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Mini Review

Transcranial Direct Current Stimulation (tDCS) on Soccer Players: A Mini-Review

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Abstract

Background: This mini-review explores the application of Transcranial Direct Current Stimulation (tDCS) in enhancing cognitive and motor performance in soccer players. This review synthesizes findings from recent studies focusing on tDCS's impact on the primary Motor Cortex (M1) and the Dorsolateral Prefrontal Cortex (dlPFC).

Results: studies conducted to date show that tDCS can enhance muscle strength, reduce perceived fatigue, and improve well-being in soccer players. For instance, anodal tDCS applied to the primary motor cortex has been shown to temporarily increase quadriceps strength, while stimulation of the dlPFC has improved recovery post-match and enhanced cognitive functions like reaction time and implicit motor learning.

Conclusion: the mini-review highlights the need for more targeted research, emphasizing the importance of individualized protocols and advanced neuroimaging techniques to better understand tDCS's mechanisms and optimize its use in sports. Future directions suggest adopting neurocircuit-based strategies such as RDoC to tailor interventions more precisely to athletes' needs. This integration could potentially maximize the benefits of tDCS, offering a holistic approach to enhancing athletic performance and recovery in soccer players.

Introduction

The brain naturally possesses the capacity for neuronal plasticity, meaning it can alter its structure and functions in response to ongoing environmental changes. While these principles are thoroughly validated in animal models, extending this understanding to a broader human population has become feasible primarily through the use of Noninvasive Brain Stimulation (NIBS) methods [1]. Noninvasive Brain Stimulation (NIBS) encompasses a variety of methods to stimulate the central nervous system in vivo without requiring surgical procedures or anesthesia [2]. Recent years have seen a growing interest in the use of Transcranial Direct Current Stimulation (tDCS). Transcranial Direct Current Stimulation (tDCS) is considered one of the most promising due to its low cost, ease of use, and high portability [3]. tDCS involves applying weak electrical currents, typically between 1 mA to 2 mA, to the scalp using at least two electrodes: a positively charged anode and a negatively charged cathode. The current is believed to subtly alter the resting membrane potential of neurons based on the electrode's polarity. Anodal stimulation generally causes depolarization of the membrane potential, increasing cortical excitability, whereas cathodal stimulation usually leads to hyperpolarization, reducing cortical excitability [4]. There's a prevailing assumption that a positive anodal current transiently enhances behaviors linked to the cortical area beneath the targeted electrode, whereas a negative cathodal current suppresses behaviors [5]. Research indicates

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that tDCS can enhance neuroplasticity, particularly in healthy older adults [6].

In recent years, numerous studies have employed neuroimaging techniques to examine how the brain governs exercise and, conversely, how exercise impacts brain function [7].

Researchers have examined specific regions of the brain using Transcranial Direct Current Stimulation (tDCS) to assess its impact on various aspects related to exercise. Target regions of Transcranial Direct Current Stimulation (tDCS) for improving exercise performance have been identified to include the primary Motor Cortex (M1), Dorsolateral Prefrontal Cortex (dlPFC), Supplementary Motor Area (SMA), and Insular Cortex (IC). Figure 1 shows the use of tDCS in the field of exercise science. Specifically, the targets used in the studies shown in the figure were the primary motor cortex, dorsolateral cortex, and temporal cortex (Figure 1). The primary motor cortex stands out as the brain region most linked to sports performance due to its role in driving the exercised muscles [8]. It has been seen that fatigue can impact exercise performance, but it is not yet clear which brain areas are connected to it. It has shown that the decreased excitability of motor neurons and the limited ability of the primary cortex to maintain or increase neural impulses can decrease the muscular ability to produce a force and this leads to the concept of fatigue. Related to this, it was seen in a study that a single session of tDCS in M1 leads to an increase in performance [9]. tDCS over the Dorsolateral Prefrontal Cortex (dlPFC) was found to improve implicit motor learning [10,11]. In addition, Dubreuil-Vall, et al. showed that anodal tDCS to the left DLPFC (F3 region) led to faster reaction times and cognitive improvement in healthy individuals [12]. The SMA is involved in the generation of increased perceived exertion (RPE), which is an important factor for exercise performance [13] and also influences the affective response to exercise [14]. Finally, targeting the Insular Cortex (IC) with transcranial Direct Current Stimulation (tDCS) could potentially enhance exercise performance and perceptions associated with exercise. This may occur through changes in cardiac autonomic control, leading to adjustments in cardiovascular responses such as decreased heart rate and blood pressure. Additionally, tDCS might impact interoception, affecting the perception of bodily signals, as well as emotional processing during exercise [7].

Transcranial Direct Current Stimulation (tDCS) has attracted interest as a potential tool for improving cognitive and motor performance in soccer players [15,16].

This mini-review analyzes recent studies on the use of tDCS in the context of soccer, evaluating the safety of this

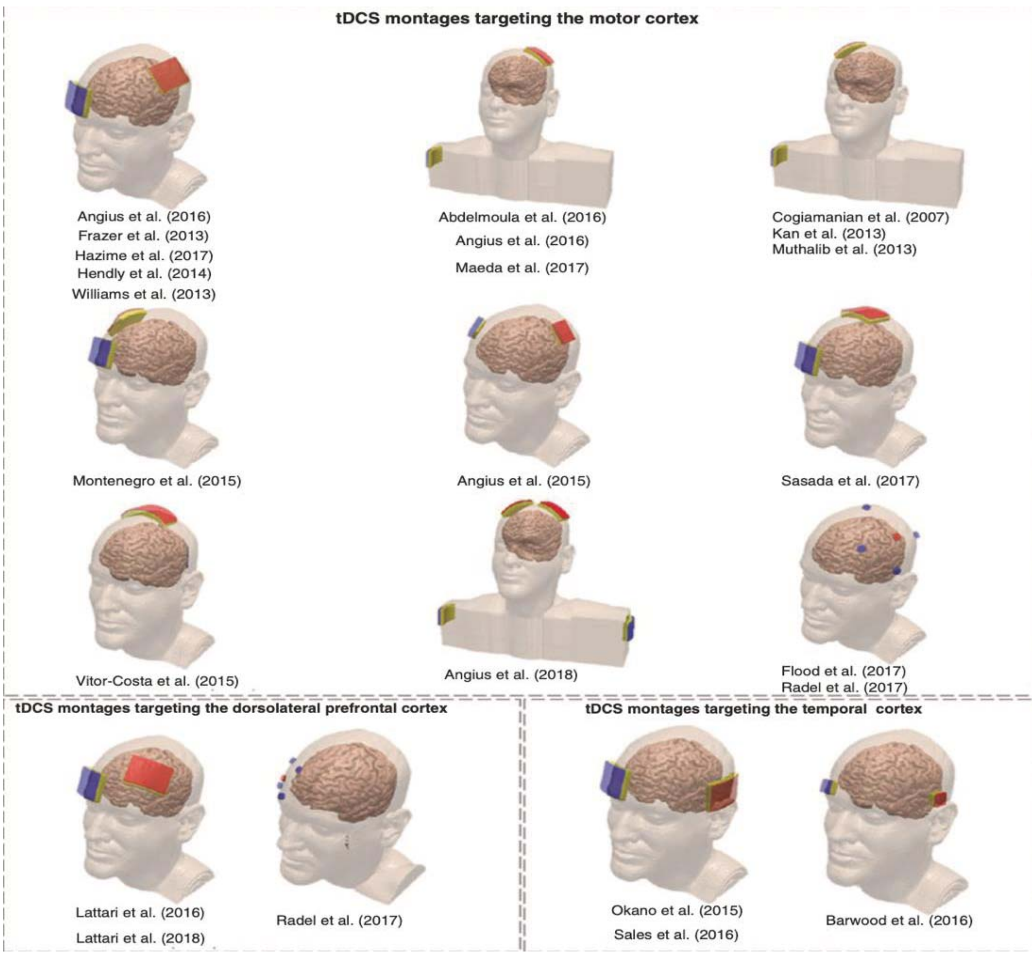

Figure 1: Examples of Transcranial Direct Current Stimulation (tDCS) configurations employed in different studies within the field of exercise science. These configurations specifically target the primary motor cortex, the dorsolateral prefrontal cortex, and the temporal cortex [7].

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technique in improving cognitive and behavioral variables such as perceived fatigue, well-being, reaction speed, working memory, attention, and other cognitive and motor skills crucial to success on the field.

The mini-review considered 5 studies aimed at investigating the use of tDCS in soccer players by targeting two main areas for stimulation: the primary Motor Cortex (M1) and the Dorsolateral Prefrontal Cortex (dlPFC).

Methods and materials

The search was conducted using the PubMed database to identify relevant studies on the use of Transcranial Direct Current Stimulation (tDCS) in soccer players. Keywords used included "transcranial direct current stimulation," "tDCS," "football players," "soccer players," "cognitive enhancement," "motor performance," "attention," "working memory," and combinations of these.

Inclusion and exclusion criteria

Articles included in the review had to be written in English, published in peer-reviewed journals, and contain experimental data on the use of tDCS in soccer players. Studies that did not meet these criteria or that did not provide specific data on the effects of tDCS on the cognitive or motor performance of soccer players were excluded.

Evaluation of studies

For each included study, several factors were evaluated, including study design, participant characteristics (e.g., age, gender), tDCS stimulation protocol (brain area stimulated, intensity, duration), and outcomes measured (e.g., well-being, perceived fatigue, reaction speed). The most stimulated brain areas were identified, with emphasis on the primary motor cortex and dorsolateral prefrontal cortex. Table 1 summarizes all the results of the studies considered.

Results

The results indicate growing evidence supporting the safety of tDCS in enhancing cognitive and motor performance in soccer players, with significant implications for training and athletic preparation. Recent research on the use of Transcranial Direct Current Stimulation (tDCS) in soccer players offers an interesting perspective on optimizing athletic performance. The study by Vargas, et al. [17] recruited 20 female soccer players. The study was conducted in two weeks: in the first week, the participants were distributed in two groups: an active anodal tDCS group and a sham tDCS group, both during 20 minutes [17]. In the second week, they were switched to the other type of stimulation. In this study, in particular, quadriceps muscle strength was analyzed, which was assessed before the tDCS session, during the tDCS session (after 13 minutes), 30 minutes after the tDCS session, and after 60 minutes of tDCS [18]. The results show that the MVIC of the knee extersor increases significantly during active tDCS 30 min after and 60 min after the tDCS session, but not for the sham condition. This outlines how tDCS may temporarily increase quadriceps strength in female soccer players, and this could be helpful both to increase strength through training in healthy subjects and as a rehabilitation tool. In addition, tDCS could accelerate the process of recovery after surgeries or lesions [17].

Similarly, another study examined the effectiveness of tDCS in improving the recovery of professional female soccer players after official matches, suggesting that tDCS could accelerate recovery and improve post-match well-being [16]. The study recruited 13 female soccer players. They applied anodal tDCS over the left dorsolateral prefrontal cortex with 2 mA for 20 minutes the day after the match. Participants were randomly divided into two groups: active tDCS or sham tDCS. Before undergoing a tDCS session, participants were asked to complete a questionnaire designed to assess well-being (Well-being Questionnaire – WBQ) and recovery. Then, they received sham or active tDCS (two sessions of either condition); after that, they participated in recovery training sessions. Finally, on the morning of the day after the intervention, they completed the questionnaire again, in order to assess possible changes in well-being and recovery [16]. Results show that no adverse effects were observed among participants. Again, the study of Moreira, et al. [7] shows that a-tDCS combined with a recovery training session may positively influence the recovery status of the players, increasing perceived well-being, examined through higher scores on the Well-Being Questionnaire (WBQ).

The same group of researchers decided to conduct a similar study to evaluate the effects of tDCS on well-being and autonomic function (HR-related measures) in professional male soccer players [15]. The outcome measure was the Heart Rate (HR) variable and perceived well-being. The study recruited 12 male soccer players. They were divided into two groups: active tDCS and sham tDCS. Anodal tDCS was applied, in the days after official matches, over the left Dorsolateral Prefrontal Cortex (dlPFC) with 2 mA for 20 minutes. Before and after undergoing the tDCS session, participants completed the Well-Being Questionnaire (WBQ) and performed the Submaximal Running Test (SRT). Heart rate was determined during the last 30 seconds of the SRT. Heart Rate Recovery (HRR) was recorded at 60 seconds after SRT [15]. Results show that no adverse effects were observed among participants. Moreira, et al. [7] show that both a-tDCS and sham tDCS were associated with higher values in WBQ and positive changes in HRR. However, there was no effect of the condition (sham and active tDCS). This suggests that placebo effects could have occurred [15]. These results could be a starting point for using tDCS as a recovery-enhancing strategy tool.

Next, a triple-blinded, controlled, and randomized study showed that contrary to what has been seen in previous studies, bi-hemispheric anodal tDCS does not improve the overall performance of soccer players, underscoring the need for further studies to evaluate its effectiveness [19].

Rocha, et al. [19] recruited 27 soccer players and divided them into three groups: active tDCS, sham tDCS, and control group. Anodal tDCS was applied over the primary Motor Cortex (M1) with 2 mA for 15 min. The outcome measures were the Visual Pain Scale (VAS) and Subjective Recovery Scale (SRS)

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Table 1: Summary description of the 5 studies included in the review.

Study	Design	Participants	Target tDCS	Stimulation duration (min)	Number of sessions	Groups	Outcome	Results
Vargas, et al. 2018 [7]	Cross-over	20 soccer players (all F)	M1	20 min	2 weeks	Active vs Sham	Voluntary Isometric Contractions (MVICs)	The application of active tDCS induced an increase of 5.2% in the MVIC of the dominant quadriceps during active tDCS, 6.3% in the MVIC 30 minutes after active tDCS, and 9.4% in the MVIC 60 minutes after active tDCS, when compared with baseline (prestimulation).
Rocha, et al. 2024 [19]	Cross-sectional	27 soccer players (M/F)	M1	15 min	3 sessions (24 h interval between session)	Active vs Sham vs Control	Visual Pain Scale (VAS) Subjective Recovery Scale (SRS) Countermovement Jump (CMJ)	tDCS did not change the performance
Neto EM, et al. 2020 [20]	Double-blind	30 soccer players (M)	IDLPFC	20 min	5 sessions (24 h interval between session)	Active vs Sham	Choice reaction time (CRT) Trail Making Test (TMT) Digit Span Test	Reduce the choice reaction time (CRT) in both active and sham. there were no differences between the groups in terms of cognitive function
Moreira, et al. 2021 [7]	Cross-over	12 soccer players (all M)	IDLPFC	20 min	session post-match	Active vs Sham	WBQ HR measures	Both active and sham associated with positive change in WBQ and HR Placebo effects
Moreira, et al. 2021 [7]	Cross-over	13 soccer players (all F)	IDLPFC (A) rDLPFC (C)	20 min	Session post-match	Active vs Sham	Well-being questionnaire (WBQ)	Higher value for WBQ compared to sham Positively influence the recovery status of the players

and monitored before and after the tDCS session. In addition, participants performed the Countermovement Jump (CMJ) before and after tDCS intercalate with Heart Rate (HR) and Rating of Perceived Exertion (RPE). Results show that no adverse effects were observed among participants. In addition, according to the results, tDCS did not influence performance on the CMJ and perception of effort and recovery. These results suggest that tDCS could be a promising addition to the athletic training of soccer players, although further research is needed to delineate optimal stimulation protocols and evaluate its long-term effects.

Finally, a randomized controlled trial showed that adding tDCS to visuomotor training can significantly improve Choice Reaction Time (CRT) and cognitive function in amateur soccer players [20]. They recruited 30 male amateur soccer players and divided them into two groups: active anodal tDCS and sham tDCS. Both groups performed Visuomotor Training (VMT), but only the intervention group was undergoing tDCS sessions over the left dorsolateral prefrontal cortex. The tDCS was applied at 2 mA for 20 min for five consecutive sessions (24 h intervals) [20]. The VMT protocol was administered during the tDCS application and involved kicking a ball (according to what light was turned on (left light, to kick the left ball; right light, to kick the right ball) for 10 minutes (from the fifth to the fifteenth minute of the 20-minute tDCS session). The primary outcome was evaluated by changes in CRT during reaching (non-trained limb) and kicking (trained limb) tasks. Secondary outcomes included overall cognitive function, assessed using the Trail Making Test parts A (TMT-A) and B (TMT-B), as well as Digit Span Test Forward (DSF) and Backward (DSB) scores. All outcomes were measured before and after the intervention [20]. The results indicated that CRT decreased for both the rectus femoris (trained limb) and triceps (non-trained limb) after five consecutive sessions of online anodal tDCS over the DLPFC combined with VMT, compared to sham tDCS combined with VMT. However, there were no differences between the groups in terms of cognitive function [20]. However, further research is needed to define optimal stimulation protocols and evaluate the long-term effects of tDCS on athletic performance and athlete well-being.

Discussion

The studies analyzed so far have shown that neuromodulation treatments were safe and well tolerated, with no significant side effects reported. Furthermore, the results indicate that these treatments led to improvements in several aspects of athletes' performance. Among the benefits observed were perceived well-being, reduction in perceived fatigue, increased muscle strength, and improved cognitive functions.

These results suggest that despite the current limited focus on the Anodal tDCS protocol, neuromodulation could have a positive impact on athletic performance and overall well-being of athletes. However, for a complete understanding of the potential benefits, it will be essential to expand future research to also include the Cathodal tDCS protocol and to develop more accurate assessment methods. In the tDCS literature, "anodal tDCS "and "cathodal tDCS" are described based on polarity: anodal tDCS depolarizes neurons, thereby increasing cortical excitability, whereas Cathodal tDCS hyperpolarizes neurons, diminishing cortical excitability [21,22]. An interesting point that has emerged from some studies is that both Anodal and

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Cathodal tDCS protocols can increase BDNF (Brain-Derived Neurotrophic Factor) levels The Brain-Derived Neurotrophic Factor (BDNF) is the most important neurotrophin (Eskander, et al. 2019). BDNF is a neuronal growth factor crucial for neuronal development and plasticity. It increases the growth, survival, and health of different neurons [23]. Increased BDNF levels could explain the observed improvements in the performance of athletes treated with tDCS as a more plastic nervous system is better able to adapt to training and sports stress situations. Moreover, in addition to increasing BDNF levels, it decreases psychological symptoms such as depression, anxiety, stress, and cravings for drugs [23].

In summary, while tDCS appears to be a promising tool for enhancing athletic performance and recovery, its application in sports like soccer needs further refinement. The variability in results across different studies underscores the importance of establishing optimal stimulation protocols and understanding the mechanisms underpinning tDCS's effects. Future research should focus on long-term effects, individual differences in response to tDCS and sham tDCS, and its integration into comprehensive training and recovery programs. This will help to establish clearer guidelines and maximize the benefits of tDCS for athletes in competitive sports.

In sports, the results obtained so far are not easy to interpret. This is because they have often proceeded by considering the athlete as a generic category. When trying to apply clinical knowledge to the field of sports, many studies have been conducted by defining a subject as healthy or as a practitioner of a particular sports discipline. This generalization is one of the main limitations of the studies conducted so far and makes it difficult to understand what really happens when neuromodulation techniques are applied to athletes. For example, if we talk about a soccer player, we cannot precisely define what it means to have "a soccer player's brain." In contrast, in the clinical setting, we know much more about the brain of a person suffering from panic attacks. It is clear that there are significant differences between the various roles in a soccer team: the brain of a goalkeeper is likely to be different from that of a striker, partly because of the different spatial and cognitive needs associated with their position on the field. Hence, for the study of the brain, more rigorous definitions need to be adopted and, more importantly, more specific and precise results (outcomes) need to be considered, which are generally related to the athlete's level of performance. This performance needs to be defined in much more detail. To improve our understanding, we need clear and measurable parameters to observe before and after the intervention. For example, advanced techniques such as neuroimaging or neurophysiology, such as quantitative electroencephalography (EEG-q), could provide valuable data.

Unfortunately, these methodologies have not generally been applied in existing studies. Adopting such techniques would allow us to gain a deeper and more accurate understanding of the effects of neuromodulation and changes in the brain functioning of athletes. In addition, it would be useful to define the phenotype of athletes, which is the set of their morphological and functional characteristics that result from the interaction between their genotype and environmental influences. Clearly identifying and describing these phenotypes can help us better understand how different factors influence performance and brain health in athletes. At this point, it would be advantageous to apply the Research Domain Criteria (rDOC) approach to a well-defined phenotype. In addition, the safety of Transcranial Direct Current Stimulation (tDCS) in soccer players could be maximized through the implementation of customized programs based on the Research Domain Criteria (RDoC) method. The Research Domain Criteria (RDoC) has been developed as an approach to explore the connection between psychiatric disorders and brain connectives. It is also a method to study clinical evidence in relation to the functioning of brain connectivity. The same can be used not only for psychiatric disorders but especially for finding correlations between brain areas and behaviors.

The same approach was The Research Domain Criteria (RDoC) was introduced by the National Institute of Mental Health (NIMH) in 2009 as a novel approach aimed at developing an empirically based model of psychopathology [24,25]. Unlike traditional models such as the DSM, which rely heavily on expert opinion, RDoC seeks to transcend these limitations [26,27]. The RDoC framework initially included five functional domains: positive valence systems, negative valence systems, cognitive control systems, arousal and regulatory systems, and social processes systems. However, at the beginning of 2019, the Sensory-Motor Systems domain was added to the matrix (Figure 2). This addition was intended to encourage research into the role of disruptions in motor systems across various mental disorders [28] but can be especially useful in sports.

Integrating RDoC into tDCS stimulation programs could provide a more comprehensive and detailed view of players' individual characteristics and performance needs.

First, RDoC could allow us to explore the connection between athletic gestures and specific parts of the brain involved in it. This approach would allow more precise tailoring of tDCS interventions to the specific needs of each player. Second, RDoC could help select brain areas to be stimulated in a more targeted way. For example, if a player shows difficulty in visual attention during play, stimulation of the visual cortex might

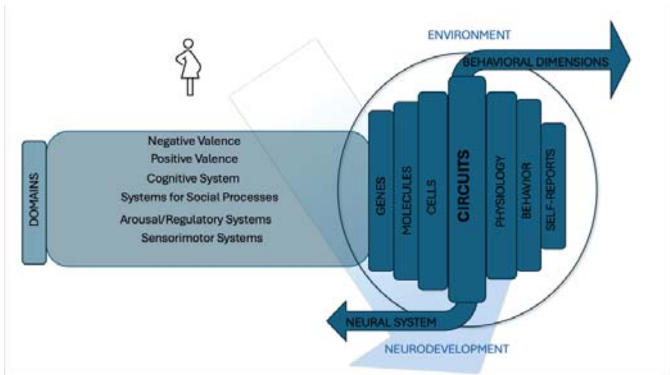

Figure 2: Image of the RDoC Framework from the National Institute of Mental Health.

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be prioritized. Similarly, if another player needs to improve his or her ability to make quick decisions, stimulation of the prefrontal cortex might be more appropriate. This size-based personalization of the RDoC could improve the effectiveness of tDCS interventions.

Finally, RDoC could facilitate the integration of tDCS with other training and recovery strategies by identifying dimensions relevant to sports performance as mirrored in brain connectivity. In this sense athletic gesture performance and brain connectivity might offer an extraordinary opportunity of mutual enlightment.

In conclusion, the implementation of individualized programs based on the Research Domain Criteria method could be a significant step forward in the effective use of transcranial direct current stimulation in soccer players. Integrating RDoC into tDCS protocols could improve the accuracy, relevance, and effectiveness of interventions, leading to optimal sports performance and individualized improvements in soccer.

Transcranial Direct Current Stimulation (tDCS) in soccer players could also offer benefits in injury prevention. Although further research is still needed to fully understand this potential, there are some ways in which tDCS could help reduce the risk of injury in soccer players, such as through improved cognitive and motor performance and reduced mental and physical fatigue.

In addition, the adoption of neurocircuit-based approaches in target selection of Transcranial Direct Current Stimulation (tDCS) could offer numerous advantages in optimizing personalized protocols for soccer players. Identifying and targeting specific neural circuits can allow stimulation interventions to be tailored to maximize benefits for each individual.

Using this approach, we could have a greater awareness of the neural processes involved in athletic performance and injury risk, enabling a more informed and targeted design of stimulation interventions.

Another interesting perspective would be to investigate the peripersonal space, the region of space immediately surrounding our bodies and in which objects can be grasped and manipulated [29]. It would be interesting to evaluate and investigate the representation of each player's peripersonal space to work through training.

Conclusion

Overall, tDCS emerges as a promising tool in the context of soccer, with potential applications in enhancing muscle performance, aiding in recovery, and possibly improving cognitive and motor skills.

Despite the promising results of the analyzed studies, it is crucial to recognize some significant limitations that could affect the generalizability and robustness of the conclusions. First, the small sample size reduces statistical power and may not adequately represent the general population. This suggests the need for future studies with larger samples to confirm our results.

In addition, the lack of double-blind studies is another major limitation. The possibility of bias arising from participants' or researchers' awareness of experimental conditions could influence the results. The inclusion of rigorous double-blind protocols is essential to improve the internal validity of subsequent studies.

Another limitation concerns the absence of objective measures, such as neuroimaging techniques. The use of neuroimaging techniques, such as Functional Magnetic Resonance Imaging (fMRI) or Positron Emission Tomography (PET), could provide crucial insights into underlying neurobiological mechanisms and help better correlate behavioral changes with brain activity.

Again, the use of a single Transcranial Direct Current Stimulation (tDCS) protocol (anodal tDCS) limits our ability to generalize results to other stimulation modalities or different parameters. Future studies should explore a variety of stimulation protocols.

Finally, another limitation is the exclusive use of the PubMed database for searching articles. Although PubMed is a widely recognized resource for its large collection of high-quality, peer-reviewed articles in the biomedical field, the possibility that there are other valid databases that might contain relevant research cannot be excluded. However, PubMed was selected because it represents one of the most reliable and comprehensive sources for access to high-quality scientific literature, thus justifying the choice to focus on it.

In conclusion, while the results of the studies offer valuable insights into the effects of tDCS, further research is needed to overcome these limitations and refine its use in sports.

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