Transcranial direct current stimulation (tDCS) and sporting performance: A systematic review and meta-analysis of tDCS effects on physical endurance, muscular strength, and visuomotor skills

Trish Chinzara¹², Gavin Buckingham¹, David Harris¹

1. Department of Sport and Health Science, University of Exeter, UK
2. Goldsmiths University of London, London, UK

Correspondence concerning this article should be addressed to Dr David Harris, School of Sport and Health Sciences, University of Exeter, St Luke’s Campus, Exeter, EX1 2LU. Contact: D.J.Harris@exeter.ac.uk. ORCiD: https://orcid.org/0000-0003-3880-3856

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Abstract

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique that has been linked with a range of physiological and cognitive enhancements relevant to sporting performance. As a number of positive and null findings have been reported in the literature, the present meta-analysis sought to synthesise results across endurance, strength and visuomotor skill domains to investigate if tDCS improves any aspect of sporting performance. Online database searches in August 2020 identified 43 full-text studies which examined the acute effects of tDCS compared to sham/control conditions on physical endurance, muscular strength, and visuomotor skills in healthy adults. Meta-analysis indicated a small overall effect favouring tDCS stimulation over sham/control (standardized mean difference (SMD) =0.25, CI95%[0.14;0.36]). Effects on strength (SMD=0.31, CI95%[0.10;0.51]) and visuomotor (SMD=0.29, CI95%[0.00;0.57]) tasks were larger than endurance performance (SMD=0.18, CI95%[0.00;0.37]). Meta-regressions indicated effect sizes were not related to stimulation parameters, but other factors such as genetics, gender, and experience may modulate tDCS Effects. The results suggest tDCS has the potential to be used as an ergogenic aid in conjunction with a specified training regime.

Keywords: ergogenic; neurodoping; neuroenhancement; sport; performance
1. Introduction

Successful sporting performance is dependent on an athlete’s ability to consistently perform at their peak. In the increasingly competitive sporting environment, there is heightened pressure to mitigate factors that limit physical and cognitive performance for accelerated results (Davis, 2013), which has prompted athletes to seek an advantage through ergogenic aids and neuroenhancement (Banissy and Muggleton, 2013). Transcranial direct currents stimulation (tDCS) is a form of brain stimulation that has been linked with a range of performance improvements in cognitive function (Banissy and Muggleton, 2013), exercise endurance (Cogiamanian et al., 2007) and muscular strength (Hazime et al., 2017). tDCS has a number of practical advantages over other methods of brain stimulation, such as transcranial magnetic stimulation (TMS), due to the cost, safety, and portability of stimulation devices (Davis, 2013; Bikson et al., 2016). The attraction for athletes is clear and tDCS has moved outside of controlled laboratories to the wider community, with stimulation kits being endorsed by athletes as a quick alternative to improve performance (Mansfield, 2016; Edwards, 2017). Yet, the accessibility of tDCS, rather than robust research findings, may have driven adoption of the technique.

Transcranial stimulation paradigms have grown in popularity due to their potential to provide a non-invasive method of modulating cognition and behaviour by increasing (anodal) or reducing (cathodal) cortical excitability (Stagg and Nitsche, 2011). tDCS has been explored in a variety of clinical conditions (Bennabi and Haffen, 2018; Inoue and Taneda, 2019; Lima and Fregni, 2008), but as well as treating clinical Conditions and impairments, tDCS has also been touted as a method of performance enhancement or ‘neurodoping’ (Davis, 2013). The inhibitory effects of stimulation have also found to be promising. For instance, TMS can suppress cortical activity to reduce the amplitude of tremors, resulting in improved motor control (Kang and Cauraugh, 2017). Alternatively, cathodal-tDCS also has the potential for performance enhancement effects via a reduction in declarative processing, in favour of more procedural processing (McKinley et al., 2016).

If reliable, emerging tDCS effects could signal considerable benefits in sport and related fields (e.g., the military or aviation) through improvements in physiology,
cognition, and motor learning. For instance, single session tDCS may mitigate
against the negative effects of cognitive fatigue on endurance performance (Reardon,
2016), improve cognitive performance through exciting higher brain areas via cross-
activation and modulating neuroplasticity (Stagg and Nitsche, 2011), and improve
motor performance or accelerate motor learning via excitation of motor cortex when
used in conjunction with a pre-established training regime (von Rein et al., 2015).
However, the ethical and practical applications of cognitive enhancement should be
considered alongside these observed benefits, as outlined by Davis (2017).

tDCS induces a weak but constant electrical current from a cathode (negative
electrode) to an anode (positive electrode) which modulates the activity of cortical
neurons near the electrode, and diffuse locations nearby (Stagg and Nitsche, 2011).
tDCS stimulation is proposed to facilitate neural activity through reducing the
negative polarisation across the neural membrane at the anode or inhibit activity
through hyperpolarisation at the cathode. The polarity-dependent effects of tDCS
may, however, be over-simplistic as a result of a non-linear dose-response (i.e.
possible anodal inhibition or cathodal excitation) (Esmaeilpour et al., 2018; Jamil et
al., 2016). Most tDCS devices use rubber electrodes, between 25-35cm² in size,
applied to the scalp over a targeted brain region determined by the intended effect.
These electrodes provide current at a range of 1-2mA, typically activated for 10-20min. Side effects are minimal with a mild tingling sensation being the most
commonly reported (70.6%) and insomnia (0.98%) being the worst (Poreisz et al.,
2007).

The motor cortex (M1) is typically a target for stimulation due to its role in
sustaining neural drive within motor neurons, thereby improving performance
by compensating for central fatigue (Papale and Hooks, 2018).
Derosière et al. (2014) showed increased ipsilateral M1 activation during a
unilateral handgrip task when the force was above 30% maximum voluntary
contraction (MVC), indicating a cross-activation effect. The cross-activation/
facilitation hypothesis is supported by evidence from Hendy et al. (2014) who report
application of anodal tDCS to ipsilateral M1 resulted in an increase in maximal
strength and cross-activation. The results support a hypothetical model proposed by
Lang et al. (2004), that tDCS can increase the synaptic effectiveness of corticospinal
cells though cross-activation making them last longer than the duration of
polarisation. Studies have also shown stimulation of motor regions can influence motor learning retention and corticospinal excitability in participants for up to an hour after delivery (Nitsche and Paulus, 2007). These findings suggest tDCS may be effective for enhancing the learning and/or execution of fine motor skills required in elite sporting endeavours and related domains (e.g., surgery – see Cox et al., 2020). Consequently, stimulation of M1 for either strength or motor skill performance appears promising, which partially explains its popularity as a target for sport performance studies (Frazer et al, 2017).

Application of tDCS is not limited to the motor cortex, an alternative target for stimulation is the dorsolateral prefrontal cortex (DLPFC). The prefrontal cortex is theorised to play a role in fatigue-related feedback, and decreased prefrontal cortical oxygenation results in Performance failure in a time to exhaustion (TTE) cycling task (Thomas and Stephane, 2007). Therefore, stimulating the area could increase neuronal activity to reinforce muscle feedback by strengthening cognitive ability to delay exercise termination (Grandperrin et al., 2020). This effect has been explored by Latteri et al. (2018) who found activating the DLPFC increased exercise tolerance. The benefits of PFC stimulation may also be derived from enhanced working memory activity and its role in cognitive control (Boudewyn, Scangos, Ranganath and Carter, 2020).

While direct brain stimulation has been linked with a range of physiological and cognitive benefits, inconsistent results and differential effects as a result of widely varying stimulation protocols poses a challenge for interpreting overall efficacy (Dedoncker, Brunoni, Baekenand Vanderhasselt, 2016). The duration of stimulation has been reported as a key determinant of the prolongation of tDCS effects on performance outcomes. Nitsche and Paulus (2000) report a significant elevation of motor-cortical excitability up to 40% after 10 minutes compared to a stimulus duration of 5 min (0.6 mA). Similarly, Williams et al. (2013) found a group receiving stimulation throughout a submaximal isolated isometric (TTF) test had significantly improved endurance, whereas the group receiving stimulation for 50% of the TTF test did not show this improvement.

Moreover, the exact positioning of the surface electrodes influences the cascading effects of stimulation in the brain, which in turn influences performance outcomes. Many studies fail to report a justification or clear hypothesis as to why they target
their selected brain region. A further challenge is that individual differences in brain
localisation introduce additional Noise effects (Datta et al., 2012). Most tDCS studies
report following the international 10:20 EEG system (Klem, Lüders and Jasper,
1999) however this method is limited to a few primary cortices (Woods et al., 2016).
Angius et al. (2016) explored these parameters by comparing cephalic and
extracephalic tDCS montages, finding that only the extracephalic montage yielded
improvements to isometric knee extensors. Differences in the two montages above
may be due to alternate current directions—cathodal stimulation negates the positive
effects of anodal stimulation by decreasing excitability in the brain area (Angius et
al., 2015). tDCS effects are further complicated by the finding that stimulation
effects interact with the resting membrane potential of targeted neurons, such that the
initial state of the performer modulates the result (Benwell et al., 2015). A pertinent
issue given the potentially varying states of arousal or fatigue likely to be present in
athletes. Consequently, it may be important to explore how stimulation parameters
moderate the performance enhancing effects of tDCS.

tDCS in the field of sport and exercise sciences has begun to be examined in
previous systematic reviews which have reported some positive (Alix-Fages et al.,
2019) and some inconclusive (Machado et al., 2019; Holgado, et al., 2019) evidence
for strength and endurance improvements. These reviews, however, were limited in
identifying only a small number of studies (Lattari et al., 2018; Machado et al., 2019)
or in grouping together studies that explored disparate exercise dimensions
(Holgado, et al., 2019), which may have obscured important differences between
physiological domains. These reviews also focused exclusively on exercise
dimensions, ignoring the potential of tDCS for enhancing fine motor performance
and motor learning (Nitsche et al., 2003). Motor skill execution is a fundamental part
of sporting expertise and a number of recent studies have begun to examine the
benefits of tDCS in this area (Zhu et al., 2014; Harris et al., 2019). Hence, we aimed
to provide an up-to-date analysis of the state of the literature that 1) differentiated
studies along physiological dimensions and performed sub-analyses, 2) provided a
more comprehensive overview of performance enhancing effects by examining
physical endurance, muscular strength, and visuomotor skills, and 3) examined the
moderating effects of stimulation parameters.

This review is motivated by the growing interest and non-regulated use of tDCS
devices in sport and non-sport contexts (Angius, Hopker, and Mauger, 2017). The current available evidence on the effectiveness of tDCS on sport performance is conflicting and unclear. Additionally, the multifaceted nature of sporting performance, requiring a range of physical and mental attributes, means that findings from a range of cognitive and physiological effects need to be synthesised. The findings will be useful in directing the future direction of tDCS techniques in performance enhancement contexts and ascertaining the prospects of tailoring training using neuromodulation based on individual difference variance and for identifying the domains in which benefits are most likely to be achieved.

In reviewing this literature, we sought to address the following research questions:

i. Is there reliable evidence for performance enhancing effects in tasks relevant to sport?

ii. What is the quality of research in this field?

iii. Are there differing effects of direct current stimulation for strength, endurance, and visuomotor tasks?

iv. Are there moderating effects of stimulation parameters?

2. Methods

2.1 Protocol

A systematic review and meta-analysis was conducted following the guidelines of the Cochrane group (O'Connor, Green and Higgins, 2008) which required reporting of the review procedure, selection of eligible articles based on inclusion/exclusion criteria, quality assessment, data extraction, and a meta-analytic review of the results. This review also adheres to the PRISMA guidelines for systematic reviews (Moher et al, 2009). The PRISMA checklist (and other supplementary files) are available from the Open Science Framework(https://osf.io/8whtv/).

2.2 Literature search

The literature search was carried out using four online databases: PubMed/MedLine; Scopus; Cochrane (Embase); and SportDiscus. These databases were selected as they contain the majority of sports science and neuroscience journals. The databases were searched from inception until 28th August 2020, the date the final search was conducted. The search string contained the following MeSH terms and Boolean
operators: “Transcranial direct current stimulation” OR “tDCS” AND “Sports performance”. In addition, further searches were performed by the first author using forward and backward citation chasing, based on the reference list of the collected studies, and email correspondence with relevant researchers to retrieve studies that were not covered by the databases with the search terms.

2.3 Eligibility Criteria

Inclusion criteria:

Participants – healthy adult men and women (18-85 years) with no history of orthopaedic or psychiatric illness. The healthy participants serve to control for the high variability in tDCS outcomes (Rudroff, Workman, Fietsam and Kamholz, 2020).

Intervention – measured the acute effects of tDCS administration prior to or during endurance, strength or visuomotor tasks. Studies were included if they applied tDCS either before or during the test period.

Comparators – use of Sham-tDCS as a placebo or a control condition with no intervention (some studies included both comparators, in which case, the control condition was used). The use of blinded sham or control conditions reduces bias.

Outcomes – physical endurance (e.g. time to task failure tasks), strength (e.g. maximal knee extensors), or visuomotor sports tasks (e.g. golf putting) were analysed.

Study design – Randomised control trials that used either a cross-over or parallel study design. Randomisation minimises bias to determine clearly if there is a relationship between the intervention (tDCS) and the outcome (sport performance).

Exclusion criteria:

Studies were excluded if they: (i) were not published in English; (ii) used clinical participants or did not provide adequate information on participant health; (iii) were not published as full text records or did not comply with the purpose of the analysis; (iv) did not use endurance, strength or visuomotor tasks. Endurance tasks were
considered any tasks in which the participants were required to perform until they could no longer continue with the requisite level of effort. Strength tasks were considered any that explored maximal strength capabilities and visuomotor tasks were considered those in which participants performed a sport specific procedure that involved the visual guidance of a goal-directed movement (e.g., throwing a ball). Hence studies relating to other visuomotor tasks such as surgery were not included.

2.4 Study Selection

The primary search returned 3579 potential publications. Thirty-five additional studies were found through other searches (reference list forward citation chasing or correspondence). All records were collated using Mendeley software to remove duplicate articles and screen titles efficiently. Fifty-four duplicate items were found and removed, and as a result of screening by title and abstract 3349 articles were removed. The remaining 176 full-text articles were assessed for eligibility and 43 studies were included in the qualitative analysis of which 41 where analysed quantitatively. Figure 1 summarises the PRISMA study selection process (Moher et al., 2009).

2.5 Data Extraction, Analysis, and Synthesis

Studies were read twice by the researcher to enhance familiarity with the data before extracting and synthesising the findings (Cuijpers, 2016; Petticrew & Roberts, 2008). Each study was coded using a predefined Excel spreadsheet for the following variables (based on recommendations in Popay et al., 2006): sample size and participant characteristics (gender and age), characteristics of the tDCS stimulation protocol (including electrode location, size, stimulation intensity and duration), exercise protocol and number of sessions the study required, and performance outcome (improvement/no improvement). To minimise the risk of bias in extraction and increase confidence in the method, the data was extracted twice. In studies that had multiple outcome measures the first assessment following tDCS application was reported as the post-stimulation result. Any ambiguities were discussed amongst researchers. Where data was missing, the authors of the original papers were contacted, or values were extracted using the Webplot digitizer Version 4.4 (https://apps.automeris.io/wpd/).
Figure 1. PRISMA study flow diagram illustrating the identification and selection of relevant studies.

2.6 Assessment of Methodological Quality
A quality assessment of the included articles was performed using the Physiotherapy Evidence Database (PEDro) scale (http://www.pedro.org.au) (see supplementary materials: https://osf.io/k65c3/). The scale consists of multiple items which assesses internal validity and the statistical replicability of results graded on a ‘yes’/’no’ basis in which ‘yes’ corresponds to a point. Points are awarded if the criteria are explicitly satisfied, with a cut off score of ≥6/10 for a study of high methodological quality (see Figure 2).

As per Cochrane guidelines, further risk of bias was assessed in each included article using Review Manager software (RevMan 5.3.5; Cochrane Collaboration, Oxford, UK). The criteria comprised; (a) assessments for sequence generation (randomization), (b) allocation sequence concealment, (c) blinding of participants and researchers, (d) incomplete outcome data, (e) selective outcome reporting and (f) other bias. Each of these items were deemed as low risk of bias (+), high risk of bias (-) or unclear risk of bias (?) (see supplementary materials: https://osf.io/yv4sz/).

2.7 Statistical Analysis

To calculate pooled effect sizes, outcome measures were identified for endurance, strength and visuomotor tasks and a separate meta-analysis was conducted for each of the three study domains. Studies within each domain (endurance, strength and visuomotor) used varying outcome measures, but as our aim was to examine the broader effect in each domain a quantitative synthesis was deemed to be appropriate (Borenstein et al, 2009).

Meta-analysis and statistical analyses were performed using Jamovi R ‘MAJOR’ module (version 1.2.27) and R with the ‘metafor’ package (version 4.1.1). In each article the size of the intervention effect was calculated according to the difference in performance outcome between the experimental and control conditions. The intervention effect was measured by calculating the standardised mean difference (SMD) of the continuous data within the studies at a 95% confidence level (CI95%). SMD and CI95% were weighted by the inverse variance method. As the studies drew from a different populations and used a range of tasks, a random effects model was chosen to better account for any statistical heterogeneity and dependencies within
studies (Borenstein et al., 2009). The use of a random effects model assumes that there is not only one true effect size, but rather a distribution of true effect sizes from which we aim to estimate the mean (Cuijpers, 2016). Cochrane guidelines report standardised mean difference (SDM) using Cohens Effect Size to represent small (≤0.2), moderate (≤0.5) large (≤0.8) and very large (>0.8) effect sizes. Heterogeneity between studies was assessed using $\tau^2$ and $I^2$ which can be seen in the forest plot (Figure 5). The $I^2$ statistic was used to assess the degree of heterogeneity, with values from ≤50% indicating low heterogeneity, 50–75% moderate heterogeneity and > 75% high level of heterogeneity. A number of decisions go into selecting studies for a meta-analysis and some may have a disproportionate effect on the overall effect estimate. In order to understand whether any studies or subgroups of studies had a disproportionate effect on the overall estimate we first performed a ‘leave-one-out’ analysis and re-ran the meta-analyses (for each subgroup) leaving out one study in each analysis. The results indicated that the omission of no single study heavily biased the overall effect. SMD estimates ranged from 0.16 to 0.22 for endurance, from 0.27 to 0.34 for strength, and from 0.25 to 0.37 for visuomotor. The full leave-one-out analysis tables are available in the supplementary materials (https://osf.io/nkaej/).

Additionally, we performed a combinatorial meta-analysis which runs a series of Subset analyses based on all possible combinations of the included studies (i.e. $2^{k-1}$). The Graphical Display of Study Heterogeneity (GOSH) plots are presented in Figure 6 and display the range of possible effect sizes for all possible combinations of studies plotted against the $I^2$ for each combination (Olkin, Dahabreh, & Trikalinos, 2012).

Mixed-effects model meta-regression was used to assess how stimulation parameter choices may have moderated the results. The following variables were meta-regressed: current intensity (mA); current density (mA/cm$^2$); and stimulation duration (minutes). As stimulation intensity in the included studies fell entirely into two values (1.5mA and 2.0mA) it was treated as a categorical predictor. Borenstein et al. (2011) recommend that 10 studies are required for reliable meta-regressions, so the results for the visuomotor subgroup ($k=5$) should be interpreted with caution.
3.1 Overview

The article identification process produced 3525 unique records for screening, which resulted in 176 full-text records that were assessed for eligibility (Figure 1). The use of a clinical group was the most frequent reason for excluding studies in the screening phase (e.g. Parkinson’s disease or strokes). After exclusions, 43 studies were included, of which 41 were included in the final quantitative synthesis (meta-analysis). Two papers were outliers presenting large effect sizes (Cogiamaniam et al. 2007; Rocha et al. 2020).

3.2 Study Characteristics and Quality Assessment

An overview of the study characteristics (sample size, tDCS protocol and study outcomes) is presented in Table 1. The sample consisted of 43 articles published between 2013 and 2020, with most of the work being published recently (86% since 2015). Of the included studies, 20 examined strength-based tasks, 17 examined endurance tasks, and 6 examined visuomotor tasks. There were 790 participants in total across the studies; 546 were male and 244 were female. The studies had participants with a range of levels of physical fitness and experience varying from novice to elite athletes. The mean sample size per study was \( N = 15 \pm 6.4 \) (ranging from 9 to 73 participants), and participant age ranged from 16 to 68. The most common outcome variables were strength, muscular endurance, and accuracy.

All the studies were randomised, 35 were crossover and 8 were parallel which satisfied blinding requirements. Studies used a sham and/or control comparator group, of which 4 studies included both conditions. The participant populations of the studies varied for level of experience (novices to elite athletes) and fitness (recreationally active to trained).

With regards to tDCS procedures, all of the included studies applied tDCS before exercise using a 1.5-2 mA current for a duration of 10 - 20 min (17.2 ± 5.2).

Electrode sizes ranged between 12 to 35 cm\(^2\). 26 studies (60.5%) reported the effects of tDCS as a standalone -including Huang et al. (2019) who used a Halo device - but 14 studies (32.6%) looked exclusively at anodal-tDCS (a-tDCS) while 1 study (2.3%) looked at cathodal-tDCS (c-tDCS) and 2 studies (4.6%) explored the effects of High-Definition tDCS (HD-tDCS).

The assessment of study quality indicated that the overall quality of the studies was...
high, with a mean score on the PEDro scale of 7.6 ± 1.0 points out of 10. Additionally, the Cochrane quality assessment showed the studies had low risk of bias overall with a very small percentage of studies presenting high risk for blinding procedures (22%). All studies adequately prescribed to the sham/control methods.
<table>
<thead>
<tr>
<th>Author</th>
<th>Sample</th>
<th>Experience</th>
<th>Anode (A)/Cathode (C) Brain Target</th>
<th>tDCS Protocol</th>
<th>Study Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdelmoula et al. (2016)</td>
<td>11 (8M/3F)</td>
<td>None participated in regular strength training programs</td>
<td>A – left motor cortex (M1) C – Right shoulder</td>
<td>1.5 0.043 10</td>
<td>35% maximal torque of elbow flexors to failure Improvement - increased endurance time</td>
</tr>
<tr>
<td>Alix-Fages et al. (2020)</td>
<td>14 (M)</td>
<td>recreational resistance trained &gt;2 years</td>
<td>A – DLPC C – Right orbitofrontal cortex (opposite for C-tDCS)</td>
<td>2.0 N/S 15 75% 1RM resistance training to failure Improvement - A-tDCS increased training volume and reduced RPE values</td>
<td></td>
</tr>
<tr>
<td>Angius et al. (2017)</td>
<td>12 (8M/4F)</td>
<td>Regular aerobic training &gt;3hrs per week</td>
<td>A – bilateral M1 C – above ipsilateral shoulders (opposite for A-tDCS)</td>
<td>2.0 0.057 10</td>
<td>Cycling TTF test Improvement - A-tDCS improves endurance performance</td>
</tr>
<tr>
<td>Angius et al. (2016)</td>
<td>9 (M)</td>
<td>Recreationally active</td>
<td>A – left M1 C – dorsolateral right prefrontal cortex</td>
<td>2.0 0.057 10</td>
<td>MIVC knee extensors Improvement – TTE increased</td>
</tr>
<tr>
<td>Angius et al. (2019)</td>
<td>12 (9M/3F)</td>
<td>Recreationally active</td>
<td>A – F3 C – Fp2</td>
<td>2.0 0.170 30</td>
<td>Cycling TTF test at 70% of $W_{peak}$ Improvement – TTE was longer and reduced RPE</td>
</tr>
<tr>
<td>Angius et al. (2015)</td>
<td>9 (M)</td>
<td>Recreationally active</td>
<td>A – M1 C – DLPC</td>
<td>2.0 0.057 10</td>
<td>Cycling TTF test No improvement between conditions</td>
</tr>
<tr>
<td>Baldari et al. (2018)</td>
<td>13 (M)</td>
<td>Recreational endurance runners</td>
<td>A – M1 C – Occipital protuberance</td>
<td>2.0 0.057 20</td>
<td>Incremental ramp exercise test No improvement</td>
</tr>
<tr>
<td>Barwood et al. (2016)</td>
<td>8 (M)</td>
<td>≥150-minutes of exercise per week</td>
<td>A - T3 C - Fp2</td>
<td>2.0 0.440 20 75% peak power No improvement</td>
<td></td>
</tr>
<tr>
<td>Bryne et al. (2019)</td>
<td>23 (11M/12F)</td>
<td>Moderately active</td>
<td>A – F3 C – Fp2</td>
<td>2.0 0.057 20</td>
<td>25% MIVC Isometric contraction of leg extensors No improvement</td>
</tr>
<tr>
<td>Ciccone et al. (2019)</td>
<td>20 (10M/10F)</td>
<td>Recreationally active (2-4 times a week)</td>
<td>A – T3 C – Fp2</td>
<td>2.0 N/A 20</td>
<td>Maximal knee extensors No improvement</td>
</tr>
<tr>
<td>Codella et al. (2020)</td>
<td>17 (M)</td>
<td>Physically active</td>
<td>A – M1 C – right DLPC (C1 to C6)</td>
<td>2.0 0.080 20</td>
<td>Maximal graded exercise running test Improvement- 12% increase in endurance running capacity</td>
</tr>
<tr>
<td>Cogiamanian et al. (2007)</td>
<td>24 (10M/14F)</td>
<td>Physically active</td>
<td>A – right M1 C – Right shoulder</td>
<td>1.5 0.043 10</td>
<td>35% MVC fatiguing isometric contraction Improvement – A-tDCS improves muscle endurance</td>
</tr>
<tr>
<td>Flood et al. (2017)</td>
<td>12 (M)</td>
<td>Physically active</td>
<td>C3/C4 and 5cm around (HD-tDCS)</td>
<td>2.0 0.057 20</td>
<td>TTF task at 30% MIVC elbow flexors No improvement</td>
</tr>
<tr>
<td>Study</td>
<td>Sample Size</td>
<td>Participant Characteristics</td>
<td>Measurement Details</td>
<td>Repetition</td>
<td>Duration</td>
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<td>-----------------------------</td>
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<tr>
<td>Frazer et al. (2016)</td>
<td>14</td>
<td>Physically healthy</td>
<td>A – Left M1 C – right contralateral supra orbital area</td>
<td>2</td>
<td>0.080</td>
</tr>
<tr>
<td>Frazer et al. (2017)</td>
<td>13</td>
<td>Physically healthy</td>
<td>A – right M1 C – contralateral supra orbital area</td>
<td>2</td>
<td>0.080</td>
</tr>
<tr>
<td>Harris et al. (2019)</td>
<td>73</td>
<td>Novice (no golf experience)</td>
<td>Left supraorbital area (10:20 EEG system)</td>
<td>1.5</td>
<td>N/S</td>
</tr>
<tr>
<td>Hazime et al. (2017)</td>
<td>8 (F)</td>
<td>Regional and national</td>
<td>A – C5/C4 C– ipsilateral supraorbital region</td>
<td>2</td>
<td>0.057</td>
</tr>
<tr>
<td>Hendy et al. (2014)</td>
<td>10</td>
<td>Physically active</td>
<td>A – right M1 C – Fp1</td>
<td>2.0</td>
<td>0.080</td>
</tr>
<tr>
<td>Holgado et al. (2019)</td>
<td>36 (M)</td>
<td>Trained cyclists</td>
<td>A – DLPFC C – contralateral shoulder</td>
<td>2.0</td>
<td>N/S</td>
</tr>
<tr>
<td>Huang et al. (2019)</td>
<td>9 (M)</td>
<td>Moderately active</td>
<td>Halo sport (vertex of head)</td>
<td>2.0</td>
<td>0.083</td>
</tr>
<tr>
<td>Kamali et al. (2019)</td>
<td>17</td>
<td>Experienced shooters</td>
<td>A – CB2 C – Left DLPFC</td>
<td>2.0</td>
<td>0.057</td>
</tr>
<tr>
<td>Kamali et al. (2019a)</td>
<td>12</td>
<td>Experienced bodybuilders</td>
<td>A – M1 C – contralateral shoulder</td>
<td>2.0</td>
<td>0.057</td>
</tr>
<tr>
<td>Kan et al. (2013)</td>
<td>15</td>
<td>Physically active</td>
<td>A – M1 C – contralateral shoulder</td>
<td>2.0</td>
<td>0.083</td>
</tr>
<tr>
<td>Kenville et al. (2020)</td>
<td>25</td>
<td>Physically active</td>
<td>A – M1 Cathode – Cerebellum</td>
<td>2.0</td>
<td>0.020</td>
</tr>
<tr>
<td>Lampropoulou et al. (2013)</td>
<td>12</td>
<td>Physically active</td>
<td>A/C – left M1 A/C – Left medial deltoid</td>
<td>1.5</td>
<td>0.061</td>
</tr>
<tr>
<td>Lattari et al. (2017)</td>
<td>11 (F)</td>
<td>Physically active</td>
<td>A – left DLPCA C – right OFC</td>
<td>2.0</td>
<td>0.057</td>
</tr>
<tr>
<td>Lattari et al. (2018)</td>
<td>11 (F)</td>
<td>Physically active</td>
<td>A – left DLPCA C – right OFC</td>
<td>2.0</td>
<td>0.057</td>
</tr>
<tr>
<td>Mizuguchi et al. (2018)</td>
<td>24 (M)</td>
<td>Novice</td>
<td>A – right cerebellum C – right buccinator muscle</td>
<td>2.0</td>
<td>0.080</td>
</tr>
<tr>
<td>Montenegro et al. (2016)</td>
<td>14 (M)</td>
<td>Strength training experience &gt;6 months</td>
<td>A – left M1 C – Fp2</td>
<td>2.0</td>
<td>0.057</td>
</tr>
<tr>
<td>Study Authors</td>
<td>Participant Characteristics</td>
<td>Electrode Sites</td>
<td>Time to Task Elbow Flexions/Maximal Incremental Torques</td>
<td>Performance Improvement</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>----------------------------------</td>
<td>--------------------------------------------------------</td>
<td>-------------------------</td>
<td></td>
</tr>
<tr>
<td>Muthalib et al. (2013)</td>
<td>Physically active</td>
<td>A – right M1 C – right shoulder</td>
<td>30% of MVIC elbow flexors</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>Okano et al. (2015)</td>
<td>Experienced cyclists</td>
<td>A – T3 C – Fp2</td>
<td>Maximal incremental cycling test</td>
<td>Improvement – RPE were lower</td>
<td></td>
</tr>
<tr>
<td>Oki et al. (2016)</td>
<td>No participation in resistance exercise training in the prior 3 months</td>
<td>A – M1 C – left supraorbital region</td>
<td>Time to task elbow flexions</td>
<td>Improvement -</td>
<td></td>
</tr>
<tr>
<td>Park et al. (2019)</td>
<td>Trained endurance runners</td>
<td>A – CZ C – C5/C6</td>
<td>TTF constant load test at 80% of V0; max</td>
<td>No improvement (although increased TTF)</td>
<td></td>
</tr>
<tr>
<td>Parma et al. (2020)</td>
<td>Novice</td>
<td>A – left M1 C – right M1</td>
<td>Golf putting task</td>
<td>No improvement (although influence depending on individual task performance observed)</td>
<td></td>
</tr>
<tr>
<td>Radel et al. (2017)</td>
<td>Physically active</td>
<td>A – AF4/C2 C – 40mm around A</td>
<td>TTF at 30% MVC elbow flexor muscles</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>Rocha et al. (2020)</td>
<td>Skilled vs unskilled</td>
<td>A – right DLPFC C – left supraorbital</td>
<td>Pistol shooting task</td>
<td>Improvement – improved shot accuracy</td>
<td></td>
</tr>
<tr>
<td>Sales et al. (2016)</td>
<td>Trained</td>
<td>A – T3 C – Fp2</td>
<td>MVIC leg extension</td>
<td>Improvement – increased total work</td>
<td></td>
</tr>
<tr>
<td>Vargas et al. (2018)</td>
<td>Regional and national competitors</td>
<td>A – C3/C4 C – ipsilateral supraorbital</td>
<td>MVC of knee extensors</td>
<td>Improvement – increased MVIC</td>
<td></td>
</tr>
<tr>
<td>Vitor-costa et al. (2015)</td>
<td>Physically active</td>
<td>A – Cz C – occipital protuberance</td>
<td>TTF cycling task at 80% peak power</td>
<td>Improvement – increased endurance time</td>
<td></td>
</tr>
<tr>
<td>Washabaug et al. (2016)</td>
<td>Physically active</td>
<td>A/C – M1</td>
<td>MVIC knee extensor</td>
<td>Improvement – increased knee extension torques</td>
<td></td>
</tr>
<tr>
<td>Williams et al. (2013)</td>
<td>Physically active</td>
<td>A – M1 C – Fp2</td>
<td>TTF elbow flexors 20% of maximum strength</td>
<td>Improvement – TTF extended</td>
<td></td>
</tr>
<tr>
<td>Wrightson et al. (2020)</td>
<td>Physically active</td>
<td>A – right VL C – left deltoid</td>
<td>TTF 20% MVIC knee extensor</td>
<td>No improvement</td>
<td></td>
</tr>
<tr>
<td>Zhu et al. (2014)</td>
<td>Novice</td>
<td>A – Fp2 C – F3</td>
<td>Golf putting task</td>
<td>Improvement – enhanced putting performance in training and test phase (multi-tasking)</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1:** Studies exploring the effects of tDCS on sport performance. Participant characteristics, tDCS protocol and performance outcome of included studies. Note: F/M = Female/Male, N/A = Not addressed, M1 = motor cortex, MVC = maximal voluntary contraction, F3 = Frontal region 3, Fp2 = frontal-parietal region 2, C3/C4 = Central region 3/4, T3 = Temporal region 3, CZ = somato-sensory cortex, C5/6 = Central region 5/6, AF4 = frontal region
Figure 2. Risk of bias graph showing a review of the authors’ judgments across each risk criterion presented as percentages for all included studies.

3.3 Quantitative Analysis

3.3.1 Overall Effect. Across all studies examined, the meta-analysis indicated that participants showed a small improvement in performance after application of tDCS (SMD=0.25, CI95% [0.13,0.36], p<.001). This difference does not appear to be due to differences in study heterogeneity (I²=0%, τ²=0, p=.57), and reasonably good levels of symmetry can be seen in the funnel plot (Figure 3).

Figure 3. Funnel plot of studies included in the meta-analysis showing effect estimates (SMD) from individual studies against standard error. The effect sizes and precisions...
are fairly well spread within the funnel but might indicate some studies with negative effects are missing.

**Meta-regressions:** For time to fatigue outcomes, meta-regression analysis showed no significant effect of stimulation intensity ($\beta = 0.04$, SE $= 0.28$, $p = 0.87$, $R^2 = .00$), density ($\beta = 311 - 2.54$, SE $= 6.74$, $p = 0.71$, $R^2 = .00$), or duration ($\beta = 0.00$, SE $= 0.02$, $p = 0.90$, $R^2 = .00$) on reported effect size. For strength related outcomes meta-regressions showed no significant effect of stimulation intensity ($\beta = -0.29$, SE $= 0.37$, $p = 0.44$, $R^2 = .00$), density ($\beta = 7.26$, SE $= 6.08$, $p = 0.23$, $R^2 = .07$), or duration ($\beta = 0.03$, SE $= 0.03$, $p = 0.34$, $R^2 = .00$). Similarly, for visuomotor outcomes, meta-regressions again showed no significant effect of stimulation intensity ($\beta = -0.16$, SE $= 0.29$, $p = 0.59$, $R^2 = .00$), density ($\beta = -16.86$, SE $= 16.05$, $p = 0.29$, $R^2 = .00$), or duration ($\beta = -0.02$, SE $= 0.04$, $p = 0.67$, $R^2 = .00$) on effect size. Full details of meta-regression models are available in the supplementary materials, including diagnostic plots and measures of heterogeneity *(https://osf.io/vuqre/)* and bubble (scatter) plots are presented in figure 4.
Figure 4. Bubble plots showing the relationship between stimulation density on the x-axis and SMD on the y-axis for each study in each of the three domains. The size of the plotting symbol is inversely proportional to the variance of the reported treatment effect.

3.3.2 Time to fatigue Subgroup Analysis. The literature search originally identified 17 out of 41 studies that examined the effect of tDCS stimulation on time to task failure protocols, including 255 participants. Cogiamaniam et al. (2007) was excluded in the meta-analysis as it was a significant outlier (extreme Cook’s distance) presenting a large positive effect size which biased the overall effect (see: https://osf.io/e2naq/). It was visually identified as a clear outlier, which was confirmed using the GOSH analysis (see Figure 5). The statistical analysis revealed a small effect in favour of tDCS compared to control/sham, but the effect only
approached significance (SMD=0.18, CI\(95\%\) [0.00; 0.37], \(p=.056\)). The studies showed low heterogeneity (\(I^2=0\%\), \(\tau^2=0\), \(p=.96\)).

3.3.3 Strength Exercise Subgroup Analysis. The literature search identified 20 studies examining strength exercises, assessing 299 participants. The statistical analysis showed a small but significant overall effect (SMD=0.31, CI\(95\%\) [0.10; 0.51], \(p=.003\)) in favour of the stimulation group. The studies showed low heterogeneity (\(I^2=34\%\), \(\tau^2=0.0731\), \(p=0.07\)).

3.3.4 Visuomotor Skills Subgroup Analysis. The literature search initially identified six studies that examined the influence of tDCS on visuomotor skills. The study of Rocha et al. (2020) was removed from the final meta-analysis as it provided an extreme positive value (see: https://osf.io/e2naq/). Consequently five studies were suitable for the meta-analysis, a total of 97 participants. The quantitative analysis illustrates a small effect in favour of the tDCS group, which was marginally significant (SMD= 0.29, CI\(95\%\) [0.00; 0.57], \(p=.045\)). The studies showed low heterogeneity (\(I^2=0\%\), \(\tau^2=0\), \(p=.84\)).
### Figure 5. Forest plot of effect sizes (SMD) from all 41 studies included in the meta-analysis.

Effects > 0 indicate results favouring the stimulation group over the control group. The combined estimate and 95% confidence interval (blue diamond) indicates a small but reliable overall effect of tDCS stimulation over sham control. Time to fatigue (SMD=0.18), strength (SMD=0.31), and visuomotor (SMD=0.29) subgroups all showed effects with 95% CIs that did not cross zero. Light blue squares indicate the weight of the study in the combined analysis (based on sample size).
Figure 6. Graphical Display of Study Heterogeneity (GOSH) plots presenting a scatter plot of effect size estimates against heterogeneity for all possible study combinations in each subgroup. Left: Time to fatigue studies (all). Right: Strength studies showing study combinations both with (red) and without (blue) the study of Cogiammaniam et al. (2007) which was excluded from the meta-analysis as an outlier. The plot clearly shows that the inclusion of this study would introduce additional heterogeneity as well as shift the overall point estimate. Note: the visuomotor subgroup only included five studies which was not sufficient to perform combinatorial meta-analysis.

4. Discussion

The purpose of this meta-analysis was to explore the ergogenic effects of tDCS on sporting performance and provide a comprehensive overview of the strength of current evidence. Specifically, we examined the impact of stimulation on endurance, strength, and visuomotor domains to examine the potential use of tDCS in the context of sporting performance enhancement. The results supported an overall positive effect of stimulation (SMD=0.25), which was relatively consistent across domains (time to fatigue: SMD=0.18; strength: SMD=0.31; visuomotor: SMD=0.29), although time to fatigue (p=.056) and visuomotor effects (p=.045) were both close to the significance threshold. These findings suggest there may be some potential for utilizing tDCS for performance enhancement in
competition or training, although the ethics of such implementation is a debated area (Petersen, 2021).

4.1 Strength Exercise

The meta-analysis indicated that tDCS effects were largest and most reliable in the strength domain. Results from the reviewed studies showed that a-tDCS resulted in improved maximal isometric voluntary contraction (MIVC). One explanation for this observed effect is due to motor unit synchronisation. Previous research has suggested that a-tDCS has the ability to modify motor unit synchronisation (Schade et al., 2012; Krishnan et al., 2014). This a-tDCS mediated effect was reported by Hazime et al. (2014) who observed elevation of isometric strength. Alternatively, Fling et al. (2009) showed that motor unit synchronisation occurs at higher MIVC levels which may explain a lack of effect in the studies reporting no improvement (Farina and Negro, 2015). The effects of a-tDCS on strength are still unclear as the underpinnings of the neurophysiological mechanisms around a-tDCS stimulation are still novel. These results suggest tDCS has potential as a complimentary aid to be used alongside a training regime.

4.2 Endurance exercise

The subgroup analysis demonstrated that tDCS increased exercise endurance in TTE exercise protocols compared to sham and/or control conditions, but the effect was weaker than for strength exercise. These results aligned with the findings of Barwood et al. (2016) and Latteri et al. (2018) who suggested the use of anodal stimulation improved time to exhaustion results in a self-paced cycling test. The primary cortex (M1) is considered the principal determinant for endurance tasks as it drives the motor units. Cogiamanian et al. (2007) proposed that increased physical endurance is due to the increased cortical excitability of these regions as a result of tDCS stimulation. Abdelmoula et al. (2016) found time to task failure in the C2 (second submaximal contraction) was also extended post a-tDCS.

Interestingly, a significant difference has been found in blood-lactate levels of tDCS participants (Angius et al., 2017), as well as an improvement in cardiac efficiency, which can be attributed to parasympathetic modulation (Okano et al., 2015). Heart rate (HR) is controlled by the PFC which is especially active during a sustained contraction task. The PFC could modulate sympathetic tone, thereby reducing an athlete’s HR, which may, in part, explain the increased endurance. These findings
also explain improved performance in some of the strength studies; for example, Sales et al. (2016) reported the tDCS group had significantly reduced HR compared to the sham-tDCS group. This crossover may account for some variability between studies, but may also prove beneficial in multifaceted sports and exercise tasks that require high endurance and increased MIVC.

4.3 Visuomotor Skills

The directional effect observed in visuomotor protocols indicates a potential for neuromodulation in a visuomotor context, however the results were only weakly significant and limited to 5 studies. This finding is nonetheless promising, and indicates that further studies in this area are warranted. One of the positive effects was observed in a study by Kamali et al. (2019) who simultaneously stimulated the left DLFPC and right cerebellum, finding that the tDCS group had an improved accuracy score in a shooting task. The cerebellum is a key brain area for motor learning, especially in sensory prediction errors (DeZeeuw and Ten Brinke, 2015), which suggests a potential target for future lab-based work exploring visuomotor skills.

Both Zhu et al. (2015) and Harris et al. (2019) explored electrical montages over the left DLFPC in the context of golf-putting procedures. Zhu et al. (2015) aimed to promote implicit learning by inhibiting verbal working-memory via cathodal stimulation, which resulted in reduced conscious movement control and improved performance. Contrastingly, Harris et al. (2019) found no true-effect of anodal tDCS of the DLPFC. Consequently there are a range of potential routes for enhancing visuomotor effects through enhancing frontal function, inhibiting conscious processing, and stimulating motor control centers, but more evidence is needed to determine which of these approaches are likely to be successful.

4.4 Moderators of stimulation effects

There was considerable variability with regards to the montage targets between the studies, although the primary motor cortex was the most common. Localisation of the electrode montages for the elected tDCS procedures is a parameter which can greatly influence cortical excitability induced by tDCS (Vitor-Costa et al, 2015). However, we found no evidence that the duration of tDCS, or the intensity or density of the delivered current were related to the subsequent performance effects. Unfortunately, this means that questions about optimal stimulation parameters
514  Heterogeneity of participants in the form of genetic and environmental diversity also
515  requires consideration. The role of genetics and brain stimulation has been extensively
516  explored in animals but not in humans. There has been evidence that
517  Val(108/158)Met polymorphism in the COMT gene influences c-tDCS induced
518  brain modulation, highlighting an issue with ergogenic aids in which genetic factors
519  influence cognitive performance (Nieratschker et al, 2015). Moreover, the role of
520  BDNF polymorphism in modulating M1 plasticity was explored by Frazer et al.
521  (2016) who found Val/Val participants showed greater increase in MEP induction
522  compared to Val/Met genotype group. For progress to be made in brain-stimulation
523  studies these genetic effects need to be studied further. The challenge of examining
524  the studies and variable results also highlights the need for researchers to map out a
525  clear justification for the selected parameters; stimulation intensity and duration,
526  stimulation montage and participant characteristics such as gender and genetics.
527  The neurophysiological mechanisms of brain stimulation also need to be better
528  understood to reduce the variation caused by the existing methodology (see - Datta,
529  et al., 2018 and Davis, 2020).

4.5 Limitations

510  The present review is, inevitably, subject to limitations of the search strategy, the
511  papers that were defined to be within the current scope, and the limitations of those
512  papers themselves. For instance, randomisation was adequate for the included trials,
513  but 12 of the included studies were unable to explicitly state that analysis of data
514  was not influenced by participant or researcher bias. Further, in general small
515  sample sizes in data analysis are subject to less methodological rigour, so the
516  quality of the studies would improve if larger sample sizes could be obtained for
517  future studies. Differences in methodological approaches (e.g., target areas/type
518  of tDCS) may also have influenced data. In this meta-analysis only two studies
519  explored HD-tDCS electrical montages (Flood et al. 2017, Radel et al. 2017), and
520  non-focal tDCS has the ability to influence unintended cortical areas making it
521  difficult to apply focal stimulation.
4.6 Conclusions

The present systematic review and meta-analysis investigated the potential for tDCS to improve sporting performance with regard to physical endurance (time to fatigue), physical strength, or visuomotor skill. Pooled effect sizes supported the overall efficacy of tDCS, with more reliable findings for strength based studies, and promising but less certain effects for endurance and visuomotor studies. The varying stimulation montages and differential effects of individual differences and initial brain state all make it difficult to provide clear recommendations regarding the use of tDCS for sporting performance enhancement. For prospective studies a clear comparison of different electrical montages should be established with improved localisation of brain areas targeting the desired outcome. The unpredictable nature of tDCS makes it sensitive to a multitude of variables that need to be better controlled by individualising tDCS protocols, such as computational modelling with anatomical targeting using MRI or PET. Newer techniques for brain stimulation such as HD-tDCS should be explored as a potential alternative as it allows a focal stimulation that prevents stimulating unintended areas.
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Figure 1. PRISMA study flow diagram illustrating the identification and selection of relevant studies.
**Figure 2.** Risk of bias graph showing a review of the authors’ judgments across each risk criterion presented as percentages for all included studies.

**Figure 3.** Funnel plot of studies included in the meta-analysis showing effect estimates (SMD) from individual studies against standard error. The effect sizes and precisions are fairly well spread within the funnel but might indicate some studies with negative effects are missing.
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