Ergogenic Effects of Bihemispheric Transcranial Direct Current Stimulation on Fitness: A Randomized Cross-over Trial

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Key words
motor cortex M1, portable brain stimulation, exercise training, tDCS, physical fitness, neuromodulation

accepted 03.06.2020

Bibliography
DOI https://doi.org/10.1055/a-1198-8525
Published online: 2020
Int J Sports Med

ISSN 0172-4622

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ABSTRACT

Several types of routines and methods have been experimented to gain neuromuscular advantages, in terms of exercise performance, in athletes and fitness enthusiasts. The aim of the present study was to evaluate the impact of biemispheric transcranial direct current stimulation on physical fitness indicators of healthy, physically active, men. In a randomized, single-blinded, crossover fashion, seventeen subjects (age: 30.9 ± 6.5 years, BMI: 24.8 ± 3.1 kg/m^2) underwent either stimulation or sham, prior to: vertical jump, sit & reach, and endurance running tests. Mixed repeated measures anova revealed a large main effect of stimulation for any of the three physical fitness measures. Stimulation determined increases of lower limb power (+ 5 %), sit & reach amplitude (+ 9 %) and endurance running capacity (+ 12 %) with respect to sham condition ($0.16 < \eta_p^2 < 0.41$; $p < 0.05$). Ratings-of-perceived-exertion, recorded at the end of each test session, did not change across all performances. However, in the stimulated-endurance protocol, an average lower rate-of-perceived-exertion at iso-time was inferred. A portable transcranial direct current stimulation headset could be a valuable ergogenic resource for individuals seeking to improve physical fitness in daily life or in athletic training.

ABBREVIATIONS

ANOVA	analysis of variance
ES	effect size
ICC	intraclass correlation coefficient
PAI	physical activity index
ROM	range of motion
RPE	rating of perceived exertions
SD	standard deviation
tDCS	transcranial direct current stimulation
VO2peak	peak oxygen uptake

Introduction

A growing body of neuro- and sports science literature has been giving increased interest to transcranial direct current stimulation (tDCS). tDCS is a technique that can non-invasively stimulate a targeted brain area by exciting cortical neurons with weak direct electrical currents (below 2-3 mA) emitted for a few minutes over the scalp. This cortical excitability can be maintained for up to one hour after the end of stimulation [1]. As a result, the brain neuromodulation could be exploited in a spectrum of settings, including exercise performance, and, in fact, it has been claimed to boost several indicators of physical fitness from sprint- [2] and endurance cycling [3] to jumping [4], pinch force production [5] and dynamic balance [6]. In addition, tDCS has been deemed to enhance cognitive performance based on the ability to modulate functional plasticity [7].

This latter effect is of particular relevance, as numerous studies have shown the possibility that tDCS may reduce supraspinal fatigue by facilitating the primary motor cortex (M1) during exercise [8, 9]. Mechanistically, several explanatory attempts have been made on tDCS effects. However, a cohesive neurophysiological picture is yet to be uncovered. The inconsistencies across the studies might be due either to methodological issues (different tDCS-devices and -intervention) or high variability to corticospinal excitability [10, 11]. Moreover, several works pinpointed the lack of standardized protocols in order to control for the tDCS-triggered neuromuscular responses [12, 13]. Whatever the legitimate usage, the high viability of a compact tDCS set-up, such as a headset, might facilitate and boost muscular performance and adherence to physical activity for a variety of different populations, either recovering from depression [14], spinal cord injuries [15–17], or healthy subjects undergoing high-intensity training [18]. Since evidence in this field has been accumulating, particularly for favorable and safe tDCS effects on exercise capacity, it might be worthy studying an acute, user-friendly, tDCS administration prior to exercise in healthy participants. Hypothesizing a common tDCS use in a real sports setting, a straightforward battery of tests was envisaged concerning the representative features of physical fitness: power, flexibility and cardiovascular endurance.

The purpose of this study was therefore to evaluate whether tDCS, in the form of a portable headset, could induce ergogenic effects on young males' physical fitness, as assessed through a simple and relatively short combination of field and laboratory tests.

Materials and Methods

Subjects

To determine an *a priori* sample-size (software package, G * Power 3.1.9.2), the following input parameters were selected as per an F test for ANOVA-repeated measures-within factors analysis: a statistical power (1-β) of 0.8, a probability α level of 0.05, an effect size *f* of 0.35, two groups, three measurements. As output parameters, an actual power of 0.84 and a critical F of 3.34 were obtained. Therefore, seventeen male adults were enrolled for this study. Subjects were formerly visited by a physician who certified the eligibility for sports activity under high cardiovascular effort circumstances. Consequently, no orthopedic, cardiovascular or neurological conditions were reported to impede subjects' participation into the study.

Experimental design

This is a single-blinded, sham-controlled, crossover study with a randomized block design. After the baseline tests, using a restricted blocks randomization (computer-generated sequence), the participants were allocated either to a real stimulation (tDCS) arm (n = 8) or placebo stimulation (sham) arm (n = 9), and then exposed to the opposite treatment (▶ **Fig. 1**). This procedure allowed us to reduce variability within treatment conditions and avoid a greater familiarization training to tests. The allocation and the randomization were completed by one of the researchers without any contact or knowledge of the participants. All the trials (baseline, sham, tDCS) were spaced by an elapsed time of five days maximum and terminated in a two-week period. Flexibility was assessed in a different session from power and endurance, within a 48-h period. Therefore, subjects attended the laboratory for a total of six visits (1 for flexibility + 1 for power & endurance X 3 trials). Before the baseline tests, participants were familiarized with the ratings of perceived exertion (RPE) scale [19] (e. g. 3 = moderate; 7 = strenuous; 10 = maximal exertion). RPEs were recorded at the end of each test session, based on CR10 scale [19]: subjects were instructed to focus on exercise-induced fatigue during vertical jump, sit & reach, and endurance running.

To minimize the effects of circadian variations, subjects were tested at the same hour of the day. Subjects were also instructed to refrain from consuming alcohol, caffeine, theine, hot drinks nor undertaking exercise for 36 h prior to each trial. In addition, participants were also instructed not to take medications or supple-

▶ **Fig. 1** Flowchart of the design study.

ments during the study. Physical activity [20] – and food frequency [21] questionnaires were administered to participants at baseline in order to assess, respectively, their physical activity levels and daily dietary intake. Subjects were instructed to maintain their dietary intake and training levels throughout the entire duration of the study.

Ethics

The study protocol, including each aspect of the design, followed appropriate standards for human experimentation in accordance with the Declaration of Helsinki, the academic committee, and the ethical standards of the journal [22]. All subjects were given verbal and written information on the study and gave their written informed consent prior to participating in the study.

tDCS procedure

As to tDCS, a Halo Neurostimulation (Halo sports, Halo Neuroscience, San Francisco, CA, USA) instrument was employed. The three foam electrodes were rectangular 6.4 × 4.4 cm (primers) and they were wetted in saline (0.9 % NaCl) before being affixed to the scalp (nominal electrical contact surface = 28 cm^2). The primers were positioned over the vertex of the head, along the Cz midline central, spanning from ear to ear, therefore lying over the critical spots of the 10:20 electroencephalography system [23], i. e. from C1 to C6, with the aim to stimulate both sides of the motor cortex (▶ **Fig. 2**). The current intensity was set at 2 mA, and the duration was set at 20 min. In the active stimulation, the electrical current was gradually increased over 30 s up to 2 mA, and thereafter maintained at this level for 20 min. In the sham condition, the electrical current was first ramped up for 30 s, after which it was terminated. Similar stimulation settings have been experimented in multiple clinical trials, confirming their safety [24, 25].

The tDCS headset was worn by the study-participants for 20 min while they received the corresponding treatment, during which they completed a warm-up, including: 3 min of myofascial relaxation (foam roller); 3 min of multiple joint flexibility; muscle activation (2 min of light jogging on a Skillmill$^{\text{TM}}$ at 8 km/h as maximum speed; x5 half squats with a full recovery time of ~20 seconds) for about 15 min and then a five-min rest period. Afterward, the tDCS headset was removed, and the planned battery test was performed. Likewise, the 20-min warm-up was consistently performed prior to the baseline testing.

Sargeant test

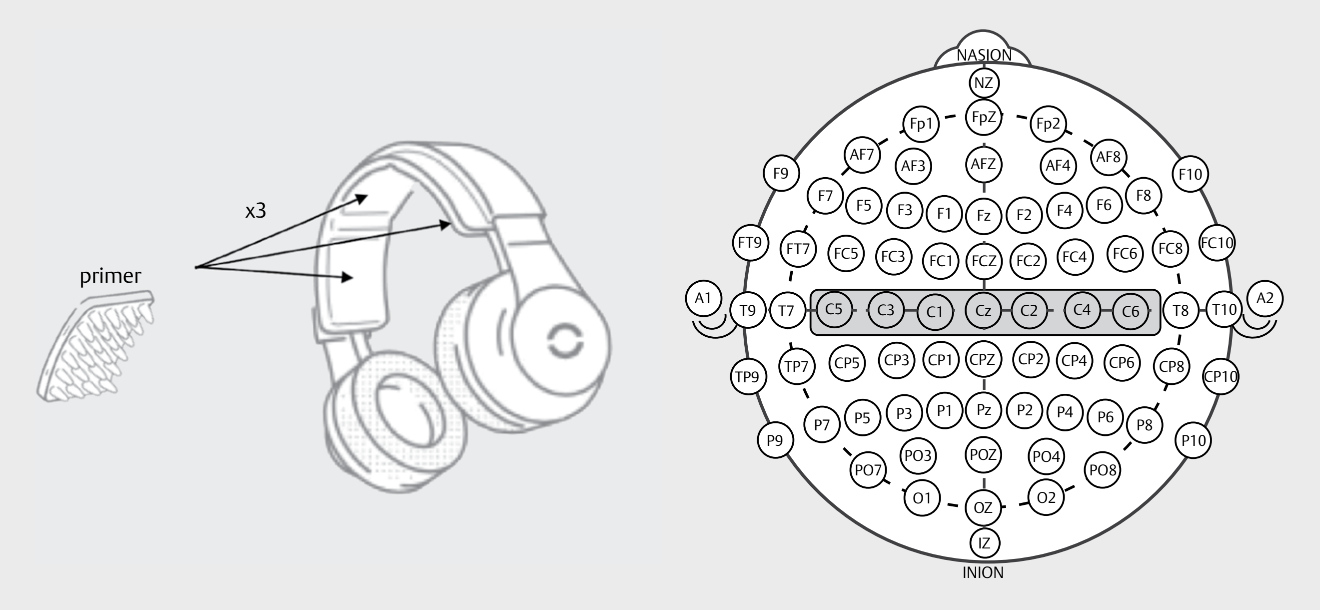
Subjects were asked to stand side against a wall and reach up with the hand closest to the wall. Feet were kept flat on the ground; fingertips marked the standing reach height by using chalk powder. Thereafter subjects stood away from the wall and, by using a countermovement jump, attempted to reach the highest point on the wall (marking the jump height). The difference in distance between standing reach height and the jump was registered as the measured score. Following warm-up and familiarization, three attempts were performed and the best one was recorded [26]. To ensure a fully recovery time, trials were separated by a 3-min interval.

Sit & reach test

Using a Flex-Tester box (Cranlea, Birmingham, UK), participants were barefoot with legs fully extended and instructed to lean forward as far as possible with the end position held for at least 2 s. The task was repeated two times. The better of the two trials from each time point was taken for further statistical analysis [27].

Cardiopulmonary test

Cardiorespiratory fitness was measured using a maximal graded exercise running test with a treadmill, based on the modified Bruce



▶ **Fig. 2** tDCS montage showing the positioning of the primers in the headset (left), and the placement of the headset on the international 10:20 system of electroencephalography [23] (right → grey highlighted horizontal bar).

ramp protocol [28, 29]. Gas exchange measurements during the exercise were performed breath-by-breath analysis using the Ergospirometry (K5, Cosmed, Italy). Peak oxygen uptake (VO_{2peak}) was recorded as the greatest mean value determined by the breath-by-breath VO_2 during 10 consecutive seconds and confirmed if two of the three criteria of VO_2max were met [30, 31]. Perceived exertion was monitored near the end of the last minute of each stage. However, an overall RPE score, registered at the end of the protocol, was considered for the comparison with other tests.

Statistical analysis

Normal distribution of the data was assessed by Shapiro-Wilk tests.

The test-retest reliability of the Sargeant and sit & reach tests was measured using an intraclass correlation coefficient (ICC, Cronbach-α) and interpreted as follows: $\alpha \geq 0.9$ = excellent; $0.9 > \alpha \geq 0.8$ = good; $0.8. > \alpha \geq 0.7$ = acceptable; $0.7 > \alpha \geq 0.6$ = questionable; $0.6 > \alpha \geq 0.5$ = poor [32].

The RPE values, originating from an ordinal scale (CR10) [19], were shown as median and quartiles and compared with Wilcoxon matched-pairs signed rank test. All other data were represented as mean ± standard deviation (SD). Mixed repeated measures ANOVAs were performed on physical fitness tests, with factors of condition (baseline; sham; tDCS) and group assignment (arms). Post hoc pair-wise comparisons were conducted utilizing Bonferroni's test when appropriate. A p value less than 0.05 was considered statistically significant. Partial eta squared (η_p^2) effect sizes (ES) were determined and interpreted using the following cutoffs: small effect, $\eta_p^2 \leq 0.03$; medium/moderate effect, $0.03 < \leq_p^2 < 0.10$; large effect, $0.10 \leq \eta_p^2 < 0.20$; very large effect, $\eta_p^2 \geq 0.20$ [33].

Analyses were carried out with the Statistical Package SPSS version 26 for Mac (Armonk, NY, USA; IBM Corp.), GraphPad Prism 8 (San Diego, CA, USA), and Excel version 16.32 for Mac (Microsoft, Redmond, WA, USA).

▶ **Table 1** Characteristics of the study participants at baseline.

Variable/parameters	(n = 17)
Age (years)	30.9 ± 6.5
Body weight (kg)	78.4 ± 9.9
Height (m)	1.78 ± 0.07
BMI (kg/m^2)	24.8 ± 3.1
Physical Activity Index (AU)	9.9 ± 1.4
Dietary intake (kcal/day)	2132 ± 434
Lower limb power (cm)	49.3 ± 9.4
Sit & reach amplitude (cm)	7.4 ± 10.4
VO_{2peak} (mL/kg/min)	37.3 ± 11.1

Data are expressed as means ± SD. BMI = body mass index; VO_{2peak} = peak oxygen uptake.

Results

Study participants

All demographic and anthropometric characteristics of the participants are provided in ▶ **Table 1**. According to the physical activity index (PAI), calculated on the basis of the Baecke's questionnaire [20], the subjects were demonstrated to be active.

Physical fitness measures

No differences were detected between baseline and stimulation tests (either sham or -tDCS) for any of the three physical fitness variables. Mean ± SD, absolute differences, and 95 % CI of the study participants' results are offered in ▶ **Table 2**.

Lower Limb Power – No significant interaction stimulation x arm assignment was found ($F_{(1,15)} = 1.35$; $p > 0.05$). A main effect of tDCS, of a very large magnitude, was registered on vertical height jump ($F_{(1,15)} = 11.82$; $p = 0.004$; $\eta_p^2 = 0.41$). In particular, active tDCS stimulation increased lower limb power with respect to sham condition ($\Delta_{tDCS\text{-}baseline} = 2.57$ cm vs. $\Delta_{sham\text{-}baseline} = -0.09$ cm, $p = 0.004$, ▶ **Fig. 3a**). The reliability of the jump-and-reach tests was excellent ($\alpha = 0.930$).

Flexibility – No significant interaction stimulation x arm assignment was found ($F_{(1,15)} = 0.56$; $p > 0.05$). A main, large effect of tDCS was found in the sit & reach amplitude ($F_{(1,15)} = 3.14$; $p = 0.048$; $\eta_p^2 = 0.16$). In particular, when subjects underwent tDCS stimulation they experienced a flexibility greater than sham condition ($\Delta_{tDCS\text{-}baseline} = 2.33$ cm vs $\Delta_{sham\text{-}baseline} = 1.56$ cm, $p = 0.0482$, ▶ **Fig. 3b**). The reliability of the sit-and-reach tests was excellent ($\alpha = 0.990$).

Endurance – No significant interaction stimulation x arm assignment was found ($F_{(1,15)} = 0.28$; $p > 0.05$). tDCS exerted a main, very large effect on aerobic capacity ($F_{(1,15)} = 4.49$; $p = 0.041$; $\eta_p^2 = 0.22$). Bonferroni's post hoc revealed that tDCS-stimulated subjects showed a VO_{2peak} with respect to sham condition ($\Delta_{tDCS\text{-}baseline} = 6.08$ mL/kg/min vs $\Delta_{sham\text{-}baseline} = 1.54$ mL/kg/min, $p = 0.0292$, ▶ **Fig. 3c**).

Rating of Perceived Exertion – As to the RPE, no significant changes were detected across all conditions (▶ **Table 3**).

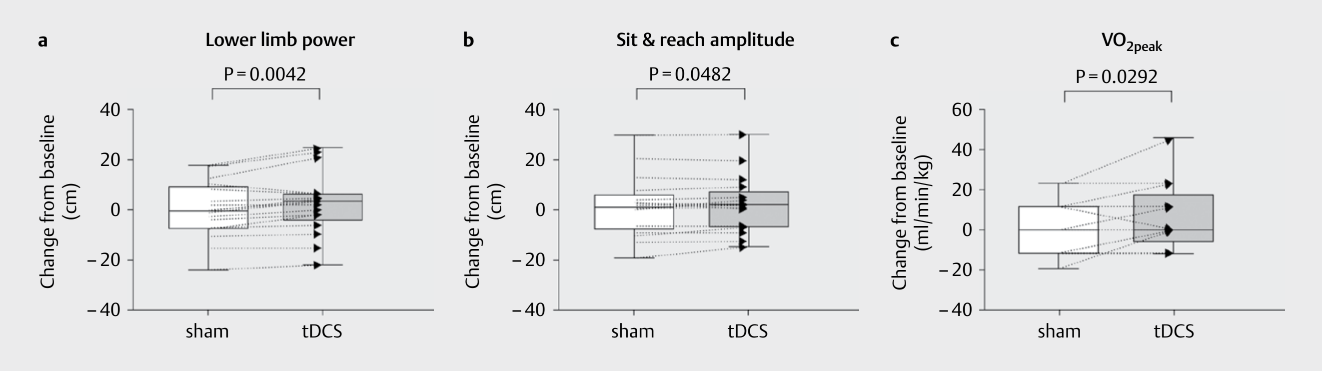
Discussion

The aim of the current study was to explore the effects of a wearable tDCS device on three variables of physical fitness in adult healthy and physically active men. In this single-blind, sham-controlled study, it was found that 20 minutes of 2mA bihemispheric tDCS administration was adequate to enhance significantly lower limb power, flexibility and endurance running by 5, 9, and 12 %, respectively (▶ **Table 2**). These findings are consistent with previous

▶ **Table 2** Study participants' results in the physical fitness tests under sham or tDCS.

	Sham		tDCS		Absolute difference Δ $_{(tDCS-sham)}$
	mean ± SD	95 % CI	mean ± SD	95 % CI	
Lower limb power (cm)	49.3 ± 9.5	44.3 to 54.2	51.9 ± 10.5 *	46.5 to 57.3	2.7
Sit & reach amplitude (cm)	8.9 ± 9.1	4.2 to 13.6	9.7 ± 8.7 *	5.2 to 14.2	0.8
VO_{2peak} (mL/kg/min)	38.8 ± 9.6	33.4 to 43.7	43.4 ± 10.1 *	38.2 to 48.6	4.6

(*) $p < 0.05$. tDCS = transcranial direct current stimulation; VO_{2peak} = peak oxygen uptake.



▶ **Fig. 3** Effects of tDCS on active men's physical fitness measures, under different experimental conditions (**a**, Sargeant test; **b**, Sit & reach test; **c**, Bruce endurance protocol). Whiskers box-plot: the hinges of the plot extend from the 25th to 75th percentiles. The whiskers go down to the smallest value and up to the largest one, passing through the median one.

▶ **Table 3** RPE (CR10) registered after the physical fitness tests.

	Baseline	**Sham**	**tDCS**
Power	7 (7–8)	7 (7–8)	7 (7–8)
Flexibility	7 (7–8)	7 (7–8)	7 (7–8)
Endurance	8 (8–9)	8 (8–9)	9 (8–9)

RPE = rating of perceived exertions. RPE levels were reported as median (percentile 25th and 75th). tDCS = transcranial direct current stimulation.

research indicating positive effects of tDCS on physical performance.

Vertical jumping ability is quite relevant in a multitude of sports disciplines requiring this lower limb strength measure on a task-oriented basis [34]. However, conflicting evidence raises doubts on the tDCS capability of increasing jump performance, such as countermovement jump (CMJ) [35]. Disparate results might be due to the modality of stimulation, since some authors described positive findings [5, 36], or no strength performance changes [35], after anodal tDCS. Other authors targeted the motor cortex bilaterally to successfully ameliorate CMJ performance [4]. In addition, anodal tDCS has been shown to potentially reduce the release of the inhibitory neurotransmitter GABA [37, 38]. GABA reduction likely improves the excitability of motor neurons through an increase in functions of cholinergic and glutamatergic neurons [39, 40], leading to an increase in vertical jump performance. Similar underlying neurophysiological mechanisms may explain the advantageous involvement of large muscle mass following tDCS on M1. In fact, young bodybuilders improved their knee extension tests (i. e. one-repetition maximum; short-term muscular endurance index) when they were excited over the M1 leg area and left temporal area [40]. In this regard, bilateral tDCS of M1 has been demonstrated to improve motor tasks, such as fast arm reaching tasks [41]. M1 is the elective brain area to modulate both bimanual tests [42] or unimanual tasks [43].

There have been only a few studies analyzing whether tDCS modifies flexibility, in terms of joint range of motion (ROM). Particularly, cathodal tDCS was reported to increase hip [44] and ankle joint [45] flexibility. These stretching advantages are reasonable, considering that joint ROM greatly relies on neural factors [46] and, in fact, tDCS may modulate the excitability of sensorimotor cortex [1, 7, 47, 48]. Another possible explanation could be connected to the findings of a study on the effects of motor imagery on lower limb flexibility [49]. Indeed, performing motor imagery during actual movement seems to improve stretching performance through reduced muscle activation. This improvement may be grounded in a cortical gain over spinal reflexes and can be directly evoked during bihemispheric tDCS administration.

Endurance performance has been demonstrated to be enhanced with different types of tDCS [13]. In the study of Park et al., with a design similar to the current one, participants ran 15 % longer in a treadmill test at constant load (80 % of VO_2max) when receiving tDCS compared to placebo stimulation [50]. Acute administration of anodal tDCS over M1 prior to exercise can lead to either improvements [40, 42, 51] or no effects [3, 52, 53]. Inconsistent tDCS effects were explained by a variety of cephalic or extra-cephalic tDCS montages [3]. The current study-results are worthy, giving that several works did not reach any significant changes in cardiorespiratory responses [50], including oxygen consumption, after tDCS with respect to sham condition. Besides, the disparity of the achieved results in the body of literature might be also due to complexity of the tasks investigated. This hypothesis fits with the observation that more complex tasks remain unaffected by tDCS [54–56]. Instead, the present set of trials envisaged very simple tests and fitness variables. Exercise performance *tout court* is influenced by several aspects, including muscle strength and endurance: if one is able to improve the key-determinants of physical fitness (lower limb strength, endurance running capacity, flexibility) then an adjunct ergogenic resource would be acquired.

In contrast to other studies [57], RPE in the current trial did not change across all the tests, although two out of three tests were immediate short bouts, for which the highest levels of fatigue were certainly difficult to be experienced. Consistently with this, during multiple-sets of resistance exercises, Montenegro et al. found similar RPE after anodal tDCS versus the sham condition in thirteen strength-trained men [58]. In one seminal study, Priori et al. showed that anodal tDCS applied to M1 could boost muscular endurance even in healthy subjects, modulating premotor areas and decreasing fatigue-related muscle pain [8]. According to the mechanisms postulated by some other authors [8, 59], lower RPE following tDCS have been associated to the magnitude of central motor command rising from pre/motor brain areas. Hence, if tDCS increases excitability of brain motor areas, a lesser input is required to produce a determinate muscular recruitment/output which, in turn, will correspond to a lower RPE (for a given force/power) [48, 60]. In this study, the improvement in endurance performance after tDCS, with a similar value of RPE, can be translated to an increased intensity/RPE ratio. This is equal to an average lower RPE at iso-time for the ramp protocol.

The effect size analysis included in this study exhibited a large to very large magnitude, which is promising as these findings were not limited to a singular task rather concerned a composite of physical abilities. As a strong point, the current experimental design magnified the signal-to-noise ratio associated with this study, permitting it to achieve a clear-cut significance.

As a limitation, brain response during post-stimulation was neither assessed nor monitored with instruments like electroencephalography or near-infrared spectroscopy. Therefore, the data obtained do not allow us to be assertive regarding the physiological mechanisms through which tDCS may act. Future studies might also address and identify the primary role played by neural factors, whether supraspinal or peripheral. Although tests were conducted in a maximum 10-day timespan, an absolute certainty of no-learning effect cannot be guaranteed. However, this aspect was offset by the practicability of such an ecological model. In this regard, the adoption of only one baseline, albeit chosen by other setup studies [60, 61], may represent a limitation. In addition, the present research was restricted to male subjects, therefore generalizations cannot be inferred and applied to a wide range of the population. Beyond enrolling different genders, further findings could be made by stratifying results by gender, age and levels of physical fitness.

Ultimately, this procedure could additionally provide insights into the extent of tDCS-gained benefits that can be preserved over the long term.

Giving its ascertained ability to alter motor unit firing rate and pattern [62, 63], tDCS has been broadly used in a variety of pathological and neurological conditions [64]. To date, an extensive body of research has been accumulating in the sports field, as well. A recent review [12] identified 12 studies relating tDCS and exercise performance, eight of which found a performance boost. On the other hand, two meta-analyses of 22 [65] and 24 [13] studies concluded the lack of a compelling evidence regarding the tDCS effects in favor of a possible athletic boost.

If studies have demonstrated that acute tDCS is free from any major side-effects [66], with no known health risks, the fact that this modulatory brain technique may represent a sort of "neurodoping" is still a matter of debate [67, 68]. Certainly, the dilemma is controversial although, as it stands, it remains to be proven whether this ergogenic method violates the spirit of sport, according to the World Antidoping Code criteria [69].

Regular exercise and physical training are crucial for maximizing individual efforts to promote overall health, healthy living and reducing the risk for numerous lifestyle diseases. A relatively inexpensive, readily available device – comparable to normal headphones – may serve as an adjunctive boost to adhering to daily recommended doses of physical activity for anyone, whether for healthy and impaired individuals.

tDCS has been leaving the functional laboratories and reaching into the community at large, including the sports and the fitness fields. Based on these trial outcomes, the ergogenic potential of such a portable device is considerable.

Conclusions

Previous work has indicated that bilateral tDCS over M1 is an effective method to improve exercise performance in healthy individuals. The present trial showed that bihemispheric tDCS applied over M1 increases vertical jump height, sit & reach amplitude, and endurance running capacity. These findings suggest that a convenient, wearable tDCS device could be a valuable resource for individuals seeking to improve physical fitness in their daily life or in athletic training.

Author Contributions

R.A. performed the studies. R.C. analyzed the data. R.C. wrote the manuscript. R.C., R.A., L.F., L.L. contributed to the discussion and reviewed the manuscript. R.C. designed and supervised the studies. All authors edited the manuscript. R.C. is the guarantor of this work and, as such, had full access to all the data in the studies and takes responsibility for the integrity of the data and the accuracy of data analysis.

Acknowledgements

The authors would like to thank all the men that participated to the study.

Funding Information

This work was supported by Italian Ministry of Health Ricerca Corrente – IRCCS MultiMedica

Conflict of Interest

The authors declare they have no competing interests relevant to the study.

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