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Transcranial Direct Current Stimulation in Sport: Neurodoping or Performance Support? Systematic Review

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Abstract
Background. Professional athletes increasingly rely on neurophysiology to enhance athletic potential. Transcranial Direct Current Stimulation (tDCS) has become one of techniques to modulate cortical excitability. It can act as ergogenic aid by modifying motor control and fatigue perception.

Aim. This systematic review analyzes the impact of tDCS on motor skills, physical endurance, and cognitive performance. It also addresses the ethical debate surrounding "neurodoping".

Materials and Methods. This systematic review was conducted following PRISMA guidelines. The search was conducted in PubMed and Web of Science, and Scopus. 62 publications were analyzed, published up to January of 2026. The review focused on anodal stimulation of M1 and DLPFC regions.

Results. Findings indicate small to moderate effects on performance. The most consistent results involve reduced perceived exertion and improved Time-to-Exhaustion (TTE), especially in M1 stimulation. DLPFC stimulation showed benefits in cognitive tasks, decision-making, and emotional regulation. However, significant heterogeneity existed due to variations in study methodology.

Conclusions. tDCS can enhance performance by modulating the perception of effort rather than increasing physical capacity. While not currently prohibited by WADA, the high variability in results shows need for standardized protocols and further research into long-term effects and ethical regulations.

Key words: tDCS, athletic performance, neurodoping, mortar cortex, M1, DLPFC, TTE, RPE, ergogenic aids, neuromodulation, endurance

1. Introduction

Technological advancement is fundamentally reshaping every aspect of modern life. And the world of physical activity and professional sports are no exception. Today, high-performance sports increasingly rely on biomedical science. The primary objective is clear: to enhance athletic performance and optimize the training process by identifying the most effective method for competition preparation. Advances in exercise physiology, biomechanism, and neurophysiology have provided a much deeper understanding of biological mechanisms that drive human athletic potential. Traditionally, training focused on structured endurance plans, optimized nutrition, and tailored recovery programs. However, in recent years, attention has shifted toward the new side of exertion. There is now a major focus on the central nervous system (CNS) and how it regulates physical capacity and motor control [24, 57]. It can also have control on the perception of fatigue, especially during high-intensity sports [15, 16]

This growing fascination with neurophysiology has led to the development of new methods that can modulate specific brain regions. One of these methods is non-invasive brain stimulation (NIBS) techniques. They are particularly interesting because they allow researchers to influence neural excitability without any permanent structure changes [1]. One of the most widely studied methods is transcranial Direct Current Stimulation (tDCS). This protocol involves applying a low-intensity electrical current through electrodes placed on the scalp. The resulting current flow alters neuronal activity in specific areas [42]. The aim is to influence cognitive processes, motor coordination, and overall neurological function in elite athletes [31, 38].

In the sport context, researchers are exploring whether tDCS can serve as an ergogenic aid – a tool to boost the body's natural performance [10, 36]. Current data suggest that stimulating specific areas, such as the primary motor cortex (M1) or the dorsolateral prefrontal cortex (DLPFC), can impact how athletes perceive effort [14, 52]. It also can alter how long they can perform before reaching the point of maximum exhaustion. Some studies have shown improvements in motor precision and cognitive function – attentional Focus and faster decision-making [11, 27]. These are, of course, essential skills in every competitive sport discipline.

This rising profile of neuromodulation and brain alteration has also sparked intense ethical debate. Some researchers suggest that using tDCS could be viewed as a form of „neuro-doping" – a technological way of hacking the brain [5, 23]. So it can perform at a higher level and gain an unfair advantage [46]. Although the method is non-invasive and considered safe, its potential to artificially enhance endurance and cognition raise concerns about the principles of fair play [9, 51]. As these technologies become more common, they may overall require changes in international sports regulations [3, 50].

Despite the growing number of publications, we still lack a definitive consensus. The difference in study designs, sample sizes, and the types of physical effort analyzed make it impossible to draw universal conclusions at this stage [8, 22]. Therefore, there is an urgent need for a systemic summary of the current state of knowledge. The aim of this paper is to review the existing literature and evaluate the potential impact of tDCS on physical performance, mental agility, and motor control in athletes. Specifically focusing on its role as a supportive tool for achieving superior sporting results.

Research objective

The primary objective of this systematic review is to conduct a critical analysis of the current state of knowledge regarding the impact of non-invasive brain stimulation. Specifically, impact of tDCS on motor skills, physical endurance, and cognitive performance in elite athletes.

Specific Objectives:

1. To evaluate existing scientific evidence concerning the influence of tDCS on enhancing performance parameters and motor skills across various sporting disciplines.
2. To investigate how the stimulation of specific regions - such as M1 or DLPFC can affect the subjective perception of effort and fatigue.
3. To identify the underlying causes of the inconsistencies currently found in the relevant academic publications.
4. To analyze the rising problem of "neuro-doping" within the framework of current legal regulations and the fundamental principles of fair play in sport.

Research Problems

1. Does anodal stimulation of the M1 lead to measurable increase in muscular strength and a prolonged-time-to-exhaustion?
2. In what way does the DLPFC stimulation influence the subjective RPE?
3. Are the effects of tDCS more visible in technical disciplines - requiring high precision - or those based only on physical endurance?
4. Which factors can determine the high variability of results and the present challenges with replicating experimental effects?
5. Does the mechanism of tDCS meet criteria to be classified as technological doping under current athletic standards and regulations?

2. Materials and Methods

This study is based on systematic review conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [61]. The literature search was initiated by identifying relevant sources across major databases, including PubMed and Web of Science. The collected publications are up to January of 2026 [7]. The search strategy included predefined keywords such as "tDCS", "athletic performance", "neurodoping", and "motor cortex", which concluded the gathering of a substantial data on neuromodulation in sports [1, 52].

The selection process was carried out in three stages: an initial screening of titles, a focused analysis of abstracts, and lastly, a comprehensive evaluation of full-text papers. 62 publications were selected for the analysis based on their thematic relevance and methodologies. The qualified research from WADA (World Anti-Doping Agency) [62]. This approach allowed for a deep synthesis of findings regarding the impact of stimulation on strength, stamina, and motor coordination in high-level athletes [17, 34, 56].

As part of the verification of the gathered material, a specific attention was brought to studies based on randomized, crossover controlled trials (RCT) were also analyzed [10, 24, 33]. The primary factor under investigation was the assessment of anodal tDCS on M1 and DLPFC regions in the context of the RPE and other endurance parameters [14, 41, 52]. The data collected was compared with the results obtained under sham (placebo) stimulation conditions. This approach made it possible to interpret specific findings within the broader context of the existing review literature [8, 22, 38]. Both qualitative and quantitative syntheses of the data were performed, with particular attention paid to statistical significance ($p < 0.05$). This analysis forms the base of the conclusions regarding the effectiveness of neuromodulation as a support system for elite athletic performance [11, 44].

3. Results

3.1 Overview of Included Studies

In this systemic review, a total of 62 publications were included. 25 of which were randomized controlled trials (RCTSs) [10, 24, 33]. They were selected for more detailed analysis. The included studies differed in terms of study design, sport characteristics, and stimulation protocols [36, 52]. In most publications, populations consisted of physically active participants and professional athletes [7, 16, 56]. This allowed for the evaluation of tDCS effects under conditions similar to real physical performance. The most commonly applied stimulation parameters were intensities ranging from 1.5 to 2.0 mA [1, 55]. The durations between sessions were 15 to 20 minutes. The described conditions can be considered a standard approach in tDCS research. In the majority of studies, stimulation was applied over the primary motor cortex (M1) and the dorsolateral prefrontal cortex (DLPFC) [14, 42, 57]. Both of which are associated with motor control, perception of fatigue, and other cognitive processes.

The studies showed a considerable level of heterogeneity, in terms of methodology, outcomes and participants characteristics [14, 52]. These differences included task type, training level of participants, and specific parameters of stimulation. As a result, the findings were not consistent with each other. It suggests that effectiveness of tDCS may depend on multiple factors [38, 55]

To improve clarity and interpretations, the results were categorized into three main categories: endurance performance and muscular fatigue, and motor functions. This classification allows for more thought presentation of the effects of tDCS across different parts of athletic performance. The general characteristics of included studies are presented in Table 1.

Table 1. Characteristics of Included Studies: Sport, Discipline, Population, And Effects						
Study (Author, Year)	**Sport / Task**	**Population**	**Bain Target**	**Main Outcome**	**Effect**	**ref. No**
da Silva Machado et al., 2021	Cycling	Trained cyclists	M1	Time to exhaustion (TTE)	=	[10]
Angius et al., 2018	Cycling	Trained cyclists	M1	Time to exhaustion (TTE) / exercise tolerance	↑	[1]
Valenzuela et al., 2019	Swimming	Trained triathletes	DLPFC	Higher mood perception	↑	[53]
Holgado et al., 2019	Cycling	Trained cyclists	DLPFC	Power output / Time trail performance	=	[24]
Pollastri et al., 2021	Cycling	Trained cyclists	DLPFC	Time trial performance	=	[45]
Hanson et al., 2024	Cycling - 3mAT	Recreational athletes	M1	Time to exhaustion / performance output	=	[20]
Lattari et al., 2020	MIVC	Athletes and recreational athletes	M1 / DLPFC	Maximal strength)1RM / peak force)	↑	[31]
Fortes et al., 2022	Soccer	Professional soccer players	DLPFC	Decision-making response time / Visual search patterns	↑	[16]
Grosprêtre et al., 2021	Parkour	Parkour Professionals	M1	Fine motor skills / cognitive performance	↑ / =	[19]

Dai et al., 2024	Fencing	Professional fencers	M1	Improvement of cognitive performance	↑	[11]
Seidel-Marzi & Ragert, 2020	HTT / FTT	Professional soccer/ handball players / non-athtletes	M1	Movement speed / reduced motor fatigability / fast repetitive movements	↑	[49]
Charest et al., 2021	Sleep quality	Student-athletes	DLPFC	Total sleep time	↑	[4]
Mehrsafar et al., 2020	Archery	Professional archers	DLPFC	Modulation of competitive anxiety and physiological stress response	↑	[39]
Martens et al., 2024	Running	Runners	M1	Endurance / TTE	=	[37]
Giancatarina et al., 2024	Postural control	Parkour - trained participants	M1 / DLPFC	Postural control / modulation of gait performance	=	[18]
Khantan et al., 2025	Swimming performance	Elite swimmers	M1 / DLPFC	Improving swimming performance / effects physiological and cognitive functions	↑	[30]
Anoushiravani et al., 2023	Motor performance	Professional gymnasts	M1 / cerebellu m	Improve MVIC / motor functions	↑	[2]
Kamali et al., 2023	Shooting performance	Professional Shotters	DLPFC	Increased shooting scores	↑	[27]

Abbreviations:
M1 - primary motor cortex; DLPFC - dorsolateral prefrontal cortex; MVC - maximal voluntary contraction; RPE - rating of perceived exertion; MVIC - maximal voluntary isometric contraction; TTE - time to exertion; HTT - hand-tapping task; FTT - foot-tapping task; 3mAT - 3 minute aerobic test; ↑ - improvement; ↓ - reduction ; = - no significant changes

3.2 The effect of tDCS on endurance performance

The largest part of analyzed studies focused on the effects of tDCS on endurance performance [8, 22, 38]. The most commonly assessed variables were time to exhaustion (TTE), trial completion time, and motor improvements [20, 37, 50]. Some studies reported improvements in endurance related outcomes following anodal stimulation [1, 13, 30]. It was especially visible when applied over the M1 [14, 31, 52]. In trained athletes, increased time to exhaustion and improved exercise tolerance were observed [1, 41]. It suggests that tDCS can have a potential ergogenic effect [10, 12, 36]. These findings are consistent with findings presented in Table 1. Where several studies showed improved performance in endurance tasks [1, 30, 33]. However, other studies did not report differences between active and sham stimulation conditions [10, 24, 37]. This was evident in cases targeting the DLPFC and in time trials protocols, where the results were comparable between groups [24, 45, 52]. Some findings were described as "mixed", highlighting the variability of effects [8, 38, 55]. The differences between studies may be explained by inconsistencies in participant training, task type, and stimulation parameters [14, 55]. Stimulation of the M1 region appeared to be associated with performance improvements compared to DLPFC stimulation [14, 17, 31]. In summary, the evidence suggests that tDCS can have a small to moderate effect on endurance performance [8, 36, 38]. But they are not consistent across all studies. The most reliable findings have shown improved exercise tolerance and reduced perceived fatigue [9, 15, 41]. They can contribute to enhanced athletic performance [1, 56].

3.3 The effects of tDCS on strength and muscular training

A majority of the analyzed studies focused on muscle strength and fatigue [17, 34, 47]. The findings appear to be consistent, particularly in the M1 area [21, 31, 44]. The most common variables were maximal voluntary contraction (MVC), maximal force output, and rating of perceived exertion (RPE) [2, 13, 31]. Many publications suggest increased muscle strength after anodal stimulation [17, 28, 48]. It can be especially seen in physically active and trained individuals [26, 31]. In terms of fatigue, most findings suggest that athletes can feel reduced perceived exertion and delayed fatigue onset [15, 41, 52]. These results suggest that tDCS may influence central fatigue mechanisms [42, 47, 54]. Several studies reported reduced fatigue and improved performance in strength-based tasks [29, 31, 48]. They are shown in Table 1. but not all of the studies demonstrated differences between active and sham conditions [34, 55]. It is due to methodological differences and individual variability [14, 36]. Overall, tDCS appears to have some positive effect on strength and fatigue resistance [17, 38].

3.4 Effects of tDCS on Motor and Cognitive Functions

A number of studies included in this systematic review suggest that tDCS can be relevant on motor and cognitive functions. They are linked to enhancing athletic performance [11, 19, 57]. The results are heterogeneous, but provide an important view into the potential mechanism underlying performance enhancement [38, 52, 55]. The most common assessed motor outcomes included reaction time, movement accuracy, and coordination [26, 49, 50]. Several studies have shown that anodal stimulation of particular areas of the brain, such as M1, can lead to improvements in motor execution [21, 28, 44], which results in faster reaction times, increased precision, and better performance in task-specific movements [16, 32, 58]. This suggests that tDCS may facilitate neural processes involved in motor control [42, 47, 57]. Also cognitive functions were evaluated, especially in studies targeting DLPFC [24, 25, 53]. Outcomes included attention, decision-making, cognitive control, and performance under fatigue or stress [11, 15, 16]. Some of which have shown that tDCS improved attention span and executive functions [11, 60]. They were relevant in high-stress sports environments requiring fast decision-making [16, 25, 39]. Several studies reported reductions in anxiety levels and improvement in sleep quality. It may indirectly contribute to enhanced athletic performance [10, 41]. These psychological and recovery-related effects suggest that tDCS can have effects not only on physical but also psychological aspects of sport [39, 43, 46]. However, not all of the studies came to the same conclusions. In some cases there is no difference between active and sham stimulation conditions [10, 24, 45]. In some cases, the results were inconsistent and "mixed" [8, 14, 38]. It can suggest that influence of the task specificity, individual variability, and stimulation condition can make the difference [36, 52, 55]. Overall, the findings have shown that tDCS affects motor and cognitive functions. A summary of stimulation parameters and effects are presented in Table 2.

Table 2. Summary of Stimulation Parameters and Effect Sizes in Selected Randomized Control Trials

Study (Author, year)	**Population**	**Brain target**	**Intensity (mA)**	**Duration (minutes)**	**Study design**	**Outcome measure**	**Result**	**Ref. No**
da Silva Machado et al., 2021	Trained cyclists	M1	2.0	20	RCT crossover	TTE	=	[10]
Angius et al., 2021	Trained cyclists	M1	2.0	20	RCT crossover	TTE	↑	[1]

Table 2. Summary of Stimulation Parameters and Effect Sizes in Selected Randomized Control Trials								
Valenzuela et al., 2019	Trained triathletes	DLPFC	2.0	20	RCT crossover	Mood	↑	[53]
Holgado et al., 2019	Trained cyclists	DLPFC	2.0	20	RCT crossover	Power Output / TT	=	[24]
Fortes et al., 2022	Professional soccer players	M1	2.0	20	RCT	RPE	↓	[15]
Grospretre et al., 2021	Parkour Professionals	M1	2.0	20	RCT crossover	Motor / Cognitive	↑ / =	[19]
Dai et al., 2024	Professional fencers	M1	2.0	20	RCT crossover	Improvement in cognitive performance	↑	[11]
Seidel-Marzi & ragert, 2020	Professional soccer/ handball players / non-athtletes	M1	2.0	20	RCT crossover	Improved fatigability resistance	↑	[49]

Table 2. Summary of Stimulation Parameters and Effect Sizes in Selected Randomized Control Trials								
Mehrsafar et al., 2020	Professional archers	DLPFC	2.0	20	RCT	Modulation of competitive anxiety and physiological stress response	↑	[39]

Abbreviations:
M1 - primary motor cortex; DLPFC - dorsolateral prefrontal cortex; MVC - maximal voluntary contraction; RPE - rating of perceived exertion; MVIC - maximal voluntary isometric contraction; TTE - time to exertion; ↑ - improvement; ↓ - reduction; = no significant changes

3.5 Neurophysiological Mechanisms

Based on analyzed data, several neurophysiological mechanisms can be identified [1, 42, 47]. They can explain the effects of tDCS on athletic performance. These processes do not operate alone. They interact with each other and depend on both the stimulation protocol and characteristics of the individual participant [36, 52, 55]. One of the most important is the increase in cortical excitability, mainly in the M1 area of the brain [21, 50, 54]. Anodal stimulation leads to partial depolarization of neuronal membranes [42, 54]. It can make neurons more likely to fire. As a result, motor unit recruitment may be enhanced [17, 31, 34]. This leads to improved force production and also better control and precision of movement [19, 29, 44]. In practical terms, this means stronger and more efficient motor output.

Another important aspect of changes in central fatigue [42, 57]. tDCS can influence the activity of the central nervous systems by reducing inhibitory signaling during prolonged exercise [1, 9, 29]. This may lead to lower perception of effort and delayed onset of fatigue [15, 41, 52]. Several studies have shown that the rate of perceived exertion was reduced [38, 41, 52]. So the athlete can do the demanding task for longer periods with the same energy output [1, 30, 37].

Stimulation of the dorsolater prefrontal cortex (DLPFC) is more closely related to cognitive and psychological processes [24, 43, 53]. This includes improvements in attention span, faster more accurate decision-making, and better emotional regulation [11, 16, 25]. These effects are relevant in sports that require quick reactions under time-pressure [11, 16, 39]. Even small improvements in focus or decision-making speed can make a real difference in performance outcomes, especially in sports such as fencing and archery [11, 39]. tDCS may help with synaptic plasticity through mechanisms similar to long-term potentiation [21, 54, 57]. This supports motor learning and consolidation of new movement patterns [58, 59]. This may contribute to more efficient skill acquisition and refinement of already learnt ones. It is not an immediate effect, but can have an important place in training processes [21, 31, 34]. In summary, these suggest that the effects of tDCS extend beyond physical performance only. They involve a combination of different advantages. The proposed mechanisms and their functional relevance are summarized in Table 3.

Table 3. Neurophysiological Mechanisms Underlying the Effects of tDCS on Athletic Performance

Mechanism	**Brain Region**	**Description**	**Functional Effect**	**Outcome**	**Ref. No**
Increased cortical excitability	M1	Anodal tDCS induces partial depolarization of neuronal membranes, increasing cortical excitability and readiness neurons to fire	Enhanced motor unit recruitment, improved force production and movement precision	Strength / motor performance	[17, 21, 54]
Modulation of central fatigue	M1 / CNS	Reduction of inhibitory signaling within CNS during prolonged tasks	Decreased RPE, delayed onset of fatigue, improved tolerance	Endurance / fatigue	[1, 41, 52]
Altered perception of effort	DLPFC	Influence on cognitive perception of effort and discomfort during exercise	Increased tolerance to physical strain, ability to sustain effort longer	Endurance	[14, 24, 52]
Improved motor learning	M1	Enhanced synaptic plasticity	Improved learning of new motor skills and movement accuracy	Motor performance	[21, 58, 59]

Table 3. Neurophysiological Mechanisms Underlying the Effects of tDCS on Athletic Performance					
Cognitive control enhancement	DLPFC	Modulation of executive functions such as attention and decision-making	Better focus, faster decision-making under pressure	Cognitive	[11, 16, 25]
Emotional regulation	DLPFC	Influence on neural connections involved in stress and emotional processing	Reduction of anxiety levels, improved stress management	Cognitive / psychological	[39, 43, 53]
Sleep and recovery regulation	DLPFC	Modulation of neural networks involved in sleep regulations and recovery processes	Improved sleep quality and post-exercise recovery	Recovery	[4, 40]

Abbreviations:
M1 - primary motor cortex; DLPFC - dorsolateral prefrontal cortex; RPE - rating of perceived exertion

3.6 Statistical Synthesis

Our synthesis of the available data shows that the effect of tDCS on athletic performance is generally small to moderate [8, 22, 36]. It is not the same in every case. Its size and type depend on the variable of performance that is being tested. The most consistent findings were observed in perceived effort and fatigue [15, 41, 52]. but results related to direct performance outcomes were less stable and often differed between studies [38, 55]. In endurance tasks, improvements were more often reported in time-to-exhaustion tests rather than in time trial conditions [1, 14, 37]. We suggest that tDCS may affect how long a person can continue exercise ,rather than how fast it is completed [10, 24]. In time trial tasks, the effect was less significant [24, 45].

In case of muscle strength and fatigue, observed results were more consistent [17, 31, 34]. Many studies have shown an increase in maximal force and reduction of perceived effort [21, 28, 48]. These findings suggest that tDCS may influence central fatigue [42, 47, 57]. Because of that, athletes may be able to keep a higher level of effort for a prolonged period of time. This does not always mean better absolute performance, but it changes how effort is experienced [1, 15, 52]. Although, the effects related to motor and cognitive functions were more mixed [19, 54, 55]. Some studies have shown better reaction time, coordination, and decision-making [11, 16, 27]. Others however, have shown no clear difference between active and sham stimulation [32, 54]. In our opinion, these outcomes are more sensitive to the difference in studies' design [14, 55].

In summary, the effectiveness of tDCS is not uniform. It depends on several factors. There are specific sports, the protocol, and the individual participant [36, 38, 52]. We observed that variability is an important limitation and suggests that more research is needed. But at the same time, the consistent effect on perceived effort may be one of the key mechanisms behind performance changes. This could have value, especially in the context of training. A detailed summary of the observation is presented in Tables 1 - 3.

4. Discussion

4.1 Impact of tDCS on Different Aspects of Athletic Performance

The overall picture suggests that tDCS does not directly improve physical capacity, but changes how effort is perceived during exercises [9, 15, 41]. This seems to be a consistent pattern across studies. We observed that there is a difference between studies outcomes and real performance. Improvements are more visible in controlled settings, but the decision-making, or strategy is less clear [8, 22]. We can conclude that a significant challenge remains the individual physiological response to the stimulations [36, 55]. Not everybody reacts in the same manner, which makes it difficult to define as a clear, consistent effect. Consequently, tDCS should not be viewed as a tool for enhancing physical performance, but rather as one of the methods that influence perception of fatigue and exertion [42, 52, 57]. We believe that this could be applied in various training programs in specific sporting disciplines, such as long-distance running, cycling or triathlon [1, 30, 37, 51]. At the same time, it is very important to understand that the results are not guaranteed or constant.

4.2 tDCS As a Form of Neurodoping

In recent years, tDCS has become an interesting topic in discussions about doping. In many opinions it can be qualified as a form of "neurodoping" meaning enhancing brain activity in sport specific tasks [5, 23, 46]. This raises a relevant question - is it doping or not? In our systematic review, the results indicate that the effects of stimulation are minor and hard to replicate [8, 38]. However, we should understand that even the slightest advantages can be significant in elite sports. Other problems shown are accessibility and safety of tDCS [9, 42]. It concerns us that it is difficult to confirm both efficacy and the safety of the applied stimulation.

As of today, there are no regulations regarding use of tDCS. According to the World Anti-Doping Agency this protocol is not listed as a prohibited method [62]. The conditions to be qualified as banned are not clearly met [46, 50]. Also we should distinguish between therapeutic use and performance enhancement [3, 50]. It is essential to recognize the use of tDCS in treating neurological and psychiatric disorders, its use in boosting physical performance raises a lot of ethical questions [9, 43, 46]. This method is somewhere between technological innovation and potential ways of doping.

Due to lack of current regulations and the limited data, we cannot say with full conviction that application of this method in sports is ethical and safe. This topic needs further and more detailed research and broader debate about its use in sports [3, 43].

4.3 Limitations

The findings of this systematic review must be interpreted in light significant limitations [61]. We observed a predominant number of analyzed studies focused on small sample sizes, which can influence statistical power and make harder generalizations of results. Another problem was the high variability of stimulation protocol that can prevent the conclusion of standardized application of tDCS [36, 55].

Another challenge that we analyzed was the heterogeneity of the study populations. Our analysis revealed that even in the same sport population it is hard to obtain similar results [14, 38]. The individual neuro-sensivity can alter performance response in athletes. A further limitation was diversity of outcome measures. Almost every study used different forms of performance indicators and subjective measures. This makes interpretation more challenging and limits comparability across studies [8, 22]. We also considered the potential influence of the placebo effect [20, 52]. The expectations of participants can also alter the results.

Finally, most studies focused on short-term effects of tDCS. We do not have enough data about long-term results [38, 47, 55]. For these reasons, future studies should focus on more standardized protocols, include larger samples and check prolonged effects of tDCS.

4.4 Future Directions and Practical Implications

The evolution of the sport neuromodulation requires that the future research must change from short-term effects to long-term adaptations [21, 30, 56]. Most of the current data is focused on single stimulations, but main potential lies in the cumulative effect of tDCS [34, 47]. We believe that investigation of the effects of the repeated stimulation should be the highest priority.

Finally, the integration of tDCS protocols as one of the training strategies requires cooperation between scientists, ethics, and governing bodies of WADA [46, 50, 62]. As technology becomes more apparent and portable, the focus must include long-term neurological safety and preservation of "fair play" [3, 9, 43]. Establishing clear guidelines seems to be the biggest challenge for the next years of sports science.

5. Conclusions

tDCS shows a small to moderate effect on athletic performance, but results are not consistent. The most clear findings are its modified perceived effort and fatigue. The effectiveness depends on multiple factors such as sport specific movements and individual response of participants. Because of that we believe that it cannot be considered as a tool for enhancing physical performance. But we also see that its ability to modify the effort perception may have practical value in sports such as cycling, long distance running and triathlons. What also should be considered is the effects depend on the individual athlete. Further research is needed to fully understand the place of tDCS in the future of sports.**Disclosure:**

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During the preparation of this work, the authors used AI tools to improve grammar and language clarity. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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