreational resistance trained men and had at least 2 years of resistance training experience (4.1 ± 3.3 years). They were instructed to avoid any strenuous exercise 2 days before each testing session. All participants signed an informed consent prior to the beginning of the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board.

Study design

A double-blind crossover design was used to explore the feasibility of tDCS for increasing performance during a resistance training session (Fig. 1). Participants attended the laboratory three times separated by 1 week. The order of the three experimental sessions (ANODAL, CATHODAL, and SHAM) was randomised using the Research Randomizer website (https://www.randomizer.org). During each experimental session, the 1RM and the *F–V* relationship parameters were determined before and after receiving the tDCS. Subsequently, participants completed a resistance training session consisting of sets of five repetitions with 1 min of inter-set rest against the 75%1RM until concentric failure (i.e., inability to lift the weight without any external assistance). After reaching concentric muscular failure, the resistance training session ended. The total number of repetitions performed before reaching muscular failure, movement velocity of all repetitions, and RPE values of all sets were recorded. The bench press exercise was performed in a Smith machine (Technogym, Cesena, Italy) to allow more reproducible velocity measurements. All sessions were held in the morning at the same time of the day for each participant and under similar environmental conditions (~ 22 °C and ~ 60% humidity).

Procedures

One repetition maximum and *F–V* relationship

All sessions began with a standardised warm-up that consisted of jogging, dynamic stretching, and three sets of 10, 5, and 3 repetitions during the bench press exercise performed with the 30%, 45%, and 60% of the participants' self-reported bench press 1RM, respectively. Afterwards, participants performed one repetition against three loads (70%1RM, 80%1RM, and 90%1RM) at the maximum possible velocity. Participants rested 2–3 min between trials. The mean values of force and velocity were collected with a linear position transducer (Chronojump, Barcelona, Spain) that was attached perpendicularly to the barbell to determine the individual load–velocity (*L–V*) and *F–V* relationships by means of linear regression models.

The 1RM was estimated from the individual *L–V* relationship instead of performing an actual 1RM test to minimize fatigue. Although the maximum theoretical force expressed as F_0 and the 1RM are highly correlated as it has been previously shown in the bench press and the squat exercises (García-Ramos et al. 2016; Rivière et al. 2017), they have been included to provide normative values and allow the comparison between studies. Note that performing two 1RM assessments before the training session could have compromised the subsequent performance. A cut-off velocity of 0.17 m s^{-1} was used to estimate the 1RM, because this is the average velocity of the 1RM trial (V1RM) reported in previous studies (González-Badillo and Sánchez-Medina 2010) and because a general V1RM of 0.17 m s^{-1} has been shown to provide an accurate estimation of the bench press 1RM (García-Ramos et al. 2018a, b). The maximal capacities of the muscles to produce force (F_0; force-intercept), velocity (V_0; velocity-intercept), and power ($P_{max} = F_0 \cdot V_0/4$) were determined from the individual *F–V* relationships (Garcia-Ramos and Jaric 2018). The 1RM and the *F–V* relationship parameters were also determined 5 min after the application of tDCS following identical procedures (including warm-up). Therefore, the *L–V* and *F–V* relationships were determined twice in each testing session (before and after the application of tDCS).

Transcranial direct current stimulation

Participants remained seated during the implementation of tDCS and were stimulated for 15 min at 2 mA. Note that 2 mA was shown to be effective to induce an ergogenic effect during resistance training (Lattari et al. 2016, 2018a, b, c)

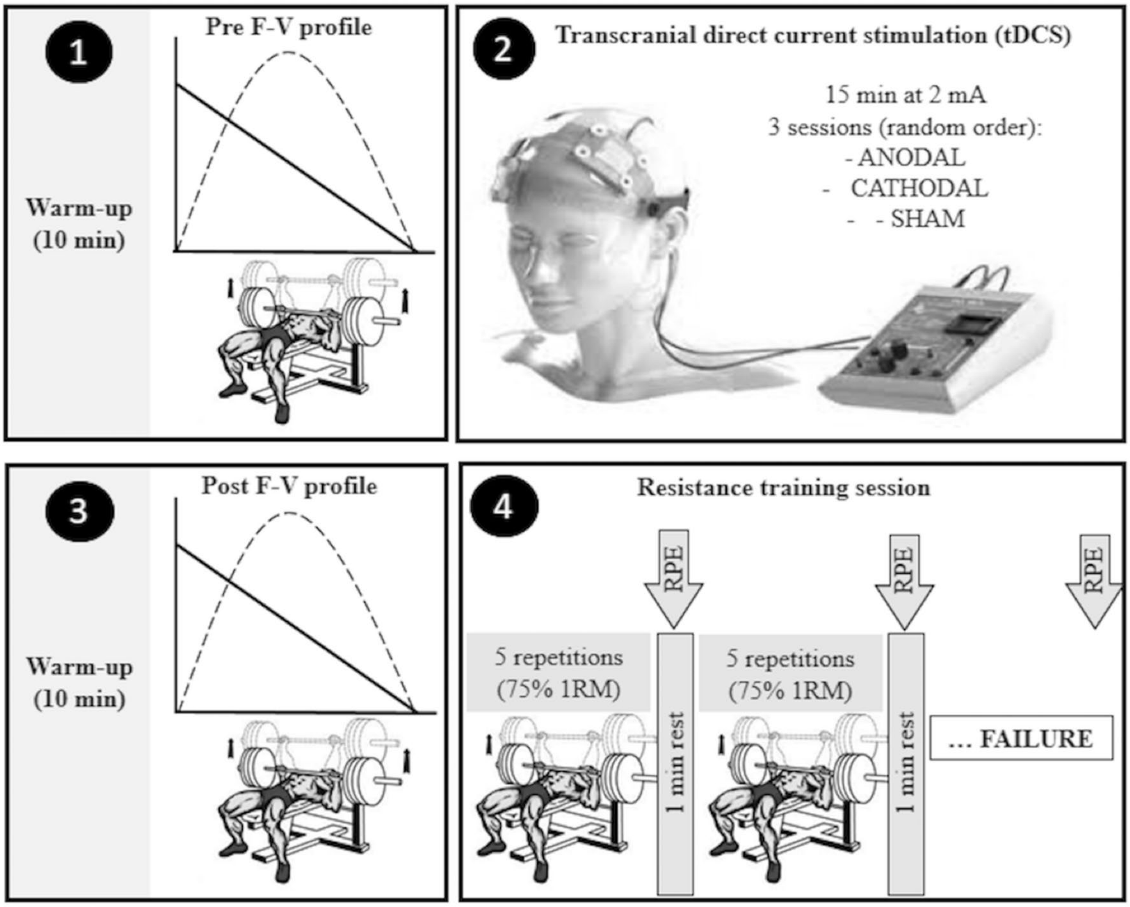

Fig. 1 Overview of the experimental protocol. The force–velocity (*F–V*) relationship was measured before (1) and after (3) the application of transcranial direct current stimulation (2). Subsequently, a resistance training session consisting of sets of 5 repetitions with 1 min of inter-set rest against the 75% of the one-repetition maximum (1RM) was performed until subjects failed to complete the 5 repetitions of the set (4). Ratings of perceived exertion were measured after each set

and the tDCS longer than 10 min (Alix-Fages et al. 2019). The tDCS was applied using two pads soaked in saline comprising the two electrodes (7.6 × 7.6 cm). The electrodes (anode and cathode) were connected to a continuous current stimulation device (ApeX Type A 18V, ApeX Electronics, NY, USA). For the ANODAL tDCS, the anode was placed in the left dorsolateral prefrontal cortex (DLPC) in accordance to the international 10–20 system EEG and the cathode in the right orbitofrontal cortex (Herwig et al. 2003; DaSilva et al. 2011). The opposite placement was used for the application of the CATHODAL tDCS. For the SHAM tDCS, the electrodes were placed in the same position as for the ANODAL tDCS, but the stimulator was switched off after 30 s to blind the participants with respect to the type of tDCS received (Gandiga et al. 2006). The compensatory mechanism of the prefrontal cortex in reduced motor cortex activation because of the fatigue (Menotti et al. 2014) could improve performance in strength tasks (Lattari et al. 2018a) like the training performed in this study. The ergogenic effect of this tDCS configurations found previously in typical resistance training exercises (Lattari et al. 2016, 2018b). To follow a double-blind design, the researcher who applied the tDCS was not present during the physical measurements, while the researcher responsible for the physical measurements did not know the type of tDCS received by the participant.

Resistance training session to volitional failure

The resistance training session began 3 min after performing the last repetition used to determine the *F–V* relationship post-tDCS. The resistance training session consisted of sets of five repetitions with 1 min of inter-set rest against the 75%1RM load. Participants started each repetition with their elbows fully extended, they lowered the bar in a controlled motion of 3 s until touching their chest, and immediately after they performed the concentric phase as fast as possible (i.e., touch-and-go technique). The session ended when participants failed to complete the five repetitions of the set. Note that with the 75%1RM load approximately 11 repetitions can be performed before reaching muscular failure (García-Ramos et al. 2018b), but the incomplete recovery (only 1 min) promoted that the participants were not able to complete five repetitions after several sets. Participants were encouraged to complete as many sets as possible and they were instructed to perform all repetitions as the maximum intended velocity using the touch-and-go technique. The mean velocity of all repetitions was collected with a linear position transducer (Chronojump, Barcelona, Spain). Immediately after finishing each set, the participants gave their RPE value using the OMNI-RES scale (0–10), where 0 is extremely easy and 10 represents extremely hard (Robertson et al. 2003). An image of the OMNI-RES scale was shown to the participants immediately after performing the last repetition of each set and they verbally reported their RPE value. Participants were asked to "think about your feeling of exertion" following the instructions used by Robertson et al. (2003), indicating that zero is "extremely easy" and 10 is "extremely hard". The perception of physical exertion was defined as the "subjective intensity of effort, strain, discomfort, and/or fatigue that you feel during exercise" (Robertson et al. 2003). Furthermore, all participants were familiarized with the OMNI-RES scale before the initiation of the study. The total number of repetitions, movement velocity, and RPE values were considered as performance indicators of the resistance training session.

Velocity and RPE were measured at the selected time points to allow the within-subjects comparison of temporal changes during the resistance training session. The shortest resistance session was identified for each participant over the three visits and considered as 100% isotime. The values for both velocity and RPE obtained at the final set of the shortest session was compared to the value obtained at the equivalent set in the other two visits. The number of sets identified as 100% isotime was divided by five and rounded up to obtain the value corresponding to 20, 40, 60 and 80% isotime. Isotime values for 0% were attained by taking into account data at the initial set of the resistance training session.

Statistical analyses

Data are presented as means and standard deviations (mean ± SD). The normal distribution assumption was tested by the Shapiro–Wilk test. Inter-session (Pre_ANODAL, Pre_CATHODAL and Pre_SHAM) reliability was determined for F_0, V_0, P_{max} and 1RM using intra-class correlation coefficients (ICCs) from the mixed-effect model. The ICC was interpreted with values below 0.5 indicating low reliability, values between 0.5 and 0.75 indicating moderate reliability, values between 0.75 and 0.9 indicating good reliability, and values higher than 0.90 indicating excellent reliability. Two-way repeated measures ANOVAs (condition [ANODAL, CATHODAL and SHAM] × time [pre-tDCS and post-tDCS]) were applied on the 1RM value and the *F*–*V* relationship parameters (F_0, V_0 and P_{max}). The Friedman test was used to explore the effects of tDCS condition on the total number of repetitions completed in the training session, because the normal distribution assumption was violated. The effect of tDCS condition on movement velocity and RPE values were tested through two-way repeated measures ANOVAs (condition [ANODAL, CATHODAL and SHAM] × time [initial set, set20%, set40%, set60% and set80%]). A one-way repeated-measures ANOVA was performed to test the differences in the mean velocity attained at the last repetition of the training session between the tDCS conditions. When a significant *F* value was achieved, a Holm–Bonferroni follow-up test was performed. The magnitude of the differences was also calculated through the Cohen's *d* effect size (ES) and the following scale was used for interpretation: negligible (< 0.2), small (0.2–0.5), moderate (0.5–0.8), and large (≥ 0.8) (Cohen 1988). Statistical analyses were performed using the software package SPSS (IBM SPSS version 22.0, Chicago, IL, USA). Statistical significance was set at $p < 0.05$.

Results

Reliability and baseline values

The data showed good to excellent inter-session reliability for the 1RM, F_0, and P_{max} with ICCs ranging from 0.871 to 0.980 (all $p < 0.001$), with the exception of V_0 that showed moderate reliability (ICC = 0.666, $p = 0.008$). Furthermore, there were no differences in the pre-values for all the variables measured, indicating similar baseline levels at the beginning of each experimental session.

One-repetition maximum and force–velocity relationship

No significant main effects of condition (*p* range = 0.656–0.950), time (*p* range = 0.377–0.973), or condition × time interaction (*p* range = 0.511–0.836) were observed for the 1RM or for any of the *F*–*V* relationship parameters (Table 1).

Number of repetitions

Significant differences were observed in the number of repetitions completed between the experimental conditions ($p = 0.001$) with higher values obtained for the ANODAL (77 ± 45 repetitions) compared to the CATHODAL (62 ± 36 repetitions; $p = 0.025$; ES = 0.37) and SHAM (58 ± 35

Table 1 Comparison of the one-repetition maximum and force–velocity relationship parameters between the different experimental conditions

Variable	Time	Condition			ANOVA		
		ANODAL	CATHODAL	SHAM	Condition	Time	Condition × time
1RM (kg)	Pre	108.4 ± 14.6	109.4 ± 12.8	109.3 ± 13.2	$F_{2,12}=0.059$ $p=0.950$	$F_{1,13}=0.373$ $p=0.552$	$F_{2,12}=0.566$ $p=0.511$
	Post	109.0 ± 13.1	108.5 ± 13.6	108.6 ± 12.9			
F_0 (N)	Pre	1228 ± 191	1257 ± 146	1237 ± 156	$F_{2,12}=0.436$ $p=0.656$	$F_{1,13}=0.837$ $p=0.377$	$F_{2,12}=0.388$ $p=0.686$
	Post	1237 ± 160	1229 ± 168	1220 ± 142			
V_0 (m s^{-1})	Pre	1.45 ± 0.20	1.41 ± 0.23	1.46 ± 0.23	$F_{2,12}=0.491$ $p=0.726$	$F_{1,13}=0.033$ $p=0.859$	$F_{2,12}=0.244$ $p=0.828$
	Post	1.45 ± 0.24	1.44 ± 0.23	1.45 ± 0.19			
P_{max} (W)	Pre	439.4 ± 51.7	438.0 ± 71.6	447.8 ± 66.4	$F_{2,12}=0.346$ $p=0.715$	$F_{1,13}=0.035$ $p=0.854$	$F_{2,12}=0.413$ $p=0.670$
	Post	442.4 ± 68.7	437.5 ± 70.3	441.4 ± 65.4			

1RM, one-repetition maximum: F_0, maximal force capacity; V_0, maximal velocity capacity; P_{max}, maximal power capacity

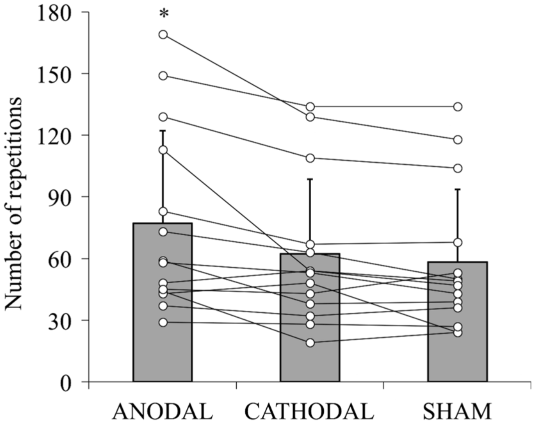

Fig. 2 Comparison of the number of repetitions performed between the three experimental conditions. The individual values (dots), averaged across the subjects values (bars) and standard deviations (error bars) are depicted. asterisk, significantly higher than SHAM and CATHODAL conditions

repetitions; $p=0.009$; ES = 0.47) conditions, while no significant differences were observed between the CATHODAL and SHAM conditions ($p=0.349$; ES = 0.11) (Fig. 2).

Movement velocity

The two-way ANOVA revealed a significant main effect of set ($p<0.001$) and of the interaction condition × set ($p=0.014$), while the main effect of condition did not reach statistical significance ($p=0.218$). The increase in the number of sets was associated with a decrease of movement velocity (initial set = 0.42 ± 0.04 m s^{-1}, set20% = 0.39 ± 0.05 m s^{-1}, set40% = 0.36 ± 0.05 m s^{-1}, set60% = 0.34 ± 0.05 m s^{-1}, and set80% = 0.31 ± 0.05 m s^{-1}). The significant interaction was caused by the lower decrement in movement velocity observed for the ANODAL condition as the training session progressed compared to the CATHODAL and SHAM conditions (Fig. 3). The velocity of the last repetition of the

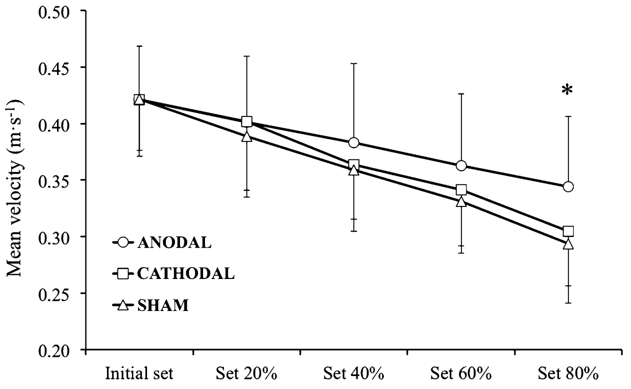

Fig. 3 Comparison of movement velocity (mean ± standard deviation) between the three experimental conditions. asterisk, significant differences between ANODAL and SHAM conditions ($p=0.021$ with Bonferroni corrections). Values are reported as mean (± SD)

session did not significantly differ between the three experimental conditions ($p=0.890$; ANODAL = 0.20 ± 0.05 m s^{-1}, CAHODAL = 0.20 ± 0.05 m·s^{-1}, and SHAM = 0.19 ± 0.06 m s^{-1}).

Ratings of perceived exertion

The two-way ANOVA revealed a significant main effect of condition ($p=0.030$) and set ($p<0.001$), while the interaction condition × set did not reach statistical significance ($p=0.315$) (Fig. 4). The ANODAL condition [6.79 ± 1.44 arbitrary units (a.u.)] provided lower RPE values compared to the CATHODAL (7.22 ± 1.18 a.u.; $p=0.119$; ES = 0.33) and SHAM (7.36 ± 1.20 a.u..; $p=0.150$; ES = 0.44) conditions, while no significant differences were observed between the CATHODAL and SHAM conditions ($p=1.000$; ES = 0.12). The increase in the number of sets was associated with higher RPE values (initial set = 5.96 ± 0.87 a.u., set20% = 6.38 ± 0.93 a.u., set40% = 7.06 ± 0.93 a.u., set60% = 7.80 ± 0.94 a.u., and set80% = 8.42 ± 1.04 a.u.).

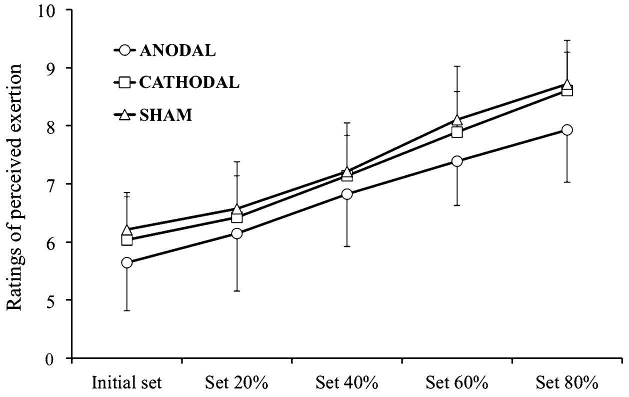

Fig. 4 Ratings of perceived exertion values (mean ± standard deviation) obtained at the different time points following the three experimental conditions. Although the ANOVA revealed a significant main effect of the experimental condition ($p = 0.030$) due to lower RPE values following the ANODAL condition, Bonferroni post hoc procedures failed to show any significant pairwise comparison

All subjects reported a RPE of 10 a.u. at the end of all training sessions.

Discussion

This study was designed to further explore the possible ergogenic effect of tDCS during resistance training sessions. The main finding of the study was that the application of ANODAL tDCS, but not CATHODAL tDCS, prior to a resistance training session increased the number of repetitions performed before reaching muscular failure, enabled the maintenance of higher movement velocities, and reduced RPE values. These improvements were not related to an increase of the maximal capacities of the muscles to produce force, velocity or power. These results suggest that ANODAL tDCS could be used as an ergogenic aid during resistance training programs, enhancing the total volume of the resistance training sessions, which could be of particular interest for long-term goals (Krieger 2010; Radaelli et al. 2015; Ralston et al. 2017; Schoenfeld et al. 2017).

Supporting our hypothesis, none of the *F*–*V* relationship parameters or the 1RM showed an improvement after the application of tDCS. These results are in line with the vast majority of studies that have reported no significant improvements in the maximal voluntary isometric strength after the application of tDCS (Kan et al. 2013; Washabaugh et al. 2016; Flood et al. 2017). However, it should be noted that some studies have also revealed significant improvements in the maximal voluntary contraction (Hazime et al. 2017; Vargas et al. 2018) and vertical jump performance (Lattari et al. 2017) after the application of ANODAL tDCS. The reason for the discrepancies between these studies is unclear, since they generally used similar tDCS configuration parameters, being possible that the high inter-individual variability in the response to tDCS could at least partially explain these results (López-Alonso et al. 2014; Laakso et al. 2015). The absence of significant changes in the *F*–*V* relationship parameters agrees with the lack of significant differences between the three experimental conditions observed for the velocity recorded during the first set of the training session. The results of the present study suggest that the application of tDCS is not effective to increase maximal upper-body force production.

Although no significant changes were observed for any parameter derived from the *F*–*V* relationship, the training volume (i.e., number of repetitions) increased after the application of the ANODAL tDCS compared to the CATHODAL and SHAM conditions. This result is in consonance with previous studies that demonstrated an ergogenic effect of ANODAL tDCS over the DLPFC on the number of repetition performed during single sets of the leg press (Lattari et al. 2018b) and elbow flexion (Lattari et al. 2016) exercises. However, the novelty of the present study is the longer duration of the task, which consisted of multiple sets as it is commonly performed in resistance training programs. This change the metabolic claims of the task (de Freitas et al. 2017) getting closer to an endurance task compared to previous studies. In this regard, our results agree with most of the scientific literature that has reported an increase in endurance performance after the application of ANODAL tDCS (Williams et al. 2013; Okano et al. 2015; Angius et al. 2016, 2018; Lattari et al. 2018a). Endurance performance has been commonly evaluated as the time to task failure during an isometric contraction (Williams et al. 2013; Angius et al. 2016), but an ergogenic effect of ANODAL tDCS has also been described during cyclic movements (close movements that are performed repetitively in a quasi-periodic manner like running or bicycling (Rosati et al. 2017)) (Okano et al. 2015; Angius et al. 2018; Lattari et al. 2018a). However, it should be acknowledged that some studies did not find a significant change in the time to task failure after the application of ANODAL tDCS (Muthalib et al. 2013; Kan et al. 2013). The results of the present study add to the scientific literature that the ANODAL tDCS may also be a valuable tool to increase training volume during a resistance training session conducted with the bench press exercise. These results could extend previous findings regarding the positive effect of tDCS on endurance performance to resistance training requiring multiple sets of high-intensity (75% 1RM) bench press exercise with short inter-set rest periods.

This is the first study that has compared movement velocity during a resistance training session between different tDCS conditions. The development of high movement velocities during resistance training is believed to be an important factor to maximise strength training adaptations

(González-Badillo et al. 2014). In this regard, it is important to note that the application of ANODAL tDCS was effective to counteract the velocity loss occurred during the last sets of the training session in comparison with the CATHODAL and SHAM conditions. It is known that, until getting to the ceiling effect point for training volume (Ralston et al. 2017; Hackett et al. 2018; Heaselgrave et al. 2018; Barbalho et al. 2019), a higher resistance training volume is positively associated with both strength (Ralston et al. 2017) and hypertrophy (Krieger 2010; Schoenfeld et al. 2017, 2019) gains. This is reasonable due to the dose–response relationship between training volume and the phosphorylation of some important proteins for the muscular protein synthesis (Terzis et al. 2010). Although intensity likely is the most important variable for inducing strength gains (Schoenfeld et al. 2016), training volume should also be considered, because previous studies have demonstrated higher increments in maximal strength when multiple sets per exercise are performed in training (Krieger 2009).

It has also been suggested that a resistance training session should be terminated when a given velocity loss is reached (Pareja-Blanco et al. 2017). Therefore, the results of the present study suggest that the application of ANODAL tDCS could be effective to increase the training volume performed at high velocities. Longitudinal studies should verify whether the application of ANODAL tDCS before training could further stimulate strength-training adaptations in comparison to a traditional (no stimulation) routine. Although the increase in training volume found in the present study following ANODAL tDCS could be beneficial to induce higher gains in strength and hypertrophy, experimental evidence is needed to confirm the positive effects of ANODAL tDCS on strength and hypertrophy gains. This is a promising strategy given than spending 15 min using this safe brain stimulation (Poreisz et al. 2007) could improve the performance during the subsequent training without showing any adverse effect.

The RPE has been one of the most explored variables in the literature related to tDCS and physical exercise (Angius et al. 2017). Several investigations have found that the improvement in endurance performance after the application of ANODAL tDCS is associated with a reduction in RPE values when a given amount of work is done (Okano et al. 2015; Angius et al. 2016, 2018). In line with previous studies (Lattari et al. 2016, 2018b), we observed a reduction in RPE values after the ANODAL tDCS compared to the CATHODAL and SHAM conditions. The differences in RPE values were consistent across the different sets. Therefore, these results confirm that the increase in bench press training volume observed after the application of ANODAL tDCS is associated with lower RPE values and not with an increment in the maximal capacities of the muscles to produce, force, velocity, and power.

It is well known that the primary motor cortex (M1) has an important role in the motor drive that is necessary to activate the motor units through the corticospinal tract (Teka et al. 2017) and, thus, it is commonly considered as a key determinant in endurance tasks (Taylor et al. 2016). However, there are other cortical regions that play an important role in the regulation of endurance exercise, such as the sensorimotor cortex, prefrontal cortex (PFC), cingulate gyrus, supplementary motor area, and cerebellum (Liu et al. 2003). Indeed, the PFC is indirectly connected with major motor control regions via the premotor area and it seems to be an important area in sport performance, because it integrates the cognitive and peripheral information and modulates the motor cortex drive by them, even redistributing the blood and oxygen in the body (Robertson and Marino 2016). In this way, it has been demonstrated that the prefrontal cortex has also an important role in cognitive and emotional integration, which could inhibit peripheral fatigue cues and affect to the decision of stopping the physical task because of motivational reasons and advantages and disadvantages of continue performing the task in the thoughts of the athletes (Perrey et al. 2016). Thus, high fatigue could requires the prefrontal cortex to inhibit the anterior cingulate and insula activated in proportion to the degree of subjective fatigue (Hilty et al. 2011). In this regard, our data are in line with previous studies of Lattari and colleagues (Lattari et al. 2016, 2018b) indicating that the stimulation of the DLPFC prolonged the time to task failure and reduced the perception of effort. These results provide a rationale for stimulating this cerebral region for enhancing performance in endurance-oriented tasks.

A number of limitations and directions for future research should be considered. Although DLPFC stimulation is effective to improve performance in different tasks such as submaximal isometric contractions to volitional failure (Williams et al. 2013), 10RM tests (Lattari et al. 2016, 2018b), and cycling tests to exhaustion (Lattari et al. 2018a), bilateral M1 stimulation has also shown positive effects on time to task failure (Angius et al. 2018) and maximal power production (Lattari et al. 2017). Therefore, future studies should test whether bilateral M1 stimulation could enhance both the F–V relationship and repetitions to failure during a resistance training session. Furthermore, the different outcomes observed in tDCS research are likely a consequence of differences between exercise type and/or tDCS set up (e.g., montage, duration, brain area stimulated, etc.), but also due to the inter-individual variability in the response to this neuromodulatory technique (López-Alonso et al. 2014; Li et al. 2015; Laakso et al. 2019). In this regard, when we look at the individual data of the number of repetitions, we found that 11 out of 14 subjects (78.6%) performed more repetitions during the ANODAL condition compared to both the CATHODAL and SHAM conditions. Similar rates of responders vs. non-responders were found after the application of ANODAL tDCS to increase cortical excitability (i.e., higher motor evoked potentials), which also may help to explain the inter-individual differences in the present and previous studies (López-Alonso et al. 2014). Finally, not including a neurophysiological measurement could also be considered as a limitation of the present study, so it is recommended that future studies also perform these type of measurements (e.g., cortical excitability and SICI (Short Interval Intracortical Inhibition) to obtain a deeper insight into the mechanisms responsible for the ergogenic effect of ANODAL tDCS.

In conclusion, the results of the present study revealed that the application of ANODAL tDCS immediately before the warm-up was effective to enhance performance during a resistance training session. Specifically, ANODAL tDCS increased training volume, enabled the maintenance of higher movement velocities, and reduced RPE values compared to the CATHODAL and SHAM conditions. These acute improvements suggest that the application of ANODAL tDCS prior to a training session may be an effective strategy to promote greater gains in muscle hypertrophy and strength in comparison with a traditional routine. Longitudinal studies should be conducted to verify this hypothesis. However, the non-significant differences in the magnitude of the *F*–*V* relationship parameters between the different experimental conditions do not support the application of tDCS when the goal of training is to increase maximal power production.

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Author contributions CA-F, AG-R, DC-P and GM conceived the study design. CA-F, GC-N, DC-P and GM conducted the experiments. AG-R and GM conducted the statistical analyses. AG-R, DC-P, SR-A, MF-O and GM interpreted the results. CA-F, AG-R, DC-P, SR-A, MF-O and GM: wrote the manuscript. All authors read and approved the final manuscript version.

Compliance with ethical standards

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

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