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Research Trends and Prospects of Combined Application of tDCS and Physical Training in Sports

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ABSTRACT

This review systematically explores the research trends in the combined application of transcranial direct current stimulation (tDCS) and cognitive-related tasks in sports, analyzing its theoretical foundations and physiological mechanisms, diagnosing its current status and limitations, and proposing future research directions. The analysis results indicate that the combined intervention shows stronger enhancing effects in specific domains (e.g., executive function, motor skill acquisition speed, skill retention) compared to the application of tDCS alone. However, several unresolved issues persist, such as insufficient optimization of stimulation parameters, limited consideration of individual differences, ecological validity concerns in laboratory settings, and a lack of evidence for long-term effects and safety. The conclusion states that this combined application is a promising research paradigm. Future research should focus on: developing optimized and personalized protocols, enhancing field applicability, validating long-term effects and safety, elucidating neurophysiological mechanisms, and establishing ethical standards.

Keywords: Transcranial direct current stimulation, physical training, sports, combined intervention.

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1. Introduction

With the maximization of athletes' physical, technical, and tactical abilities in modern sports, relying solely on traditional training methods is increasingly inadequate for achieving leaps in elite athletic performance. In this context, the introduction of scientific training aids has become an inevitable trend. Among these, transcranial direct current stimulation (tDCS) has garnered significant attention in sports science in recent years due to its ability to non-invasively modulate the excitability of the central nervous system, potentially enhancing athletic performance and learning capacity (Qi et al., 2024).

tDCS applies a low-intensity direct current (typically 1–2 mA) through electrodes attached to the scalp, inducing depolarizing changes in the membrane potential of target brain regions, thereby modulating cortical excitability. Early research in the motor domain primarily demonstrated that anodal stimulation of the primary motor cortex can temporarily improve motor learning speed, strength performance, and muscular endurance in healthy adults (Nitsche & Paulus, 2000; Reis et al., 2009). These findings support the hypothesis that increased cortical excitability enhances motor command efficiency, promotes motor unit recruitment, and facilitates the neural plasticity required for skill acquisition.

Consequently, there is growing interest in combining tDCS with existing physical training methods to enhance athletic performance. The core logic of this paradigm is: "Optimizing the preparatory state of the central nervous system via tDCS induces a synergistic effect with the peripheral adaptations (e.g., muscle hypertrophy, neuromuscular coordination) elicited by concurrent or sequential physical training." This approach not only adds a training stimulus but also acts as an amplifier of cognitive-neural connections, aiding the brain in processing and learning more efficiently (Marcos-Frutos et al., 2023; Wang et al., 2021).

Early international research exploring tDCS effects on sports performance primarily focused on healthy non-athletes, examining immediate effects on simple motor tasks (e.g., finger tapping, isometric contractions). For instance, the pioneering study by Nitsche and Paulus (2000) showed that a single tDCS session over M1 could facilitate motor learning in a hand motor task; Reis et al. (2009) suggested that multiple tDCS sessions might enhance complex motor skill learning over time. Additionally, Cogiamanian et al. (2007) reported that tDCS could reduce muscle fatigue, sparking interest in its potential to improve exercise endurance.

However, these foundational studies were biased toward validating the isolated effects of tDCS and failed to systematically analyze its synergistic effects with specific training modalities such as resistance training, blood flow restriction training, or plyometric training, which are central to practical sports training. For example, Vitor-Costa et al. (2015) indicated that the effects of tDCS on cycling performance might differ depending on the stimulation site (prefrontal vs. motor cortex), hinting at the importance of precise targeting, yet clear guidance on combining tDCS with sport-specific physical training remains lacking. Furthermore, previous comprehensive reviews on the combination of tDCS and physical training have expanded into areas such as neurorehabilitation, exercise in the elderly, and cognitive enhancement, lacking a dedicated analysis focused on the objective of improving sports and competitive performance.

To address these gaps and limitations in prior research and to advance tDCS as a scientific training aid, this review focuses on the sports domain, with the ultimate goal of enhancing athletic performance. It provides a systematic and clear analysis of experimental research literature related to the combined application of tDCS and physical training. Specifically, centered on 21 empirical studies, it aims to identify trends in research subjects (professional athletes, sports major students, healthy non-athletes) and purposes, characteristics and variations in intervention methods (training type, synchronicity, stimulation parameters, application period), patterns of effects and influencing factors (differences based on subject, method, period), and based on this, diagnose the comprehensive limitations of current research, proposing specific prospects and directions for future research and practice. It is hoped that this will contribute to establishing tDCS as an effective tool in sports science and ultimately to enhancing athletes' competitive performance and developing scientific training methodologies.

2. Current State of Review Studies on the Combined Application of tDCS and Physical Training

To understand recent research trends on the combined application of physical training and tDCS, we searched academic databases including CNKI, PubMed, Web of Science, and EBSCOhost using keywords such as "sports," "transcranial direct current stimulation," "tDCS," "physical training," and "combined with." Four relevant review studies were identified.

Reviews related to the combined application of tDCS and physical training do not focus primarily on the sports field itself, but rather on general performance enhancement, neuroscientific mechanisms, or rehabilitation medicine. This is evident from the following analysis (Table 1).

Table 1 Current State of Review Studies Related to the Combined Application of tDCS and Physical Training.

Researcher(s)	Period of Included Studies	Subjects of Included Studies	Application Domain of Included Studies
Marcos-Frutos et al. (2023)	2013–2023	Healthy adults; Neurological disorder patients; Musculoskeletal disorder patients	Performance enhancement, strength & balance training; Stroke rehabilitation, multiple sclerosis, Parkinson's disease, mild cognitive impairment in elderly; Chronic ankle instability, knee osteoarthritis, patellofemoral pain syndrome
Liu et al. (2024)	2013–2024	Healthy adults	Maximal strength & lower limb explosive power enhancement, cortical excitability enhancement
Steinberg et al. (2019)	2012–2018	Healthy adults; Neurological & psychiatric disorder patients	Cognitive enhancement, performance enhancement, learning & working memory enhancement, fatigue delay; Motor function recovery & cognitive rehabilitation
Wang et al. (2021)	2008–2020	Young (healthy); Elderly (healthy); Chronic low back pain patients; Chronic	Promoting motor learning, increasing motor cortex excitability, partial improvement in strength & performance, limited improvement in pure balance

	ankle patients	instability	ability; Improving balance & postural stability, enhancing motor learning & memory, increasing motor cortex excitability; Improving postural control; Balance & rehabilitation

- **Period:** The periods of experimental studies analyzed in these reviews mostly range from 2012 to 2024, indicating active research on the combined application of tDCS and training over the past decade.
- **Subjects:** Marcos-Frutos et al. (2023) included healthy adults, neurological, and musculoskeletal patients, emphasizing rehabilitation and clinical aspects. Liu et al. (2024) included only studies on healthy adults, focusing on general performance enhancement. Wang et al. (2021) covered young adults, elderly, and chronic patients, adopting a lifespan and rehabilitation perspective. Steinberg et al. (2019) included both healthy adults and neurological/psychiatric patients, addressing integrated cognitive-motor research.

In summary, previous reviews have focused more on inclusive subject groups such as non-athletes, patients, and various age groups, rather than primarily on athletic populations like sports athletes or sports major students.

- **Application Domain:** Marcos-Frutos et al. (2023) centered on rehabilitation and clinical applications, covering performance, strength, balance, stroke rehab, Parkinson's, hip pain, etc. Liu et al. (2024) focused on basic exercise physiology aspects like maximal strength, lower limb explosive power, and cortical excitability. Wang et al. (2021) involved various motor-related functions such as motor learning, cortical excitability, strength, balance, and rehabilitation. Steinberg et al. (2019) aimed at integrated cognitive-motor research, including cognitive enhancement, performance, learning, working memory, and fatigue delay.

In essence, application domains specific to "competitive performance enhancement" or "sport-specific training" within the sports field were not distinctly emphasized.

Through this analysis, the following limitations in prior review studies on tDCS combined application can be confirmed:

- **Generalization of Subjects:** Primarily covering non-athletes, patients, and multi-age groups, rather than athletic populations aiming for performance enhancement like sports athletes or sports major students.
- **Rehabilitation/Clinical Focus:** Emphasizing rehabilitation, cognitive enhancement, exercise for the elderly, and elucidation of neuroscientific mechanisms, with the application goal of enhancing competitive performance not being highlighted.
- **Fragmentation of Fields:** Research is dispersed across neurorehabilitation, exercise for the elderly, cognitive-motor, clinical exercise therapy, etc., lacking dedicated, systematic analysis focused on the sports domain.

Therefore, this study aims to fill this gap by systematically analyzing research trends and prospects of tDCS combined application specifically in the sports domain, clearly articulating tDCS application strategies for sports science and competitive performance enhancement.

3. Research Status of Combined Application of tDCS and Physical Training in the Sports Domain

To understand the research status of the combined application of physical training and tDCS in the sports domain over the past decade (2013–2025), we searched CNKI, PubMed, Web of Science, and EBSCOhost using keywords such as "sports," "transcranial direct current stimulation," "tDCS," "physical training," and "combined with."

The search focused on the core theme of the sports domain, analyzing subjects, content of combined application with tDCS, and application domains. Subjects excluded patients, the elderly, and minors, selecting athletes, sports major students, and healthy non-athletes. Regarding combined application content, physical training content was selected over physical testing tasks. For application domain, studies aiming to enhance performance capacity rather than fatigue recovery were selected. As a result, 21 studies combining tDCS with physical training targeting professional athletes, sports major students, or healthy individuals were identified.

To clarify the status of research on the combined application of physical training and tDCS, key items were selected: researcher(s), subjects, training type combined with tDCS, application domain, synchronicity (on-line/off-line), experimental groups, stimulation site, intensity, duration, electrode size, tDCS application period & frequency, effects, and final conclusions. The summarized results of the empirical analysis are presented in Table 2.

Table 2 Summary of Empirical Research Analysis on the Combined Application of tDCS and Physical Training in Sports

#	Researcher(s)	Subjects	Training Type Combined with tDCS	Application Domain	Synchronicity	Experimental Groups	Stimulation Parameters	Period & Frequency	Effects (Effective/Ineffective)	Final Conclusion
1	Zhou Yuping (2021)	Sports University Males (n=29)	Post-activation Potentiation (PAP) Training	Continuous Vertical Jump Ability	Off-line	Control, PAP, tDCS, Combined	M1, 2.2mA, 20min	Single session	**Effective:** Significantly improved jump height, peak power, shortened ground contact time, increased β-wave activity	Both tDCS+PAP and single applications improved continuous vertical

										in specific brain regions. **Ineffective:** Not superior to single interventions; no significant changes in θ & δ waves.	jump performance in male college students, with an interaction effect; tDCS was the main effect.
2	Wang Jingfeng (2025)	Sports College Males (n=28)	Blood Flow Restriction Training (BFRT)	Upper Body Muscle Strength	Off-line	Combined, BFRT, tDCS, Control	M1, 2 mA, 20 min	4 weeks, 3x/week	**Effective:** Combined group showed most significant improvement in upper body max strength and long-term performance. **Ineffective:** tDCS alone had limited long-term effects; no consistent advantage in explosive power.	tDCS and BFRT have synergistic effects, improving upper body strength and endurance in both short and long term. tDCS alone lacks long-term stability.
3	Sun Mingming (2025)	Sports College Males (n=28)	Low-Intensity BFRT	Lower Limb Explosive Power	Off-line	Combined, BFRT, tDCS+Low-Intensity, Control	C3/C4, 2 mA, 20 min	6 weeks, 3x/week	**Effective:** Combined group showed most significant improvement in lower limb explosive power, max strength, etc., with statistical difference vs. control. **Ineffective:** Some indicators in tDCS alone	Combined intervention is superior to single training for improving lower limb explosive power and strength, and is an effective

									group showed no difference vs. control; no change in RMS of related muscles.	method for sports college males.
4	Wu Koukou (2023)	Sports College Males (n=36)	Unilateral Resistance Training	Lower Limb Explosive Power	Off-line	Combined, tDCS, Unilateral Training	C3/C4, 2 mA, 20 min	6 weeks, 3x/week	**Effective:** Combined group showed most significant improvement in all lower limb explosive power indicators, superior to single methods. **Ineffective:** tDCS alone showed no significant improvement in strength and explosive power indicators except for CMJ-related metrics.	tDCS combined with unilateral training is the optimal method for improving lower limb explosive power in this group, with effects superior to single interventions.
5	Wang Zichen (2024)	University Athletes (n=24)	Lower Limb Strength Training	Lower Limb Vertical Jump Ability	Off-line	Combined, Control (sham)	M1, 2 mA, 20 min	5 weeks, 2x/week	**Effective:** Experimental group showed significantly better countermovement jump height, peak power, and relative peak power than control. **Ineffective:** No significant difference in squat 1RM,	tDCS can improve lower limb vertical jump-related kinetic performance in university athletes by modulating motor cortex

									jump speed, etc.	excitability.
6	Wang Zhuangzhuang (2024)	Sprinters (n=24)	Variable Resistance Training (VRT)	Lower Limb Explosive Power	Off-line	Combined, tDCS, VRT	M1, 2 mA, 20 min	6 weeks, 3x/week	**Effective:** Combined intervention showed more significant improvement in squat 1RM, vertical jump reach, knee extensor peak torque, etc. **Ineffective:** No statistical difference in CMJ-related indicator improvement among the three groups.	Combined training has superior effects on improving lower limb explosive power and max strength in sprinters.
7	Wu Li (2023)	Sports College Males (n=30)	Low-Intensity BFRT	Muscle Strength, Anaerobic Capacity	Off-line	Control, tDCS, BFRT, Combined	M1, 2 mA, 20 min	4 weeks, 3x/week	**Effective:** Combined intervention significantly outperformed single interventions in improving lower limb strength and anaerobic exercise capacity. **Ineffective:** No additional advantage shown in explosive power and fatigue resistance.	Combined intervention is more effective than single methods for improving lower limb strength and anaerobic exercise capacity, with good application prospects.
8	Yang Shilong (2024)	University Males (n=24)	3/7 Strength Training Method	Lower Limb Maximal Strength	On-line	Combined, Control (sham)	M1, 2 mA, 20 min	6 weeks, 2x/week	**Effective:** Combined group showed significantly better	Combining tDCS with 3/7 training can

									improvement in squat 1RM, single-leg squat 1RM, vertical jump, and 30m sprint than control. **Ineffective:** No significant difference in lean thigh circumference growth of dominant leg.	significantly improve lower limb maximal strength in male university students, with no additional effect on short-term muscle girth.
9	Zhou Zheziao et al. (2025)	Track & Field Athletes (n=15)	Resistance Training	Post-Activation Performance Enhancement (PAPE)	On-line	Sham tDCS, tDCS, Resistance Training, Combined	C3/C4, 2 mA, 20 min	Single session	**Effective:** Combined stimulation induced immediate and sustained PAPE, superior to single stimulation methods.	tDCS can induce high-quality PAPE; combined with low-intensity resistance training, the effect is additive and superior to single interventions.
10	Ni Lili et al. (2022)	Sports College Taekwondo Majors (n=16)	Squat Strength Training	Lower Limb Strength, Anaerobic Power	Off-line	Single group pre-post test	Cz, 2 mA, 20 min	5 weeks, 2x/week	**Effective:** Significantly improved peak power, mean power, peak work, and 1RM squat performance. **Ineffective:** No statistically significant improvement	Combined intervention can enhance lower limb maximal strength and short-term high-power

									in relative power and fatigue resistance.	output capacity, but does not improve unit power or fatigue resistance.
11	Xing Yingshuai et al. (2025)	Sports Major Students (n=24)	Loaded Squat Jump Training	Vertical Jump Height	Off-line	Combined I (40%1RM), Combined II (20%1RM), Control (tDCS alone)	C3, 2 mA, 20 min	8 weeks, 2x/week	**Effective:** The group combining tDCS with 40% 1RM load training showed significantly better vertical jump height increase rate than control. **Ineffective:** No significant difference between the 20% 1RM combined group and tDCS alone group.	tDCS combined with 40% 1RM loaded squat jump training is an effective method for improving vertical jump height.
12	Moshashaei et al. (2024)	Female Taekwondo Athletes (n=34)	Neuromuscular Training (NMT)	ACL Injury Prevention	Off-line	Combined, Control (sham)	Right M1, 2 mA, 20 min	4 weeks, 3x/week	**Effective:** Experimental group showed significant improvement in feedforward activity of related lower limb muscles. **Ineffective:** No significant difference in dynamic knee valgus angle.	Combining tDCS with neuromuscular training can improve muscle control; further research is needed for dynamic knee valgus

										correction.
13	Yang et al. (2024)	Freestyle Swimmers (n=24)	Basic Physical Training (Comprehensive)	High-Level Athletic Performance	Off-line	Combined, Control (sham)	C3/C4, 2 mA, 20 min	6 weeks, 5x/week	**Effective:** Combined group showed significant improvement in 5RM pull-ups, vertical jump, start distance, 400m swim time. **Ineffective:** No significant improvement in aerobic endurance and some basic strength metrics.	Combined intervention can improve swimmers' basic strength, explosive power, and anaerobic endurance, aiding competitive performance.
14	Alix-Fages et al. (2020)	Healthy Males (n=14)	Bench Press Resistance Training	Training Volume, Fatigue	Off-line	Anodal tDCS+Training, Cathodal tDCS+Training, Sham tDCS+Training	LDLPFC /OFC, 2 mA, 15 min	Single session	**Effective:** Anodal tDCS group increased training volume, slowed decline in movement speed, reduced perceived fatigue. **Ineffective:** No significant change in max strength or power output parameters.	tDCS can aid in improving training performance and reducing fatigue, but has limited effect on max power enhancement.
15	Hendy et al. (2014)	Healthy Individuals (n=10)	Unilateral Wrist Extensor Strength Training	Cross-Education Potential	On-line	Combined, Sham tDCS+Training, tDCS alone	Right M1, 2 mA, 20 min	Single session	**Effective:** Single combined session increased strength in the untrained contralateral muscle, accompanied by related	Combining unilateral strength training with synchronous tDCS can increase strength

									neuroplastic changes. **Ineffective:** Did not increase cortical excitability in the trained hemisphere; impact on some physiological variables unclear.	in the untrained limb, accompanied by neuroplastic changes.
16	Hendy et al. (2013)	Healthy Individuals (n=30)	High-Load Barbell Training	Neuroplastic Changes	On-line	Combined, Sham tDCS+Training, Control	Left M1, 2 mA, 20 min	3 weeks, 3x/week	**Effective:** Only the combined group showed increased corticospinal excitability and decreased short-interval intracortical inhibition.	Applying tDCS during high-intensity training did not provide additional strength gains but significantly altered motor cortex neuroplasticity.
17	Xiao et al. (2022)	Healthy Individuals (n=30)	Foot Core Exercise (FCE)	Foot-Ankle Sensorimotor Function	On-line	Combined, Control (sham+FCE), FCE alone	Cz, 2 mA, 20 min	4 weeks, 3x/week	**Effective:** Combined group showed increased toe flexor strength and improved ankle joint proprioception. **Ineffective:** No significant difference in static balance metrics.	Combining tDCS with FCE can enhance toe strength and ankle proprioception; further research is needed for static balance improvement.

18	Zhou et al. (2021)	Healthy Individuals (n=29)	High-Load Resistance Training (HRT)	Lower Limb Explosive Power, Repeated Jumps	Off-line	Control, tDCS alone, HRT alone, Combined	Motor cortex, 2.2 mA, 20 min	Single session	**Effective:** Combined method significantly improved vertical jump height, reactive strength index, and peak power. **Ineffective:** Combined group was superior in shortening ground contact time and enhancing β-waves vs. single interventions; changes in some brain regions were limited.	The combined group showed advantages in shortening ground contact time and enhancing β-waves over single interventions, with limited changes in some brain regions.
19	Maeda et al. (2017)	Healthy Individuals (n=24)	Eccentric Isokinetic Strength Training	Lower Limb Strength Rehabilitation	On-line	Combined, Control (sham)	Leg M1, 2 mA, 10 min	3 weeks, 7 sessions total	**Ineffective:** No statistically significant difference in strength enhancement between combined tDCS and sham groups.	Repeated anodal tDCS did not enhance lower limb strength training effects in healthy adults.
20	Hendy et al. (2015)	Healthy Individuals (n=24)	Right Biceps Brachii Unilateral Resistance Training	Maintenance of Neuroplasticity	On-line	Combined, Training+Sham, tDCS alone	Right iM1, 1.5 mA, 15 min	2 weeks, 3x/week	**Effective:** Both combined and sham+training groups increased untrained side strength and cortical excitability, and decreased	Applying tDCS during unilateral training can prolong the maintenance of strength

									SICI. **Ineffective:** tDCS alone group showed no increase in untrained side strength.	gains and related neuroplasticity in the untrained limb.
21	Washabaugh et al. (2016)	Healthy Individuals (n=22)	Low-Intensity Intermittent Quadriceps Activity	Force-Generating Capacity	On-line	Combined, tDCS+Rest	M1, 1.5 mA, 20 min	Single session	**Effective:** Combined group showed significant increase in knee extensor peak torque. **Ineffective:** No significant effect on knee flexor torque.	Low-intensity exercise can facilitate tDCS, confining its enhancing effect to the exercised muscle group.

3.1 Research Subjects and Objectives

Examining the subjects of tDCS and physical training combined application research in sports, they are mainly divided into three groups: professional athletes, sports university/major students, and healthy non-athletes. Subject classification should be reasonable based on the characteristics of the research topic (Smorawiński et al., 2000). Here, sports students cannot be considered either professional athletes or typical non-athletes, belonging to an intermediate category. Among the 21 studies, 6 targeted professional athletes (e.g., sprinters, swimmers, taekwondo athletes), 6 targeted sports university/college students, and the remaining 9 targeted healthy non-athletes.

Regarding sample size, all groups predominantly used small samples, which is a major factor limiting the statistical power and generalizability of the conclusions.

Based on the subject group, the application domains and objectives also show clear differences.

Studies on professional athletes primarily focus directly on sport-specific competitive performance (swimming times, sprint explosive power, track & field PAPE) and injury prevention (e.g., reducing ACL injury risk) related to real-world athletic contexts (e.g., Yang et al., 2024; Moshashaei et al., 2024).

Studies on sports major students primarily aim to enhance basic physical performance capacities such as strength, explosive power, and anaerobic capacity (e.g., Wang Jingfeng, 2025; Sun Mingming, 2025). This is because this group possesses suitable training responsiveness to validate the performance-enhancing effects of tDCS.

Studies on healthy non-athletes tend to explore more fundamental mechanisms or general applicability, such as neuroplastic changes, motor learning, fatigue perception, sensorimotor function, or rehabilitation potential (e.g., Hendy et al., 2014; Xiao et al., 2022).

The differences in subjects also lead to tendencies in the final conclusions. Studies on professional athletes sometimes present conditional conclusions where effects are limited to specific indicators (Yang et al., 2024: insufficient aerobic endurance). Studies on sports students often clearly affirm the superiority of the combined application (e.g., Wu Koukou, 2023). Conversely, studies on healthy non-athletes often report limited or conditional effects, focusing on increased training volume or neuroplastic changes rather than maximal strength gains (e.g., Alix-Fages et al., 2020; Maeda et al., 2017).

In summary, tDCS combination research exhibits a hierarchy in objectives and conclusions based on the training level and specialization of the subjects, consistent with the trajectory from mechanism research (Hendy et al., 2013) to training enhancement effects (Wu Koukou, 2023) and actual competitive performance research (Yang et al., 2024).

3.2 Intervention Methods and Design

The types of training combined with tDCS show specific tendencies according to subject groups.

Research on professional athletes emphasizes sport-specific training. For example, Yang et al. (2024) applied composite training for basic strength, explosive power, and aerobic/anaerobic capacity in swimmers, while Moshashaei et al. (2024) applied neuromuscular training for taekwondo athletes.

Research on sports students concentrates on strength and explosive power enhancement, with active combination studies not only with traditional resistance training but also with specialized methods like blood flow restriction training (e.g., Wang Jingfeng, 2025; Wu Li, 2023).

Research on healthy non-athletes more frequently combines with basic, functional training (e.g., single-joint exercise, foot core training, high-load resistance training) to explore mechanisms (e.g., Hendy et al., 2014; Xiao et al., 2022; Zhou et al., 2021).

Regarding synchronicity, the off-line approach is relatively more common across all three groups. Among the 21 studies, 13 used the off-line method (e.g., professional athletes - Wang Zhuangzhuang, 2024; sports students - Sun Mingming, 2025; non-athletes - Zhou et al., 2021), which is attributed to methodological practicality. The on-line method was used in 8 studies, aiming to utilize "state-dependent plasticity." This approach was primarily used in studies on healthy non-athletes (Hendy et al., 2014; Yang Shilong, 2024). Among studies on sports students, there were no cases applying the on-line method; among studies on professional athletes, none except for Zhou Zheziao et al. (2025) used it.

The tDCS stimulation parameters applied in the studies show a highly standardized trend across all three subject groups. In terms of intensity, almost all studies used the range of 1.5–2.2 mA (mostly 2.0 mA); duration was typically set at 15–20 minutes; and site selection overwhelmingly favored the primary motor cortex. However, some studies varied based on specific goals. For instance, Alix-Fages et al. (2020) stimulated the left dorsolateral prefrontal cortex aiming to improve training volume and fatigue perception; Xiao et al. (2022) targeted Cz to explore sensorimotor integration.

There are also differences in the application period. Single-session studies primarily focus on confirming immediate effects. Studies on non-athletes, with the exception of Yang Shilong (2024) and Xiao et al. (2022), chose application periods of 4 weeks or less for combined application research. Long-term intervention studies, aiming to observe cumulative effects aligned with training cycles, were most frequently used in studies on sports students (e.g., Wu Koukou, 2023: 6 weeks; Wang Jingfeng, 2025: 4 weeks). Studies on professional athletes also mostly applied long-term interventions (e.g., Yang et al., 2024: 6 weeks).

In summary, while sharing a major trend of standardized approaches prioritizing practicality, the intervention designs in tDCS combination research also show strategic variations in training types and periods based on the characteristics of the subject group and specific research objectives. Notably, the almost complete absence of on-line applications in studies on sports students or professional athletes suggests a preference for off-line designs at the practical level.

3.3 Effects

The pattern of effects distinctly differs based on the training level and specialization of the subjects: professional athletes, sports students, and healthy non-athletes.

- **Professional Athletes:** In this group, the effects of combined application are evaluated against sport-specific and complex competitive performance elements. There is relatively consistent reporting of improvement effects on basic physical outputs like maximal strength, explosive power, and anaerobic capacity. However, effects on advanced elements like aerobic endurance or technical efficiency are often limited or unclear. Additionally, effects in protective aspects like injury prevention are explored, relating to the practical management of athletes undergoing high-intensity training.

- **Sports Major Students:** In this group, combined application shows the most consistent and significant positive effects on basic, standardized 'physical output' indicators such as strength, explosive power (vertical jump), and anaerobic capacity. This is because this group possesses both high potential for training response and is in a stage of developing foundational abilities. However, effects may be limited on some more refined indicators like relative strength or fatigue metrics.
- **Healthy Non-Athletes:** In this group, effects tend to manifest more in functional, neurophysiological indicators. For example, improvements in sensory function, neuroplastic changes related to strength in the untrained limb, increased training volume, and reduced subjective fatigue. Conversely, significant effects are typically not shown on indicators like maximal strength or complex motor skill learning. This is because in the untrained state of non-athletes, muscular capacity and motor coordination themselves are primary limiting factors.

Regarding interaction with training types, the synergistic effect of tDCS appears more pronounced when the training imposes higher demands on the central nervous system. Combining with blood flow restriction training or variable resistance training shows relatively better effects because these training modalities themselves induce neural adaptations. Conversely, purely mechanical high-load training may render the additional benefits of tDCS relatively smaller.

The relative superiority of combined application was confirmed in most studies across the three subject groups, but the mechanistic explanations may differ. For athletes and sports students, synergy between enhanced central drive and increased peripheral capacity may be the primary mechanism; for non-athletes, amplification of neural plasticity and optimization of training stimulus may play the main role.

Effects also vary based on the application period. Single applications are effective for immediate performance enhancement, primarily validated in non-athletes. Long-term applications lead to structural and sustained performance improvements, mainly validated in studies on sports students with regular training cycles and professional athletes with formal training periods.

In summary, the effects of tDCS combined application are not uniform but are precisely dependent on the type and level of adaptation required by the subject's training status. The most evident and consistent positive effects are seen in the improvement of basic physical output capacities in intermediate training-stage groups like sports students. This demonstrates the clear practical value of tDCS as a training enhancement tool. Conversely, for professional athletes targeting complex goals like advanced ability enhancement or injury prevention, and for non-athletes aiming to induce basic neural plasticity, its effects and limitations require more precise elucidation.

4. Limitations and Research Prospects

4.1 Methodological Limitations and Prospects

Limitations:

- **Small Sample Sizes and Subject Bias:** Studies in the sports domain predominantly use small samples (under 30 participants), resulting in low statistical power and limiting generalizability. In particular, research involving actual competition-level professional athletes is relatively scarce, lacking direct evidence for the ultimate goal of sports science – 'enhancing competitive performance.' Furthermore, subjects tend to be concentrated among sports students and healthy non-athletes, failing to fully reflect the applicability and limitations for elite athletes exposed to high-intensity training and competitive pressure.

- **Uniform Application of Standardized Protocols:** Most studies adopt the off-line method and a fixed set of stimulation parameters (2mA/20min/primary motor cortex), a choice based on practical convenience. However, there is a lack of systematic validation regarding synchronicity, specific application timing, and individualized stimulation conditions tailored to different subjects and purposes. Particularly for professional athletes, protocol design needs to consider complex training cycles and competition schedules.

Research Prospects:

- **Subject Diversification and Large-Scale Collaborative Research Design:** The ideal approach involves expanding samples to include elite professional athletes from various sports and conducting large-scale studies under common protocols through international multi-institutional collaborative networks. Within the sports student population, stratified research elucidating individual differences in training response is needed; within the healthy non-athlete population, precise experimental designs to elucidate fundamental mechanisms are required.
- **Research on Synchronicity and Individualized Protocols:** Direct comparisons of on-line versus off-line application effects are needed, along with the development of stimulation strategies suitable for the training characteristics of professional athletes. Furthermore, research on individualized tDCS protocols considering individual physiological characteristics should be conducted.

4.2 Theoretical and Mechanistic Limitations and Prospects

Limitations:

- **Superficial Mechanism Elucidation and Lack of Multi-Metric Measurement:** Current research focuses on behavioral outcomes, lacking a comprehensive understanding of how tDCS combined with training operates at neurophysiological and molecular biological levels. In particular, studies directly measuring neural adaptations specific to professional athletes or neuroplastic changes in sports students are rare.

- **Unclear Long-Term Effects and Adaptation Mechanisms:** Most studies are limited to mid-term effects of 4–8 weeks, with almost no data on the efficacy, tolerability, and persistence of effects after cessation of long-term application. This is a significant gap for professional athletes with long training cycles and for non-athlete populations requiring sustained health management.

Research Prospects:

- **Comprehensive Mechanism Elucidation via Multi-Modal Approaches:** There is a need to expand multi-measurement studies across subject groups to elucidate the causal pathway from brain excitability changes to peripheral muscular execution, and to construct mechanism models reflecting the characteristics of each group.
- **Longitudinal Studies and Deepening Exploration of Neuroplasticity Mechanisms:** Longitudinal tracking studies lasting several months to years are needed to assess the sustainability and safety of effects. Particularly for professional athletes, research considering pre-, mid-, and post-season cycles is needed; for sports students and non-athletes, research considering the lifespan and age-related changes is required.

4.3 Practical and Ethical Limitations and Prospects

Limitations:

- **Lack of Connection to Actual Competitive Performance:** Most studies evaluate effects in laboratory or controlled training environments using standardized tasks, lacking evidence on the applicability and contribution in real competition scenarios. This is the major practical limitation for research on professional athletes.

- **Gaps in Ethical Standards and Safety Guidelines:** The ergogenic use of tDCS may raise controversies regarding neuro-technological doping in sports. While not explicitly listed on the World Anti-Doping Agency's prohibited list currently, international ethical guidelines and regulatory frameworks concerning fair competition, athlete safety, and informed consent are entirely absent. This not only potentially affects professional athletes but could also become an obstacle for the expansion of educational applications for sports students and health promotion markets for the general public.

Research Prospects:

- **Expanding Research Validating Effects in Real Competition Environments:** Research should center on professional athletes, activating studies in actual competition simulations or small-scale field competitions. For sports students, effects in practical training integrated with educational curricula need evaluation; for non-athletes, research on effects improving activities of daily living is needed.
- **Interdisciplinary Research for Developing Sports Ethics Guidelines and Regulatory Systems:** Neuroscientists, sports ethicists, sports administrators, and legal experts need to collaborate to advance prospective discussions and guideline-development research on fair-use standards, safety protocols, athlete protection schemes, and international regulatory directions for tDCS. This is essential for creating a trustworthy application environment for all subject groups.

5. Conclusion

By analyzing the current state of research on the combined application of tDCS and physical training in the sports domain, this study confirms the field's development within a trend emphasizing practical outcomes. The combined application primarily demonstrates superior effects over tDCS or training alone in enhancing physical performance indicators like strength, explosive power, and anaerobic capacity, particularly in trained athletes and sports major students. This is interpreted as resulting from a complementary mechanism where enhanced central nervous system drive synergizes with peripheral muscular adaptation.

However, current research faces methodological limitations such as subject bias, small sample sizes, and rigid application of standardized stimulation parameters, along with numerous unresolved issues including translation to actual competitive performance, understanding individual response differences, long-term safety, and ethical standards.

Therefore, future research requires a paradigm shift from a "one-size-fits-all" application toward "precision personalized intervention." Developing dynamic protocols aligned with individual physiological characteristics and training goals, elucidating mechanisms using multi-modal technologies, validating effects in real competition contexts, and establishing international ethical guidelines will become core directions. Ultimately, research on tDCS combined application holds promise for contributing to a new academic and practical framework for exploring athletic performance potential through the integration of neuroscience and sports training.

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References

- Alix-Fages, C., García-Ramos, A., Calderón-Nadal, G., San Juan, A. F., & Colomer-Poveda, D. (2020). Anodal transcranial direct current stimulation enhances strength training volume but not the force-velocity profile. *European Journal of Applied Physiology*, *120*(8), 1881–1891.
- Cogiamanian, F., Marceglia, S., Ardolino, G., Barbieri, S., & Priori, A. (2007). Improved isometric force endurance after transcranial direct current stimulation over the human motor cortical areas. *European Journal of Neuroscience*, *26*(1), 242–249.
- Hendy, A. M., & Kidgell, D. J. (2013). Anodal tDCS applied during strength training enhances motor cortical plasticity. *Medicine & Science in Sports & Exercise*, *45*(9), 1721–1729.
- Hendy, A. M., & Kidgell, D. J. (2014). Anodal-tDCS applied during unilateral strength training increases strength and corticospinal excitability in the untrained homologous muscle. *Experimental Brain Research*, *232*(10), 3243–3252.
- Hendy, A. M., Teo, W. P., & Kidgell, D. J. (2015). Anodal transcranial direct current stimulation prolongs the cross-education of strength and corticomotor plasticity. *Medicine & Science in Sports & Exercise*, *47*(9), 1788–1797.
- Liu, J., Li, C., Fang, J., Zhou, Y., & Chen, X. (2024). Effects of physical training combined with transcranial direct current stimulation on maximal strength and lower limb explosive strength in healthy adults. *Frontiers in Sports and Active Living*, *6*, 1446588.
- Maeda, K., Yamaguchi, T., Tatemoto, T., Kondo, K., & Otaka, Y. (2017). Transcranial direct current stimulation does not affect lower extremity muscle strength training in healthy individuals: A triple-blind, sham-controlled study. *Frontiers in Neuroscience*, *11*, 179.
- Marcos-Frutos, D., López-Alonso, V., Mera-González, I., & Fernández-del-Olmo, M. (2023). Chronic functional adaptations induced by the application of transcranial direct current stimulation combined with exercise programs: A systematic review of randomized controlled trials. *Journal of Clinical Medicine*, *12*(21), 6724.
- Moshashaei, M. S., Gandomi, F., Amiri, E., & Bagheri, R. (2024). Anodal tDCS improves the effect of neuromuscular training on the feedforward activity of lower extremity

muscles in female taekwondo athletes with dynamic knee valgus. *Scientific Reports*, *14*(1), 20007.

- Ni, L., Li, D., Wu, K., et al. (2022). Effect of transcranial direct current stimulation combined with squat training on lower limb anaerobic power. In *Chinese Society of Sports Science, Abstract Compilation of the 12th National Sports Science Conference – Poster Exchange (Physical Training Branch)* (pp. 41–42). Wuhan Sports University.
- Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*, *527*(Pt 3), 633–639.
- Qi, S., Yu, J., Li, L., Liu, Y., & Zhang, X. (2024). Advances in non-invasive brain stimulation: Enhancing sports performance function and insights into exercise science. *Frontiers in Human Neuroscience*, *18*, 1477111.
- Reis, J., Schambra, H. M., Cohen, L. G., Buch, E. R., Fritsch, B., Zarahn, E., Celnik, P. A., & Krakauer, J. W. (2009). Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(5), 1590–1595.
- Smorawiński, J., Kaciuba-Uściłko, H., Nazar, K., Kubica, R., Greenleaf, J. E., Kruk, B., & Chwalbińska-Moneta, J. (2000). Effects of three-day bed rest on metabolic, hormonal and circulatory responses to an oral glucose load in endurance or strength trained athletes and untrained subjects. *Journal of Physiology and Pharmacology*, *51*(2), 279–289.
- Steinberg, F., Pixa, N. H., & Fregni, F. (2019). A review of acute aerobic exercise and transcranial direct current stimulation effects on cognitive functions and their potential synergies. *Frontiers in Human Neuroscience*, *12*, 534.
- Sun, M. (2025). *Effect of anodal transcranial direct current stimulation combined with blood flow restriction training on lower limb explosive power* [Master's thesis, Jianghan University].
- Vitor-Costa, M., Okuno, N. M., Bortolotti, H., Bertollo, M., Sobral, P. R., & Altimari, L. R. (2015). Improving cycling performance: Transcranial direct current stimulation increases time to exhaustion in cycling. *PLoS ONE*, *10*(12), e0144916.
- Wang, B., Xiao, S., Yu, C., Zhou, J., & Fu, W. (2021). Effects of transcranial direct current stimulation combined with physical training on the excitability of the motor cortex, physical performance, and motor learning: A systematic review. *Frontiers in Neuroscience*, *15*, 648354.

- Wang, J. (2025). *Research on the effect of tDCS combined with blood flow restriction training on upper limb strength in male college students* [Master's thesis, Jianghan University].
- Wang, Z. (2024a). *Effect of transcranial direct current stimulation combined with variable resistance training on lower limb explosive power in sprinters* [Master's thesis, Wuhan Sports University].
- Wang, Z. (2024b). *Effect of transcranial direct current stimulation (tDCS) combined with strength training on the vertical jump ability of university athletes* [Master's thesis, Capital University of Physical Education and Sports].
- Washabaugh, E. P., Santos, L., Claflin, E. S., & Krishnan, C. (2016). Low-level intermittent quadriceps activity during transcranial direct current stimulation facilitates knee extensor force-generating capacity. *Neuroscience*, *329*, 93–97.
- Wu, K. (2023). *Research on the effect of anodal transcranial direct current stimulation combined with unilateral training on lower limb explosive power in male sports college students* [Master's thesis, Wuhan Sports University].
- Wu, L. (2023). *Effect of transcranial direct current stimulation combined with blood flow restriction training on skeletal muscle strength and anaerobic exercise capacity* [Master's thesis, Jianghan University].
- Xiao, S., Wang, B., Yu, C., Zhang, X., & Fu, W. (2022). Effects of intervention combining transcranial direct current stimulation and foot core exercise on sensorimotor function in foot and static balance. *Journal of NeuroEngineering and Rehabilitation*, *19*(1), 98.
- Xing, Y., & Xie, E. (2025). Effect of tDCS combined with exercise intervention on vertical jump height in physical education major students. *Journal of Anhui Sports Science*, *46*(2), 7–10, 20.
- Yang, S. (2024). *Effect of transcranial direct current stimulation combined with the 3/7 strength training method on lower limb maximal strength in male college students* [Master's thesis, Capital University of Physical Education and Sports].
- Yang, X., Wu, J., Tang, Y., Shen, Y., & Zhang, H. (2024). Effects of anodic transcranial direct current stimulation combined with physical training on the performance of elite swimmers. *Frontiers in Physiology*, *15*, 1383491.

- Zhou, Y. (2021). *Effects of Halo Sport2 tDCS headphones combined with resistance training on vertical jump performance in male college students* [Master's thesis, Beijing Sport University].
- Zhou, Y., Zhai, H., & Wei, H. (2024). Acute effects of transcranial direct current stimulation combined with high-load resistance exercises on repetitive vertical jump performance and EEG characteristics in healthy men. *Life*, *14*(9), 1106.
- Zhou, Z., & Liu, D. (2025). Effects of "neuro-enhancement" perspective: Transcranial direct current technology combined with loaded resistance on post-activation performance enhancement in male track and field athletes. *Journal of Beijing Sport University*, *48*(5), 107–119.