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Review Article

The effects of Transcranial Direct Current Stimulation on psychomotor performance of athletes: a systematic review and meta-analysis

Short title: tDCS and athletic performance

Thais Alves-Lobão[1], Luis Felipe Sarmiento-Rivera[1], Flavia B. Xavier Vale[1], Yan Sobral Campos[1], Fabio Alexis Rincon-Uribe[1], Rejane Célia de Souza Godinho[1], Italo Sergio Lopes Campos[1], Janari da Silva Pedroso[1], Amauri Junior[1]

[1] Universidade Federal do Pará, Campus Belém, Pará, Brasil

***Corresponding author:** NTPC/UFPA, Rua Augusto Correa 01- Guamá, EP: 66075-110, Belém-PA, Brasil. **E-mail:** agjunior@ufpa.br

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ABSTRACT

Psychomotor performance is a complex function generated by brain and motor systems integration, measured by accuracy, latency, and movement speed. In sports, to look for ways to improve movements is usual. Also, to utilize Transcranial Direct Current Stimulation (tDCS) as technique of non-invasive stimulation may produce alterations in psychomotor sport skills. We conducted a systematic review including experimental studies with sham or control groups in adults reporting tDCS effects on athletes' psychomotor performance. Cochrane Manual for Systematic Reviews and the statement on systematic reviews and meta-analysis of PRISMA-P (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols) were followed. PsycINFO, PubMed (central), Scopus, Web of Science, Embase, SPORTDiscus, and Cochrane Library databases were searched. Empirical studies published in English, Spanish, and Portuguese from 2009 onwards and whose primary results presented an effective measure of transcranial direct current stimulation in the psychomotor performance of adult athletes were included. The results list 10 articles, 6 of them entered in the meta-analyses. The articles presented a low risk of bias and low publication bias but great dispersion of stimulation areas.

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Keywords: psychomotor performance; sports; tDCS; neuromodulation.

INTRODUCTION

Humans are born with a natural capacity to learn by integration with environmental stimuli in responses generated by integration with sensory inputs and motor outputs (Hindmarch, 2014). Reflex is the simplest response and integration can be quite complex, involving Central Nervous System, and generating a motor reaction: a psychomotor response. Psychomotor function comprehends physical movement (motor) and cognitive processes. Measurement occurs by accuracy or speed (latency or reaction time) to measure psychomotor performance (Hatfield et al 2004; Kovaleva et al 2012).

One of the most evident ways to present psychomotor performance is sport activity. Movement is necessarily efficient (Hatfield et al., 2004), i.e., it has a low response cost, maxim accuracy, and minimum latency (Hatfield & Hilman, 2001; O'Dwyer & Neilson, 2000). As result, improve psychomotor performance in athletes is the objective (Hatfield & Hilman, 2001). And, to achieve that, learning techniques, psychological techniques, training, nutritional alterations, environmental manipulations, and drugs are used. Sports performance results from both genetic factors and the individual's degree of experience (Davids & Baker, 2007). The athlete’s performance level depends on his/her morphofunctional characteristics, the specific sport demands , and individual experiences in training and competition (Shyamali Kaushalya et al 2021). Some specific psychomotor skills may be stimulated in athletes at the same time with his/her physical preparation, to expand general physical fitness. Transcranial direct current stimulation (tDCS) emerges as a neuromodulation tool to modulate human performance in exercise and sport. Stimulation with this method is done in two ways: the anodal tDCS, considered stimulating neural areas; and the cathodal tDCS, normally considered as a way to inhibit brain area activity (Bruckner & Kammer, 2017).

The tDCS contributed to reinforce the important role of the brain to regulate exercise performance, integrating physiological and psychological cues (Campos et al, 2016).

Transcranial direct current stimulation (tDCS) is a technique of non-invasive brain stimulation through two electrodes that induce alterations in the polarization of cortical neurons in resting membranes (Machado et al, 2019; Nitsche, & Paulus, 2000). Therapeutics use extends to pain control, adjunctive therapy to psychological and neurological pathologiesfor example, anxiety, depression, Parkinson Disease, and panic (Lefaucheur, et al., 2017). Use in sports have been popular since 2013 (Lefaucheur et al., 2017), improving psychomotor performance by self-stimulation The literature on this topic is unclear, with positive results in some sports but not in other (Lefaucheur et al., 2017).

The tDCS use induces to changes in skills related to psychomotor performance, such as reaction time, accuracy (motor skill acquisition), and fatigue reduction (Machado et al., 2019). Some authors think that tDCS is a possible way of non-pharmacological doping and breaks the spirit of sports (Davis, 2013). However, some disagree and say tDCS is not doping cause do not contradict Wanda recommendations;maybe generate ethical questions (Holgado et al. 2019,; Zhu et al. 2019). Literature description related to experimental studies regarding tDCS effect may contribute to answering questions about use of tDCS in athletic competitions.

Although there are other reviews, their objectives are different: Machado et al. (2019) and Alix-Fages et al. (2019) focused on endurance and strength; Holgado et al. (2019b) point out about exercises and its indexes in a broad way, not in sports; Lattari, et al. (2018) concentrate on women; and Shyamali Kaushalya et al. (2021) centered on runners and cyclists. Our review focuses on psychomotor performance, as defined above.

This paper aims to present a systematic review to evaluate the effect of transcranial direct current stimulation on athletes psychomotor performance.

METHODS

This systematic review and meta-analysis followed the model "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA-P) (Moher et al., 2015) according to Cochrane Manual for Systematic Reviews. We managed citations and references in Mendeley; data were extracted and handled in Excel. This review was enrolled in the international prospective register of systematic review: PROSPERO RD42020210550. The Figure 1 summarizes this process.

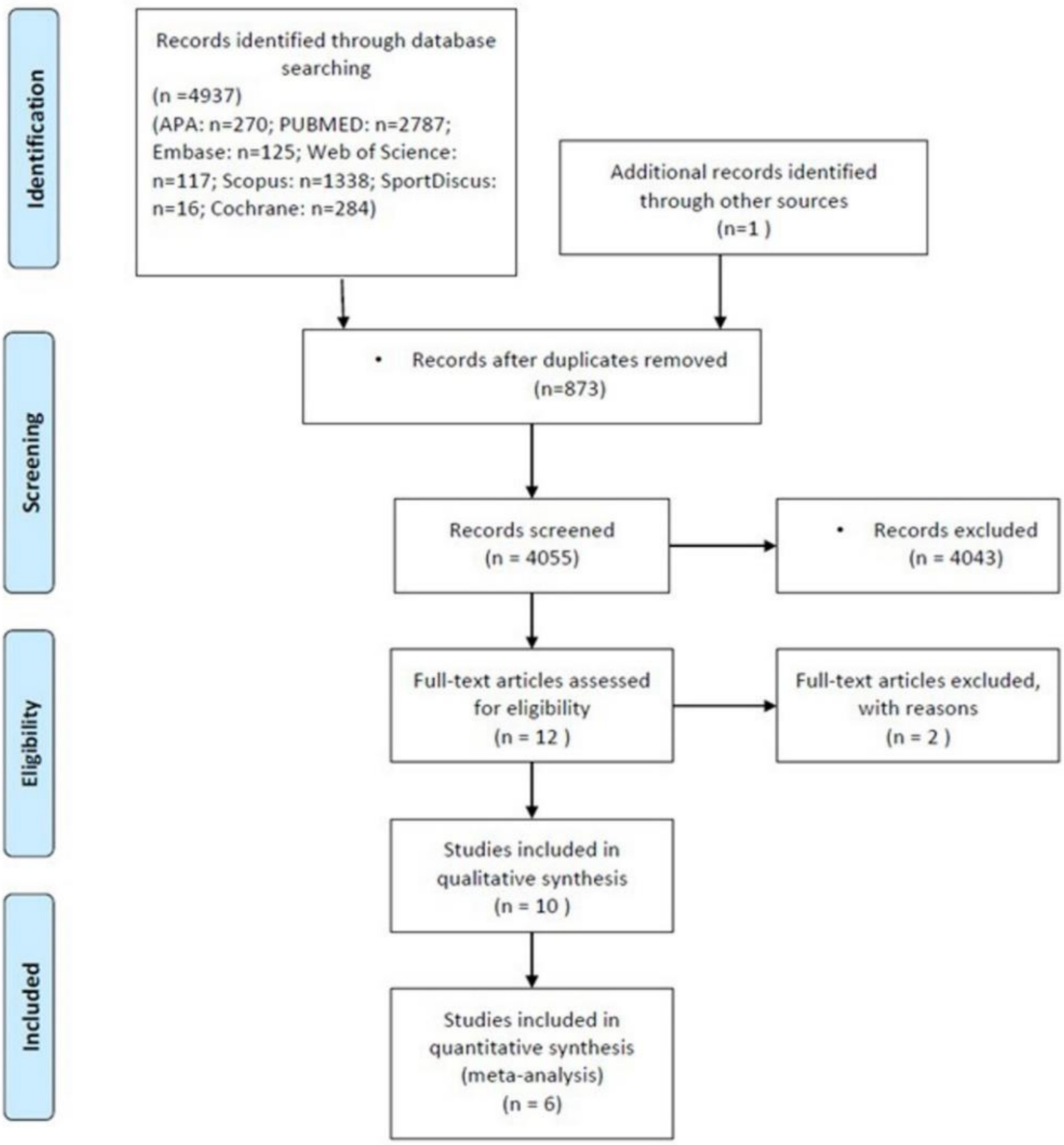

Figure 1. *PRISMA summary of the study selection process*

Eligibility criteria

Types of studies: We included experimental studies (randomized controlled trials, cohort , and case-control), cross-sectional and longitudinal studies, and sham-controlled studies reporting Transcranial Direct Current Stimulation effects (tDCS) or High-Definition tDCS (HDCS) on athletes' psychomotor performance in healthy samples. Dissertations, books, book chapters, reports, conference material, review articles, meta-analyses, instruments' validation, and scales were excluded from review.

Types of participants: We considered adults (aged 18+ years), male or female, and athletes who participated in a tDCS study including psychomotor performance.

Patient and public involvement: No patient was involved.

Types of outcome measurement: Principal result was related to the functional effect of the stimulation on modulation skill needed to psychomotor performance in motor flexibility, force, and efficacy in sports.

Search strategies: These electronic databases were searched: PsycINFO, PubMed (central), Scopus, Web of Science, Embase, SPORTDiscus, and the Cochrane Library. Empirical studies published in English, Spanish, and Portuguese from January 2009 onwards and whose primary results presented a measurable effect of transcranial direct current stimulation on t psychomotor performance of adult athletes were included.

Search Criteria: We selected studies purposing to measure tDCS effect only, using these keywords: (1) 'Transcranial direct current stimulation'; (2) 'tDCS'; (3) ‘HDCS’; (4) ‘Electric Stimulation Therapy'; (5) ‘Neuromodulation’; AND; c) In relation to sports: (6) ‘Sports’; (7) 'Athletic Performance'; (8) ‘Psychomotor Performance’. In adiction, we made a search with boolean terms: [('Transcranial direct current stimulation') OR (tDCS) OR (HDCS) OR (Electric Stimulation Therapy') OR (Neuromodulation’)] AND [(Sports’) OR ('Athletic Performance') OR (Psychomotor Performance)].

Selection process: All search results were imported into Mendeley software to manage data and eliminate duplicates. Two independent reviewers made a preliminary title and summaries texts selection for inclusion and exclusion. Subsequently, full text selection was done, and two reviewers applied inclusion and exclusion criteria to identify relevant studies to be included in the systematic review analysis. Discrepancies were solved by consensus with the intervention of a third reviewer.

Data extraction process: Data were organized by a reviewer using standardized extraction form previously prepared in Excel to collect these variables: (1) metadata (authorship, publication date, etc.); (2) demographic data (sample size in each group, age, sex); (3) types of sports (psychomotor performance measures); (4) characteristics of the tDCS technique: electrode position; current intensity; electrode size; current density (current divided by electrode area); number of data and (5) methods (randomization protocol; blind evaluation; number evasion). After extracting data, if need, reviewers addressed any disagreement by consensus with the third reviewer.

Quality assessment: Indicated which study characteristics were assessed and/or any formal risk of bias/quality assessment tools was used. The 'risk of bias' was assessed by two independent reviewers using the Cochrane Risk of Bias (RoB 2.0) tool for Randomized Controlled Trials and the Cochrane Risk of Bias in Non-Randomised Studies - of Interventions (ROBINS-I) tool for non-randomized studies (Sterne et al., 2019).

Data synthesis: This study was a meta-analysis, and statistical analysis was carried out using the R software (version 4.0.0) and the R meta-package (https://cran.r-project.org/web/packages/meta/meta.pdf). Each study calculated effect size (i.e., Cohen's d) to indicate the difference between distinct stimulation conditions considering training and post-training activities (in case of a project between subjects) or using a Cohen-adjusted formula for testing t paired (in case of a project within-subject). We believe several studies would give small sample sizes. We adjusted sample size to the bias of small decreases - Hedges 'g (Hedges & Olkin, 2014), interpreted as Cohen's d. As we expected decreased heterogeneity between studies, we calculated averages based on random-effects model for a population, varying according to study heterogeneity. Heterogeneity significance was mandatory using two tests with Q statistics Cochran's test ($P < 0.05$). The bias assessment report was presented using funnel graph asymmetry test (for example, Begg, Egger test).

Analyses were considered from variable testing. In case of categorical variables (participant characteristics such as sex, age, and outcome measures), they were based on mixed-effects of a meta-analytical categorical tests. In this model, studies within subgroups were combined with a random-effects model, and tests for significant differences between subgroups were conducted with the fixed-effects model. Analysis of continuous variables happened with maximum unrestricted likelihood meta-regression to verify significant relationship between continuous variables, considering the Z value and a corresponding p-value.

RESULTS

Overview

A total of 4055 unique records were screened and 10 full texts were assessed for eligibility. All studies about pathologies or clinical uses were eliminated from the analysis, remaining six eligible texts for meta-analysis. These low quantity of articles represents the way of data presentation. The systematic review covered the period between 2009 and November 2020. Fig 1 summarised study flow. Table 1 summarized studies data.

Table 1. Summarized data of the papers in systematic revision

Study	Design Sample and Groups	Experimental Methods And Stimulation	Psychomotor Measurement
Harris, Wilson, Buckingham, Vine, 2019	Sham-controlled, randomized-group, paired samples, one blind 73 participants (Golf athletes in 4 groups of 19 participants (frontal, 21.7± 2.8, 6F; M1,21.6± 2.9, 5F; V1:20.5±1.0, 7F; or Sham: 22.0± 3.7, 11F)	1 session 1,5 mA right DLPFC, M1 right; VI or Sham (M1), 5 min after test, 3 conditions Baseline, low pression, and High pression	performance (errors), quiet eye period; Anxiety IAMS;
Holgado, Zandonai, Ciria, Zabala, Hopker, Sanabria, 2019c	randomized, sham-controlled, single-blind, within-subject design experiment (cross over) 39 males cyclists, 27(6,8) years, 70,1 (9,5) KG, 3 conditions anodal, cathodal, and Sham	3 sessions of self-paced, 2 mA, 20 min, DLPFC	ergometric bike: power output, heart rate, flake test (inhibitory test) SRPE and EEG
Huang, Deng, Zheng, Liu, 2019	In this triple-blind, randomized, sham-controlled study 9 males (20±1,2 years), 73,1±6,5 Kg, practice 3 times/week activity in the lasts 6 months	2 sessions, 5 days interval 2,2 mA, 20m min, M1	; ergometer bike, 50 rpm, resistance 10 % weights/6 sec, with intervals 24 s. peak power output and mean power
Kamali, Nami, Yahyavi, Saadi, Mohammadi, 2019a	sham-controlled, paired samples 17 right-handed participants (9 males, 8 females; age 26 to 33 years, with 2 to 3 years of experience in pistol	2 sessions, 48 h interval, an experimental group with a session sham and other, tDCS 2 mA, 20 min, CB2 right, session 1: 20 min tDSC.	shots latency, accuracy); Mirror tracing, dynamic tremor tracing
Kamali, Saadi, Yahyavi, Zarifkar , Aligholi , Nami, 2019 b	sham-controlled, paired samples, double-blinded 12 experienced male bodybuilders (aging 18 to 44 years, weight 60-120 kg, with regular activity in the lasts 2 years	2 sessions, 72 h interval, an experimental group with a session sham and other, tDCS 2 mA, 13 min, M1 and TC	Visual analog scale; Hater hate, rated perception extension, one-repetition maximum. Short term endurance index, The Cambridge brain sciences cognitive platform. Surface electromyography and prefrontal hemodynamic response
Lattari, Campos, Lamego, Souza Maranhao Neto, Rocha, et al. 2020	sham-controlled, double-blinded, crossover study randomized 10 subjects, 22,7±3,9 years, classified advanced in strength training (47.8 6 22.7 months of training) (1), practitioners of squatting exercises (43.3 6 25.7 months),	2mA, 20 min, fp2 area, 3 sessions, anodal, cathodal, or sham with 48-72 h interval	Countermovement Jump Kinematic Test-Retest Reliability, Counter movement Jump Assessment in Experimental Conditions
Mesquita, Lage, Franchini, Romano-Silva, Albuquerque, 2019	sham-controlled, paired samples 19 TKD 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	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	Countermovement Jump. Two minutes after the warm-up the subjects performed 3 CMJs with 1-minute rest between them;

		CMJs and the FSKT immediately and 1 h after stimulation. Additionally, subjects should report their session rating of perceived exertion (session-RPE) 30 min after the performance assessment. Experimental sessions were performed at the same time of the day and were interspaced by at least 48 h 1,5 mA, 15 min, C3 and C4	Frequency Speed of Kick Test (FSKT)- Time of reaction
Okano, Fontes, Montenegro, De Tarso. Vera.S Farinatti , Cyrino, Li, Et Al (2015)	single-blinded 10 subjects, 33±9 years; national-level cyclist, 10-11 years training.	2 sessions, 24 h interval, 2mA, 20 min, TC area, anodal T3,	Maximal incremental exercise test, RPE responses
Seidel & Ragert, 2019	sham-controlled, crossover, double-blinded 46 participants, male and female divided into 3 groups (football, handball, and non-athletes. 2 years of regular practice and participation in competitions.	2 sessions, 24 h interval, 2 mA, 20 min, area M1 bilateral, session 1: 20 min tDSC, testing before, in 10 min on stimulation period, after stimulation (0 min and 30 min); session 2: idem	reaction time tasks (RTT) and tapping tasks (TT)
Seidel-Marzi, Ragert, 2020	sham-controlled, double-blinded, crossover study. 46 participants, divided into 3 groups (football, handball, and non-athletes. 2 years of regular practice and participation in competitions. 13 FB (three females, mean age = 24.00±3.89 years), 12 HB (five females, mean age = 22.50 ± 4.32 years) and 21 NA (11 females, mean age = 26.95 ± 3.43 years). On average, FB trained for 16.31 ± 5.02 years and currently 5.65 ± 2.15 h/week, whereas HB trained for 13.17 ± 4.49 years and currently 8.54 ± 3.84 h/week in their respective sports disciplines. On the other hand, NA performed an average of less than 2 h	2 sessions, 24 h interval, 2 mA, 20 min, M1 bilateral, session 1: 20 min tDSC, testing before, in 10 min on stimulation period, after stimulation (0 min and 30 min); session 2: idem	reaction time tasks (RTT) and tapping tasks (TT)

Study Characteristics

Design: All but one study (Okano et al, 2015) were randomized, and all them had some level of blinding: one triple-blinded design and two double-blinded designs. Most studies were crossover, with a sham control in some subjects; however, three of them (Kamali, et al 2019b; Mesquita et al 2019; Kamali, et al., 2019a) had a paired group design.

Sample: 50% sample was composed by high-level athletes (Seidel & Ragert, 2019; Mesquita et al., 2019; Holgado, et al., 2019c; Seidel-Marzi & Ragert, 2020; Lattari et al., 2020) and 50% by novices or non-professional athletes (Kamali et al, 2019a; Kamali et al. 2019b.; Mesquita et al., 2019; Huang et al 2019, Okano et al., 2015). Type of athletic activity varies, including football and handball (Seidel, & Ragert, 2019; Seidel-Marzi, & Ragert, 2020), cycling (Holgado et al., 2019c, Huang et al, 2019, Okano et al., 2015) golf (Harris et al 2019), taekwondo (Mesquita et al., 2019), pistol shot (Kamali et al., 2019a) and bodybuilder (Kamali et al., 2019b, Lattari et al., 2020).

Stimulation: Most studies (60 %) used 2 mA by 20 min (Seidel, & Ragert, 2019; SeidelMarzi, & Ragert, 2020, Kamali et al., 2019a; 2019 b; Holgado et al., 2019c; Huang et al., 2019; Lattari et al., 2020; Okano et al., 2015). Two studies (20 %) used 1,5 mA by 15 min (Mesquita et al., 2019; Harris et al., 2019): one of them (10 %) used 2, 2 mA by 20 min, and the other one (10%) used 2 mA for 13 min (Huang et al., 2019). The stimulation area was diversified, with the presence of M1 bilateral (Seidel & Ragert, 2019; Seidel-Marzi, & Ragert, 2020) or unilateral (Huang et al., 2019), CB2 right (Kamali et al., 2019 a; 2019b), C3 and C4 (Mesquita et al., 2019), F4, OZ DLPFC (Harris et al., 2019, Holgado et al., 2019c), FP2 (Lattari et al., 2020), TC and T3 (Okano et al., 2015).

Psychomotor measurement: The measure, quite diverse, was accomplished in time reaction (latency to response) (Seidel, & Ragert, 2019; Seidel-Marzi, & Ragert, 2020: Kamali et al., 2019a; Mesquita et al., 2019; Lattari et al., 2020), repetition (Seidel & Ragert, 2019;

Seidel-Marzi, & Ragert, 2020; Mesquita et al., 2019, Kamali et al., 2019a; Okano et al., 2015), power (Harris et al., 2019; Holgado et al., 2019c;Kamali et al., 2019b; Huang et al., 2019; Okano et al., 2019), or accuracy (Kamali et al., 2019a). Other non-psychomotor measurements were present in many articles, especially psychological measurements of anxiety and impulsivity, or physiological measurements, i.e., heart rate or EEG (Holgado et al., 2019c).

Results: Positive effects of tDCS were demonstrated in half of the studies (Kamali et al., 2019a a-b; Huang et al., 2019; Seidel-Marzi, & Ragert, 2020, Okano et al., 2015). One study analyses negative effects (Mesquita et al., 2019), and four papers presented no effects (Seidel, & Ragert, 2019, Harris et al., 2019; Holgado et al., 2019c; Lattari et al., 2020). Power dimension is the most common effect (Kamali et al., 2019b; Huang et al., 2019; Seidel-Marzi, & Ragert, 2020; Okano et al., 2015), and one study, with shooters, related effect and accuracy (Katami et al., 2019).

Power effect was investigated in objective measures (for example, motor movement's repetition or power in a cycle) and in subjective ones (fatigue test).

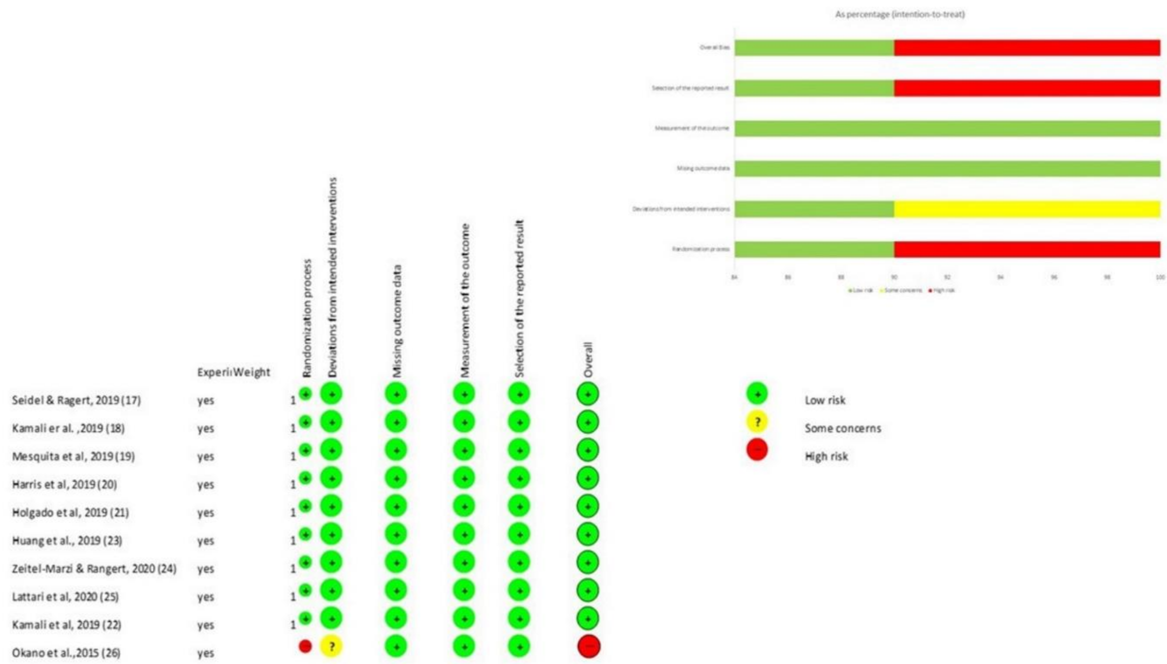

Figure 2. *Risk of bias assessment based on the evaluation domains listed in the Cochrane Collaboration Risk of Bias Tool: risk of bias graph (a), risk of bias summary (b)*

Risk of bias: Our study sample had a low risk of bias, in most of the studies. Except one with a high risk of blinding assessment. Figure 2 presents this analysis.

Meta-analysis: Meta-analysis is identified in Figures 3 and 4, and included six studies (Seidel, & Ragert, 2019; Seidel-Marzi & Ragert, 2020; Mesquita et al., 2019; Holgado et al., 2019c; Huang et al., 2019; Okano et al, 2015). General study meta-analysis identified significant heterogeneity of I2 = 72%, t2 = 0.4750, p <0.01, indicating use of random effects model is adequate. The results confirmed a significant effect Hedges' g =1.44, CI (95%): 0.92; 1.92. Assessing study publication bias, the funnel graph confirmed a degree of asymmetry. Egger's test revealed an intercept value of 2.627 [95% CI: -0.509; -5.763; t = 1,661] with a p-value of 0.1277, indicating there is no substantial asymmetry in the funnel graph, so, there is no evidence of publication bias.

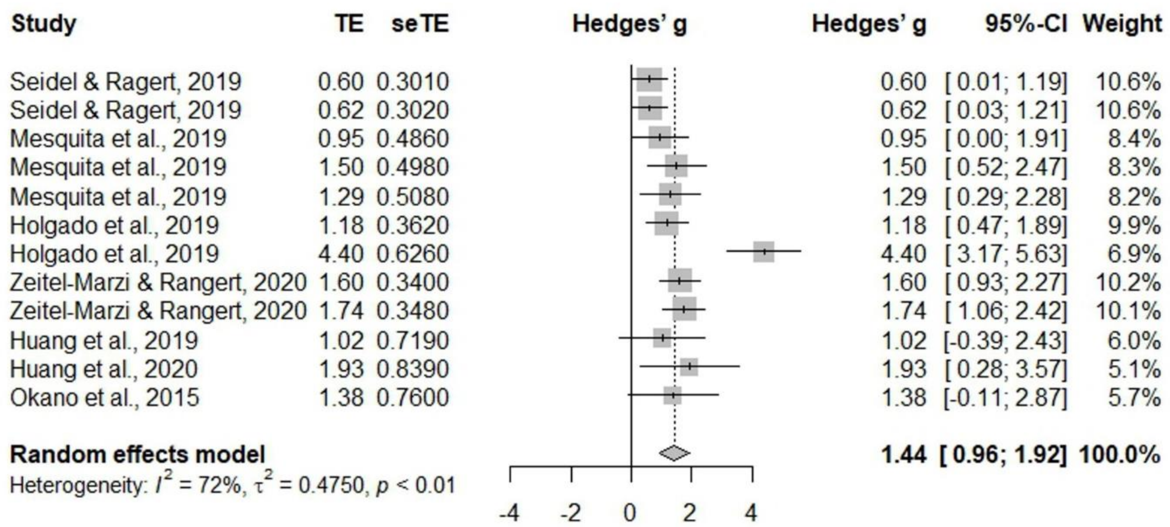

Figure 3. Forest plot of tDCS effect size on performance and subjective outcome

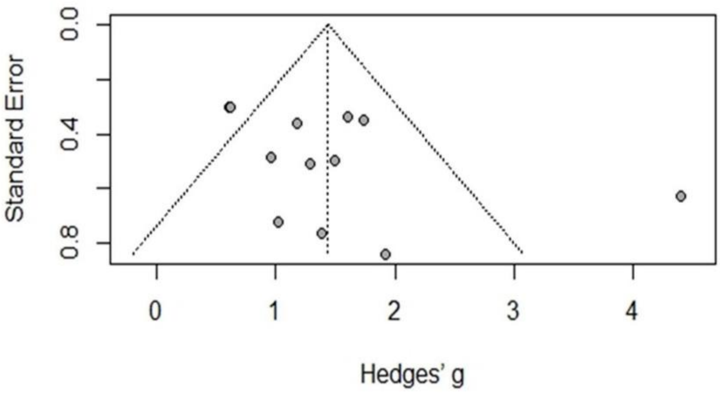

Figure 4. Funnel plot of Hedges' g effect size versus study standard error

DISCUSSION

Our analysis identified that tDCS had some effects on the athlete's psychomotor performance, however, is a controversial fact. There is no homogeneity in performance dimensions, namely, strength, accuracy, and latency. Analyzed articles confirm the effect on force dimension in those who report some effect by direct measure (W or Kg), indirect measure (perceived effort), or repetition speed measure, which can be considered as a force dimension. Even accuracy data, got from snipers, seems to indicate power data, and can be explained by better control of the weapon's retro-shot.

Relying on experimental plans and their specific objectives, either stimulated areas or test types and sports are diverse, not allowing a minimal general protocol for the tDCS use in the area. To know if there is a real effect of tDCS in each psychomotor dimension, would be needed to describe, accurately, the existence of each sport, and test these activities separately. Thus, would be required to stimulate different areas, and to test the effect of strength, accuracy, and latency (response time) in a laboratory situation. In a laboratory study concerning trained cyclists submitted to anodic tDCS before exercise, Okano et al. (2019) demonstrated an improvement in dynamic motor performance (incremental exercise test), and tolerance to athletes' physical effort. As for sport applicability, specifically concerning motor fatigue because of exhaustive physical work maintained for a long period, Seidel Marzi and Ragert (2019) evidenced that regardless of sport's requirement or athlete's training level, tDCS can reduce motor fatigue during rapid repetitive movements. On the other hand, in modalities requiring a closed motor skill such as golf, for example, which performance is particularly important to control visual attention (golf courses at baseline), no beneficial effects of tDCS were observed after receiving tDCS (Harris et al, 2019), reinforcing evidence of no learning transfer to actual sport performance. In this sense, would be necessary to consider the specific requirements of each sport to these dimensions and their combinations. Only in this way we could answer if tDCS influences sports so that it can be considered doping or not, and if the effect on psychomotricity is of such a magnitude that can be considered as a non-sports intervention.

However, we cannot make a conclusion on the current state of art reflected in this review. The articles, although having a good experimental design, do not present data density to support a definitive conclusion or construction of a stimulation protocol for athletes, in training or competition.

Our work has several limitations coming from the articles used: on the one hand, there are diverse ways to perform the tDCS; on the other hand, the methods to measure psychomotor effect vary a lot. And this has an impact on our review results.

CONCLUSIONS

The tDCS has an effect on strength, but this is not clear and may depend on the sport's requirements or procedure variations, but, curently, is not possible to define a safe and effective tDCS use protocol for athletes to increase psychomotor performance. Because of this, we necessity more parameterized studies to develop protocols to use in this population, to improve psychomotor activity.

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