Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

The Effects of Transcranial Direct Current Stimulation (tDCS) on Lower-Body Explosive Power and Kicking Impact Force in Taekwondo Athletes: A Randomised Controlled Trial

Fallahi Ahmad

afallahi@znu.ac.ir

University of Zanjan

Alizadehgoradel Jaber

University of Zanjan

Ghorbanlu Roma

Alzahra University

Saboorinia Mahshid

University of Zanjan

Shiri-Yekta Mina

Shahid Beheshti University

Article

Keywords: Transcranial Direct Current Stimulation (tDCS), Taekwondo Performance, Kicking Impact Force, Explosive Power

Posted Date: November 16th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9534035/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

The Effects of Transcranial Direct Current Stimulation (tDCS) on Lower-Body Explosive Power and Kicking Impact Force in Taekwondo Athletes: A Randomised Controlled Trial

Fallahi, Ahmad*[1]; Alizadehgoradel, Jaber[2]; Shiri-Yekta, Mina[3]; Saboorinia, Mahshid[4]; Ghorbanlu, Roma[5]

1. Department of Sport Science, Faculty of Humanities, University of Zanjan, Zanjan, Iran
2. Department of Psychology, Faculty of Humanities, University of Zanjan, Zanjan, Iran.
3. M.A. Student in Cognitive Psychology, Institute for Cognitive and Brain Sciences, Shahid Beheshti University, Tehran, Iran.
4. B.Sc. Student in Sports Sciences, Faculty of Humanities, University of Zanjan, Zanjan, Iran.
5. M.A. Student in General psychology, Alzahra University, Tehran, Iran.

Correspondence

Ahmad Fallahi, Department of Sport Science, University of Zanjan, Zanjan, Iran.

Email: afallahi@znu.ac.ir

Abstract

Enhancing lower-body explosive power and kicking force is critical for success in Taekwondo. Although transcranial direct current stimulation (tDCS) can modulate motor performance, its effects on sport-specific metrics in elite athletes remain unexplored. This randomized, sham-controlled, double-blind trial investigated the effects of multi-session anodal tDCS on jump performance and kicking force in competitive male Taekwondo athletes. Thirty male athletes (mean age 19.3 years; ≥4 years of experience) were randomly assigned to active tDCS (n=15) or sham (n=15). The intervention comprised ten sessions of 2 mA, 20-minute anodal tDCS over FCz (supplementary motor area), delivered twice daily for five days. Lower-limb explosive power was assessed using the Standing Long Jump test, and kicking impact force for both legs was measured using an electronic body protector (Hugo system). The active tDCS group showed significantly greater improvements in jump distance than the sham group ($p=0.035$). Significant Time × Group interactions were also observed for kicking force to the torso ($p=0.007$) and head ($p=0.037$), indicating greater force gains in the tDCS group for both legs. These findings demonstrate that multi-session anodal tDCS over the fronto-central region enhances sport-specific neuromuscular performance in trained Taekwondo athletes, supporting tDCS as a promising adjunct for improving explosive power and ballistic skills in competitive training.

Trial Registration: **IRCT20260119068612N1**

Funding: The author received No Funding for this work.

Keywords: Transcranial Direct Current Stimulation (tDCS), Taekwondo Performance, Kicking Impact Force, Explosive Power

Introduction

Martial arts represent a rapidly expanding segment of global sport participation, attracting large audiences and receiving increasing scientific attention. Among them, taekwondo stands out as one of the most widely practiced and competitively demanding Olympic disciplines. Historically rooted in military self-defense, taekwondo has evolved into a modern high-performance sport characterized by fast-paced bouts and an extensive repertoire of explosive kicking techniques [1,2]. Because competitive success depends on rapid information processing, precise motor control, and the ability to generate high levels of power under time pressure, understanding how to optimize neuromuscular performance in taekwondo athletes remains a critical priority for coaches and researchers.

Sports performance is inherently multifactorial, reflecting the dynamic integration of physical, physiological, cognitive, and psychological processes. A substantial body of evidence demonstrates that high-level athletic execution depends strongly on the functional interaction between the central nervous system and the musculoskeletal system [3,4]. In this context, motor skill learning -defined as the process through which the brain acquires, refines, and stabilizes movement patterns- is essential for technical proficiency and long-term athletic development. Motor learning involves adaptive modifications in distributed neural networks, including the primary motor cortex (M1), supplementary motor area (SMA), cerebellum, and dorsolateral prefrontal cortex (DLPFC), supported by changes in functional connectivity and synaptic efficiency [5,6]. These neuroplastic changes play a central role in improving balance, coordination, timing, and explosive movement execution -factors that are particularly critical in taekwondo performance.

In recent years, rapid advances in applied neuroscience have introduced new opportunities to enhance athletic performance through non-invasive brain stimulation (NIBS). Among NIBS techniques, transcranial direct current stimulation (tDCS) has gained considerable interest due to its safety, affordability, and potential to modulate cortical excitability in a polarity-specific manner. tDCS delivers a low-amplitude direct current (typically 1–2 mA) through scalp electrodes for 10–30 minutes, producing aftereffects on neuronal membrane polarization that can last for several hours [7,8]. Anodal stimulation is generally associated with increased cortical excitability, whereas cathodal stimulation tends to reduce it, although emerging evidence suggests possible nonlinear and region-dependent effects [9].

Recent empirical work supports the notion that tDCS may enhance lower-limb explosive performance under specific conditions. For example, a study using bilateral extracephalic anodal tDCS (2 mA, 20 min) in healthy young adults demonstrated significant increases in countermovement jump (CMJ) height, along with improvements in lower-limb net energy, knee power, and hip torque — suggesting more efficient force generation and energy transfer across joints [10]. Also, in a sample of professional female volleyball players, anodal tDCS over the primary motor cortex (M1) for 20 min at 2 mA enhanced both CMJ height and spike performance compared with sham, indicating that neuromodulation can augment both generic and sport-specific explosive outputs [11].

Nevertheless, the literature is far from conclusive. A triple-blinded randomized study in soccer players applying 2 mA M1-tDCS for 15 min found no significant change in CMJ performance compared with sham [12]. Similarly, a crossover investigation of healthy young men reported no effect of 15-min DLPFC-targeted tDCS on CMJ height or peak power (Romero [13]. Moreover, a recent randomized controlled trial investigating the effects of long-term anodal tDCS over the primary motor cortex combined with physical training in healthy adults found that although both the active (tDCS + training) and sham (sham tDCS + training) groups improved significantly in muscular strength, endurance, and lower-limb explosive power, intergroup comparisons revealed no additional benefit of tDCS, indicating that the stimulation protocol did not enhance performance beyond training alone [14]. This heterogeneity likely arises from multiple interacting moderators:

Montage and stimulation configuration play a critical role: Bilateral or extracephalic montages (e.g., bilateral M1 with extracephalic reference) tend to more effectively engage distributed neuromuscular networks controlling the lower limbs, potentially enhancing coordinated contributions from hip, knee, and ankle joints [15]. Computational modeling suggests that extracephalic montages increase current density in deeper cortical and subcortical regions, while bilateral or dual-site montages may yield greater motor learning gains than unilateral configurations [16]. However, these effects reflect neurophysiological potential rather than guaranteed functional improvements, which are also shaped by task complexity, athlete training status, and stimulation parameters.

Task demands and specificity: Although there is evidence that tDCS can influence motor performance, its impact appears to depend heavily on the nature of the task. A recent

umbrella review concluded that while many studies report small acute gains in psychomotor performance with tDCS, the effects are highly variable and may not hold under tasks that require complex, multi-joint coordination or high neuromuscular demands [17]. Similarly, in sport settings, improvements have been more consistently reported for relatively simple or repetitive tasks rather than for complex, coordinated movements [18]. These observations highlight that sport-specific, ballistic or multi-joint actions (e.g., kicks, explosive long jumps) may respond differently -possibly less predictably- to tDCS compared with simpler tasks such as vertical jump or isometric strength tests.

Participant training status and baseline: Inter-individual differences and athletic background are among the main factors moderating tDCS effects. As noted by Lewis, et al. [18], athletes with highly trained neuromuscular systems may exhibit ceiling effects, limiting the potential benefit from neuromodulation. When baseline performance is already optimized (e.g., in elite or well-trained athletes), incremental gains from tDCS may be minimal or undetectable. In contrast, among less-trained or recreational individuals -whose neuromuscular efficiency and coordination patterns are more plastic- tDCS may produce more observable effects. This variability complicates generalizing tDCS benefits across populations and underscores the need for athlete-specific investigations.

Dose and timing (single vs repeated sessions): The effectiveness of tDCS depends on current intensity, duration, and session frequency. Single-session tDCS often produces small, transient effects on corticospinal excitability and motor output [19]. In contrast, repeated sessions, especially when combined with training, induce more stable neuroplastic changes and cumulative performance gains [20,21]. These findings suggest that multi-session protocols are more likely to enhance explosive power, inter-joint coordination, and sport-specific motor skills than single applications [18].

Despite growing evidence that tDCS can enhance general lower-limb explosive performance [10,11], few studies have examined sport-specific ballistic movements requiring complex multi-joint coordination. In taekwondo, kick effectiveness depends not only on leg strength but also on rapid, coordinated activation of hip, knee, and ankle joints, proximal-to-distal sequencing, and trunk–limb synchrony [22,23]. This biomechanical complexity limits the applicability of findings from simple jump or sprint tasks to martial-arts performance. Accordingly, there is limited

information regarding the effects of tDCS on kicking impact force and lower limb explosive power (e.g., long jump) in trained combat athletes. These outcomes require precise inter-joint coordination, rapid neuromuscular activation, and trunk–limb synchrony, and are directly relevant to competitive performance. The lack of empirical data in this context highlights a critical gap in understanding how neuro-modulatory interventions might translate into sport-specific performance improvements.

Therefore, the primary objective of this randomized controlled trial was to determine the effects of a multi-session anodal tDCS protocol (2 mA, 20 min per session) applied over the fronto-central motor area (FCz) on sport-specific performance measures in competitive taekwondo athletes. We hypothesized that, compared with the sham stimulation group, participants receiving active tDCS would demonstrate:

- A significantly greater improvement in lower-body explosive power, as assessed by the Standing Long Jump test.
- A significantly greater increase in kicking impact force for both dominant and non-dominant lower limbs, during strikes directed to the torso and head.

Material and Method

Trial Design

The study employed a randomized, double-blind, sham-controlled, parallel-group design with a pretest–posttest assessment structure. Participants were randomly assigned in a 1:1 allocation ratio to either the experimental (active tDCS) or the sham (placebo) group. No important changes to the methods or trial design were made after the trial commenced.

Sample Size Determination

The sample size of 15 participants per group was determined a priori using GPower software (version 3.1.9.7) [24] Based on previous research investigating tDCS effects on explosive and lower-limb performance in athletes, which reported medium-to-large effect sizes [25, 26] a conservative effect size (f) of 0.40 was anticipated for the primary outcomes. For a repeated-measures ANOVA (within–between interaction) with an alpha level of 0.05 and power of 0.80, yielded a minimum total sample size of 28. To account for potential attrition, we initially recruited 32 participants.

Participants

Initially, 32 eligible male taekwondo athletes were enrolled in the study. Participants were recruited from taekwondo clubs in Zanjan City, Iran. The inclusion criteria were: age between 18 and 23 years, at least 4 years of experience in provincial or national taekwondo championships, and holding at least a red or black belt. Exclusion criteria included any history of neurological or psychiatric disorders, contraindications to tDCS (e.g., metal implants in the head, history of brain surgery), or other major health issues, as assessed through a structured interview.

During the intervention phase, two participants withdrew: one due to contracting influenza and the other due to unwillingness to continue with the stimulation sessions. Consequently, data from 30 participants (mean age = 19.27 ± 1.76 years) who completed the entire protocol were included in the final analysis. All participants provided written informed consent prior to enrollment.

Randomization and Group Assignment

A computer-generated random allocation sequence was created by an independent statistician not involved in recruitment or testing, using a blocked randomization procedure with a fixed block size of 4 to ensure balanced group sizes over time.

The allocation sequence was concealed using sequentially numbered, opaque, sealed envelopes. Each envelope contained a card indicating the group assignment (Experiment or Sham).

After obtaining informed consent and completing the baseline assessment, a research assistant who was not involved in outcome assessment opened the next consecutively numbered envelope in the presence of the participant to reveal the group assignment. Participants were then immediately introduced to the intervention administrator. Thus, the sequence was generated by an independent statistician, participants were enrolled by the principal investigator, and group assignment was performed by a research assistant.

Intervention

Participants in the experimental group underwent anodal tDCS sessions targeting the fronto-central motor area (FCz), likely engaging premotor and supplementary motor regions, with the extracephalic reference electrode positioned on the right shoulder. The intervention comprised 10 sessions of anodal tDCS (2 mA, 20 min) administered over the FCz area. Sessions were delivered twice daily for five consecutive days, with a 20-minute interval between the two daily sessions.

Conversely, the sham group utilized the identical electrode montage; however, to ensure participant blinding, the current was only applied briefly. Specifically, the device ramped up over 30 seconds, delivered 2 mA for 15 seconds, and ramped down over 30 seconds before remaining off, thereby replicating the somatic sensations of active stimulation without inducing sustained effects.

Outcomes

The pre-specified primary outcome measure was lower-body explosive power, assessed by the Standing Long Jump test. The pre-specified secondary outcome measure was maximal kicking impact force, assessed for four specific kicks (dominant/non-dominant leg to torso/head) using the Electronic Hugo system. All outcomes were assessed at two time points: at baseline (pre-test) and immediately after the final intervention session (post-test). No changes to these trial outcomes were made after the trial commenced.

Blinding

Participants and outcome assessors were blinded to group assignment. However, due to the technical requirements of operating the device and selecting the correct pre-programmed protocol (active or sham), the tDCS administrator was necessarily unblinded. To minimize potential bias arising from this, the following procedures were implemented:

- The administrator followed a strict, standardized script for interaction with all participants and was instructed not to discuss any aspect of the stimulation (e.g., sensations, expectations) beyond basic safety checks.

- The sham protocol was designed to credibly replicate the initial sensory experience of active tDCS (tingling, itching), thereby effectively blinding the participants.

- Outcome assessors were not present during any stimulation sessions and remained unaware of group allocation throughout the data collection and analysis phases.

- The interventions were identical in appearance (electrode placement, device) from the participant's perspective.

Interpretation of the results should consider that performance assessments were objective and instrument-based (e.g., jump distance, electronic force sensors), which are less susceptible to observer bias than subjective measures.

Instruments

tDCS- Transcranial direct current stimulation (tDCS) was administered via a battery-powered constant-current stimulator (ActivaDose II, Bayamed, Alborz). For the active condition, a 2 mA current was delivered for 20 minutes, including 30-second ramp-up and ramp-down phases. The anode (5 ×7 cm) was positioned over the fronto-central motor area (FCz), likely engaging premotor and supplementary motor regions, localized according to the international 10–20 EEG system, while the cathode was placed extra-cephalically over the right shoulder.

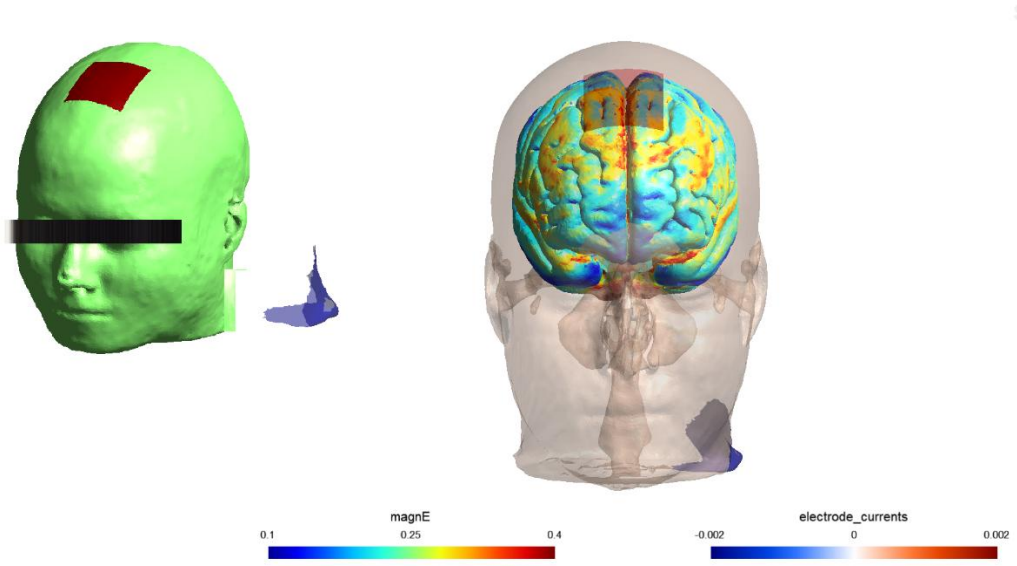


Figure 1. *Simulated electric field distribution on the cortical surface. The anodal electrode (5 × 7 cm) was placed over the fronto-central motor area (FCz), and the cathode was positioned extra-cephalically on the right shoulder (approximated at the base of the neck in the model). The simulation (SimNIBS 4.5) demonstrates a focused electric field over the target motor planning areas with a peak magnitude of approximately 0.40 V/m.*

To ensure low impedance and optimal conductivity, electrodes were encased in sponges saturated with saline solution. The sham protocol utilized an identical configuration; however, to maintain participant blinding, the current was ramped up for 30 seconds, maintained at 2 mA for 15 seconds, and then ramped down over 30 seconds to replicate the characteristic tingling sensation without delivering therapeutic stimulation.

Electronic Hugo- Kicking performance was evaluated using an electronic scoring system (HTS Chest Protector/HTS Hugo), which is commonly used in Taekwondo competitions. This system, equipped with chest protectors containing integrated impact sensors, measured kicking force in Newtons. The sensors were embedded in key target areas to ensure accurate detection and

quantification of impacts. Data were collected in real time and stored digitally for later analysis. Overall, the system provided a valid and reliable assessment of kicking force for both dominant and non-dominant legs during the pre- and post-test evaluations.

Procedure

Baseline Assessment- Prior to the intervention, all participants underwent baseline assessments. These assessments included:

- *Athlete's Competitive History:* Recording each taekwondo athlete's competition level, events participated in, and their most recent medal and competition ranking.
- *Anthropometric Measurements*: Body height and body weight were measured using standard procedures.

Pre-test and Post-test Physical Assessment- (The present data were part of a larger testing protocol designed to assess various physical and neuro-motor performance parameters in taekwondo athletes. The current analysis focuses specifically on Lower Body Explosive Power and Kicking Impact Force, while other outcomes e.g., Static Balance, Reaction Time and Quickness will be addressed separately).

Physical assessments were conducted at two time points: prior to the intervention (pre-test) and immediately following its completion (post-test). All assessment sessions were scheduled between 5:00 PM and 10:00 PM to minimize potential variability caused by circadian rhythm fluctuations. Assessments took place at the Taekwondo Provincial House of Zanjan. Pre-test evaluations were conducted during the initial session, and post-test assessments were administered following the final intervention session. To ensure consistency and comparability, both pre- and post-tests were performed in an identical sequence. Participants were instructed to exert maximal effort while maintaining correct technique throughout all procedures. Each test was administered under the supervision of trained evaluators to ensure precision and reliability. The standardized assessment protocol was as follows:

- Warm-up: 10 minutes of general dynamic exercises
- Standing Long Jump Test: three valid attempts
- Rest Period: 3 minutes
- Balance Test
- Rest Period: 3 minutes

- Kicking Impact Force Test using the Hugo device: two attempts for torso kicks and two for head kicks
- Rest Period: 3 minutes
- Reaction Time and Quickness Test: 10 repetitions

Physical Performance Assessments: To comprehensively evaluate participants' physical performance, a series of standardized tests were administered to measure key attributes. The following subsections describe each test, its procedure, and the criteria used for data collection.

Lower Body Explosive power- Explosive power of the legs was assessed using the Standing Long Jump test. Athletes stood behind a designated line, prepared for the jump by bending their knees and performing coordinated arm swings, then executed the jump. The landing position was determined by the first point of contact with the ground. Each participant performed three attempts with minimal rest between jumps, and the best distance was recorded for analysis.

Kicking Impact Force Assessment- Maximal Kicking Impact Force was assessed using a taekwondo-specific protocol involving electronic Hugo (HTS Chest protector) equipped with calibrated sensors. The sequence of strikes included four distinct kicks: (1) an Ap Dollyo Chagi kick to the torso with the dominant leg, (2) an Ap Dollyo Chagi kick to the torso with the non-dominant leg, (3) a Dollyo Chagi kick to the head with the dominant leg, and (4) a Dollyo Chagi kick to the head with the non-dominant leg. Participants were instructed to perform each kick with maximal effort while maintaining technical precision. The target mannequin was fitted with electronic scoring sensors on both the torso and head, consistent with official World Taekwondo competition standards. Each participant performed the full sequence once. The sensors automatically captured and recorded the peak impact force of each kick in Newtons (N). These values were used as indicators of Kicking Impact Force and were subsequently analyzed as four separate variables.

Data analysis

The normality of all variables was assessed using the Shapiro–Wilk test, and potential outliers were examined via stem-and-leaf plots. All variables met the assumption of normal distribution ($p > 0.05$) and no outliers were identified. Homogeneity of variances was verified using Levene's test, and sphericity assumptions for repeated measures were evaluated using Mauchly's test.

Given the study's pre-test/post-test design with control (sham) and experimental (tDCS) groups, repeated measures ANOVA (RM-ANOVA) was employed to examine changes over time, including main effects of Time, Leg (dominant vs. non-dominant), and their interactions with Group. To adjust for baseline differences, analysis of covariance (ANCOVA) was conducted with pre-test scores as covariates.

Effect sizes were reported as partial eta squared (η^2) for RM-ANOVA and ANCOVA. Additionally, within-group changes were quantified using Cohen's d. All analyses were performed using SPSS version 22 (IBM Corp., Armonk, NY) with a significance threshold set at $p < 0.05$.

Language Editing

We used ChatGPT (OpenAI, GPT-5 mini, January 2026 version) to assist in language editing and sentence refinement. All scientific content, experimental design, data analysis, interpretation, and conclusions were independently authored by the research team. ChatGPT was not involved in any conceptual or intellectual aspects of the research.

Findings

Participant Flow

Out of 32 eligible athletes, 30 were randomly assigned to either the active tDCS group or the sham tDCS group. Two participants withdrew after randomization (one due to influenza and the other due to unwillingness to continue the intervention), resulting in 15 participants per group (total n=30) who completed the entire protocol. All analyses were performed on a per-protocol basis, including only those who completed the study (Fig. 2).

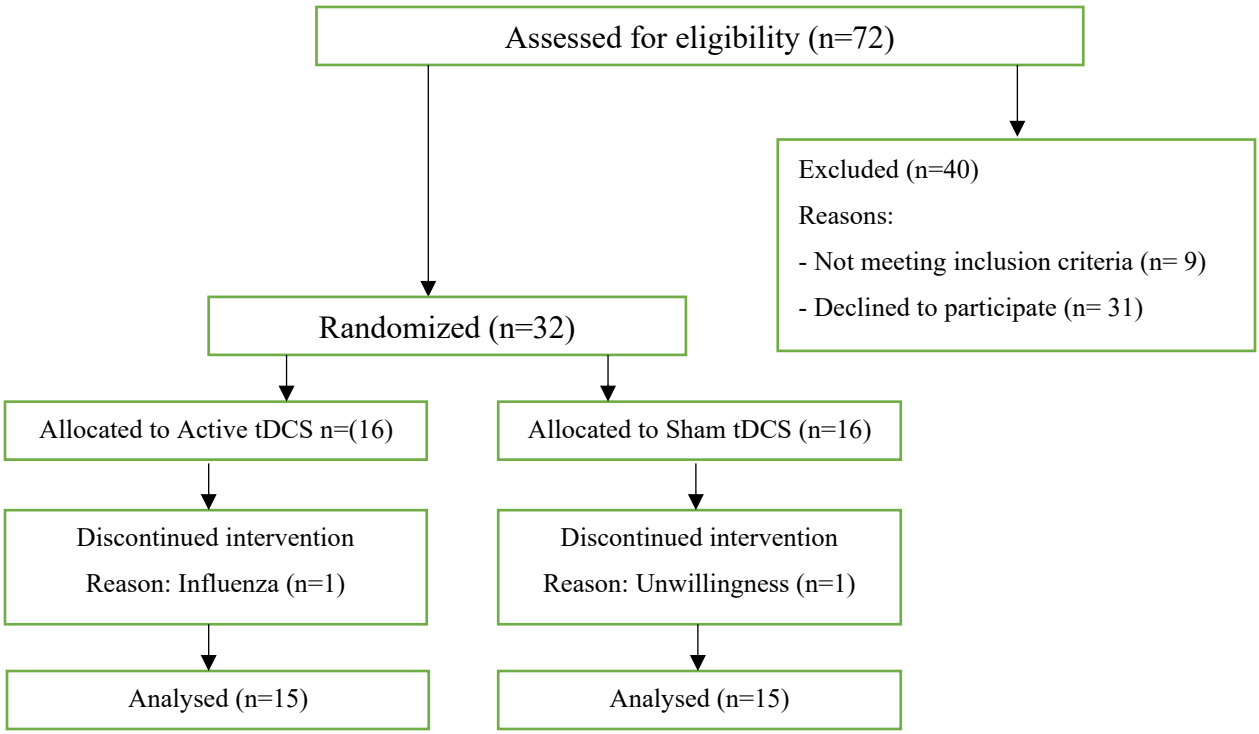


Figure 2. Participant Flow

Study Dates

Participant recruitment took place over approximately six months, from January 2025 to July 2025. Post-intervention assessments were conducted immediately following the final stimulation session.

Side Effects

Self-reported side effects following tDCS are summarized in Table 1. Participants rated the intensity of each side effect on a 0–5 scale (0 = none, 5 = severe). Overall, tDCS was well tolerated. The most frequently reported side effects were fatigue (Mean = 0.77, SD = 1.18) and tingling sensation (Mean = 0.67, SD = 0.96). Other side effects, including burning sensation, pain, redness, and problems with focus, were reported less frequently and with lower intensity (Table 1).

Table 1. Descriptive statistics of self-reported side effects following tDCS (N = 30, 0–5 scale)

Side Effect	N	Minimum	Maximum	Mean	SD
Burning sensation	30	0	4	0.62	1.09
Fatigue	30	0	5	0.77	1.18
Tingling	30	0	4	0.67	0.96
Pain	30	0	2	0.38	0.61
Redness	30	0	1	0.08	0.25
Focus problems	30	0	4	0.40	1.07

Baseline Characteristics

The baseline demographic and performance characteristics of participants in both groups are presented in Table 2. As shown, the two groups were homogenous at baseline with respect to age, height, weight, and all primary and secondary performance outcome measures (standing long jump and kicking impact force under various conditions). Statistical comparisons confirming this homogeneity are presented in the subsequent inferential analysis section.

Complete data sets for all baseline and outcome variables were available for all 15 participants in each group (total n=30). No missing or outlier data were encountered for these measures. Baseline assessments of lower-body explosive power and kicking impact force demonstrated that all variables were normally distributed according to the Shapiro–Wilk test ($p > 0.05$).

Table 2. Baseline Demographic and Performance Characteristics of Participants by Group

Variable	tDCS Group (n=15)	Sham Group (n=15)
Age (years)	19.3 ± 2.0	19.3 ± 1.6
Height (cm)	179.1 ± 8.0	180.6 ± 6.8
Weight (kg)	68.3 ± 12.9	71.4 ± 14.6
Standing Long Jump - Pre-test (m)	2.41 ± 0.11	2.34 ± 0.21
Kicking Force (Dominant Leg to Torso) - Pre-test (N)	54.9 ± 2.3	54.5 ± 2.7
Kicking Force (Non-dominant Leg to Torso) - Pre-test (N)	49.1 ± 3.9	51.7 ± 4.2
Kicking Force (Dominant Leg to Head) - Pre-test (N)	52.9 ± 2.5	52.2 ± 3.5
Kicking Force (Non-dominant Leg to Head) - Pre-test (N)	51.1 ± 4.5	51.1 ± 4.1

Data are presented as Mean ± Standard Deviation.

Lower Body Explosive Power; Long Jump Performance

Descriptive statistics for the raw pre-test and post-test long jump scores for both groups are presented in Table 3. Visual inspection of the means suggests improvement in both groups from pre- to post-test, with a larger mean increase observed in the tDCS group.

Table 3. Descriptive Statistics for Standing Long Jump Performance by Group and Time

Group	Pre-test, Mean (SD)	Post-test, Mean (SD)
tDCS	2.41 (0.11) m	2.54 (0.11) m
Sham	2.34 (0.21) m	2.43 (0.16) m

SD = Standard Deviation; m = meters.

A 2 (Time: Pre, Post) × 2 (Group: tDCS, Sham) repeated-measures ANOVA was conducted to evaluate the effects of time and the intervention. The analysis revealed a statistically significant

main effect of Time, $F_{(1, 28)} = 36.95$, $p < 0.001$, partial $\eta^2 = 0.569$, 95% CI [0.31, 0.70]. This indicates a significant improvement in jump distance from pre-test to post-test across all participants. However, the Time × Group interaction was not statistically significant, $F_{(1, 28)} = 1.48$, $p = 0.234$, partial $\eta^2 = 0.050$, 95% CI [0.00, 0.22]. This result suggests that the rate of improvement over time was not statistically different between the two groups when analyzed with this model (Table 4).

Table 4. Repeated-Measures ANOVA (Within-Subjects Effects) for Long Jump

Source	Type III SS	df	Mean Square	*F*	Sig.	Partial η^2	95% CI for η^2
Time	0.187	1	0.187	36.953	<0.001	0.569	[0.31, 0.70]
Time×Group	0.007	1	0.007	1.478	0.234	0.050	[0.00, 0.22]
Error(Time)	0.142	28	0.005				

Given the importance of baseline scores in athletic performance studies, an analysis of covariance (ANCOVA) was conducted to provide a more sensitive comparison of post-test performance while statistically controlling for pre-test scores. The dependent variable was the post-test score, with Group as the fixed factor and the pre-test score as the covariate (Table 5). The assumptions of linearity and homogeneity of regression slopes were met (Interaction term: Group × Pre-test, $p > 0.05$). Homogeneity of variance for the post-test was confirmed by Levene's test ($F_{(1, 28)} = 3.227$, $p = 0.083$). The ANCOVA yielded a statistically significant main effect of Group on the adjusted post-test means, $F_{(1, 27)} = 4.91$, $p = 0.035$.

Table 5. ANCOVA Results for Post-Test Long Jump with Pre-Test as Covariate

Source	Type III Sum of Squares	df	Mean Square	*F*	p	Partial η^2	95% CI for Partial η^2
Corrected Model	0.462	2	0.231	33.153	<0.001	0.711	[0.52, 0.81]
Intercept	0.123	1	0.123	17.615	<0.001	0.395	[0.14, 0.59]
Pre-Test Score	0.360	1	0.360	51.664	<0.001	0.657	[0.41, 0.78]
Group	0.034	1	0.034	4.907	0.035	0.154	[0.01, 0.38]
Error	0.188	27	0.007				
Total	185.907	30					
Corrected Total	0.651	29					

Note. $R^2 = .711$ (Adjusted $R^2 = .689$).

The effect size was medium (partial $\eta^2 = 0.154$, 95% CI [0.01, 0.38]). The pre-test score (covariate) was a highly significant predictor, $F_{(1, 27)} = 51.66$, $p < 0.001$, partial $\eta^2 = 0.657$, 95% CI [0.41, 0.78], confirming the necessity of controlling for baseline ability. The full model explained 71.1% of the variance in post-test scores ($R^2 = .711$, Adjusted $R^2 = .689$).

The parameter estimates from the ANCOVA model (Table 6) indicated that, after adjusting for pre-test performance, assignment to the tDCS group was associated with a significant increase of 0.069 meters in post-test jump distance compared to the Sham group (B = 0.069, p = 0.035, 95% CI [0.005, 0.133]).

To quantify the magnitude of change within each group, paired-samples Cohen's d was calculated. The tDCS group showed a very large improvement (d = 1.26, 95% CI [0.65, 1.86]), while the Sham group showed a moderate improvement (d = 0.41, 95% CI [-0.11, 0.92]). The estimated marginal means (adjusted for the covariate) indicated superior post-test performance for the tDCS group (M = 2.54, SE = 0.02) compared to the Sham group (M = 2.43, SE = 0.02).

Table 6. Parameter Estimates from the ANCOVA Model

Parameter	B (m)	Std. Error	t	Sig.	95% CI for B (Lower, Upper)	Partial η^2
Intercept	0.883	0.216	4.091	<0.001	(0.440, 1.326)	0.383
Pre-Test Score	0.660	0.092	7.188	<0.001	(0.472, 0.849)	0.657
Group [tDCS]	0.069	0.031	2.215	0.035	(0.005, 0.133)	0.154
Group [Sham]	0a	-	-	-	-	-

a Reference category.

In summary, the repeated-measures ANOVA confirmed significant improvement over time for all participants but did not detect a differential rate of improvement between groups. However, the more sensitive ANCOVA -which controlled for baseline performance- revealed a statistically significant advantage for the active tDCS group over the sham control group at post-test. This finding, supported by a medium effect size and a substantially larger within-group improvement in the tDCS condition, suggests that the multi-session anodal tDCS intervention had a positive effect on lower-body explosive power beyond practice or placebo effects (figure 3).

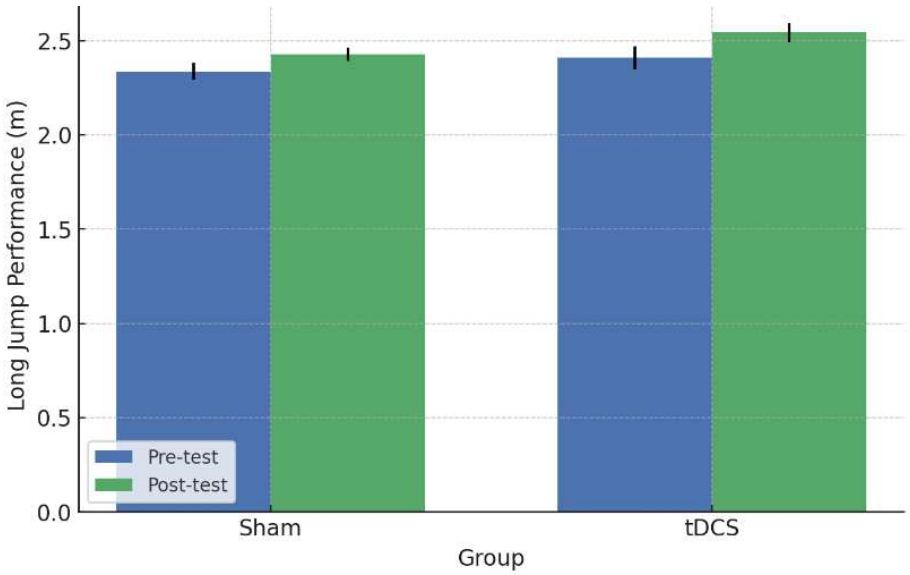


Figure 3. Pre and Post-Test Comparison of Long Jump by Group

Kicking Impact Force on Torso

Descriptive statistics for kicking impact force to the torso for both legs and time points are presented in Table 7. Visual inspection suggests improvements from pre- to post-test in both groups and legs.

Table 7. Descriptive Statistics for Torso Kicking Impact Force by Group, Leg, and Time

Group	Leg	Pre-test, Mean (SD)	Post-test, Mean (SD)
tDCS	Dominant	54.87 (2.26)	56.67 (1.95)
	Non-Dominant	49.13 (3.91)	54.07 (2.34)
Sham	Dominant	54.47 (2.70)	55.13 (1.92)
	Non-Dominant	51.67 (4.19)	53.00 (2.07)

To examine the effects of leg dominance (dominant vs. non-dominant) and time (pre-test vs. post-test) on torso kicking performance, a 2 (Leg) × 2 (Time) repeated-measures ANOVA was conducted with Group (tDCS vs. Sham) as a between-subjects factor. All assumption checks were satisfactory: the Shapiro-Wilk test indicated normality across groups and time points ($p > 0.05$), Box's M test confirmed homogeneity of covariance matrices ($F_{(10, 3748.207)} = 0.662$, $p = 0.760$), and Mauchly's test of sphericity was not applicable due to only two levels per within-subject factor, so sphericity was assumed.

The ANOVA revealed a significant main effect of Leg, $F_{(1, 28)} = 38.09$, $p < 0.001$, partial $\eta^2 = 0.576$, 95% CI [0.33, 0.71], indicating higher performance for the dominant leg. There was also a significant main effect of Time, $F_{(1, 28)} = 28.97$, $p < 0.001$, partial $\eta^2 = 0.508$, 95% CI [0.24, 0.67], demonstrating overall improvement from pre- to post-test. A significant Leg × Time interaction, $F(1, 28) = 5.58$, $p = 0.025$, partial $\eta^2 = 0.166$, 95% CI [0.01, 0.38], indicated that the magnitude of improvement differed between legs (table 8).

Importantly, the Time × Group interaction was significant, $F_{(1, 28)} = 8.51$, $p = 0.007$, partial $\eta^2 = 0.233$, 95% CI [0.03, 0.45], indicating that participants in the tDCS group improved more than those in the Sham group over time. This partial η^2 corresponds to a large effect according to Cohen's conventions. Calculated Cohen's d values for pre- to post-test changes in the tDCS group were 0.76 (dominant leg, 95% CI [0.15, 1.36]) and 0.99 (non-dominant leg, 95% CI [0.35, 1.62]), reflecting moderate to large standardized effects. The Leg × Group interaction ($F_{(1, 28)} = 2.50$, $p = 0.125$, partial $\eta^2 = 0.082$) and the three-way Leg × Time × Group interaction ($F_{(1, 28)} = 2.35$, $p = 0.136$, partial $\eta^2 = 0.078$) were not significant, indicating that the intervention effect did not differ specifically by leg. The between-subjects main effect of Group was also non-significant, $F_{(1, 28)} = 0.032$, $p = 0.859$, partial $\eta^2 = 0.001$.

Table 8. Repeated-Measures ANOVA (Within-Subjects Effects) for Torso Kicking Impact Force

Source	Type III Sum of Squares	df	Mean Square	*F*	Sig.	Partial η^2	95% CI for Partial η^2
Time	143.008	1	143.008	28.967	<0.001	0.508	[0.24, 0.67]
Time × Group	42.008	1	42.008	8.509	0.007	0.233	[0.03, 0.45]
Error(Time)	138.233	28	4.937				
Leg	330.008	1	330.008	38.094	<0.001	0.576	[0.33, 0.71]
Leg × Group	21.675	1	21.675	2.502	0.125	0.082	[0.00, 0.29]
Error(Leg)	242.567	28	8.663				
Time × Leg	27.075	1	27.075	5.584	0.025	0.166	[0.01, 0.38]
Time × Leg × Group	11.408	1	11.408	2.353	0.136	0.078	[0.00, 0.28]
Error(Time×Leg)	135.767	28	4.849				

In summary, while both legs improved over time, the greater gains in the tDCS group (significant Time × Group interaction) highlight the efficacy of multi-session tDCS in enhancing torso kicking performance (figure 4).

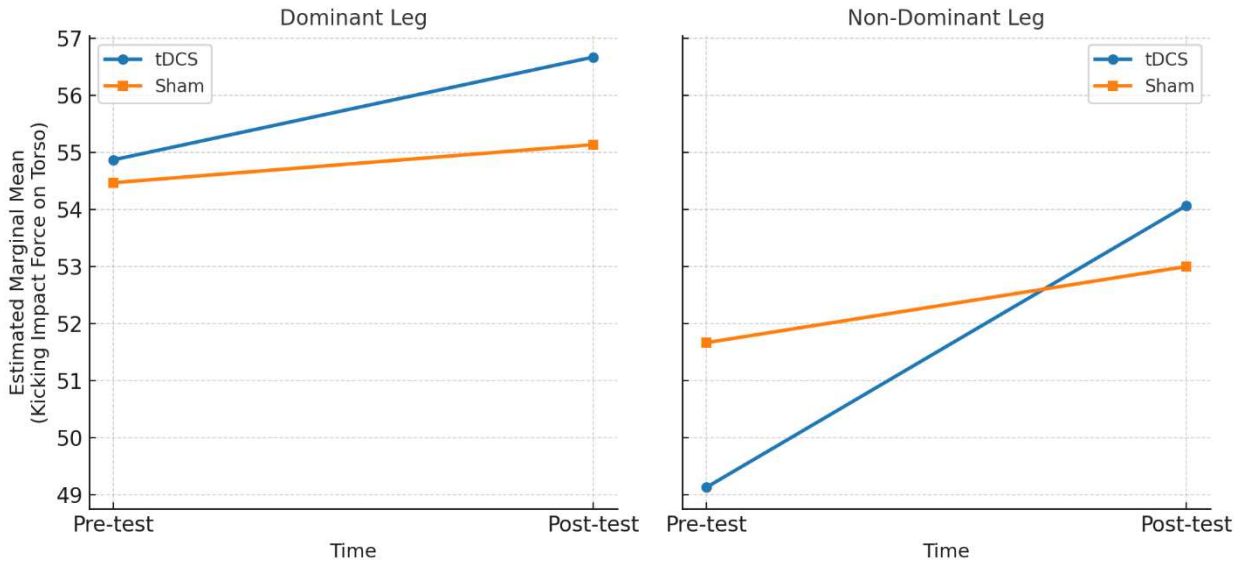


Figure 4. Pre and Post-Test Comparison of Kicking Impact Force on Torso by Group and Leg Dominance

Kicking Impact Force on Head

Descriptive statistics for kicking impact force to the head for both legs and time points are presented in Table 9.

Table 9. Descriptive Statistics for Head Kicking Impact Force by Group, Leg, and Time

Group	Leg	Pre-test, Mean (SD)	Post-test, Mean (SD)
tDCS	Dominant	52.93 (2.52)	55.73 (1.87)
	Non-Dominant	51.13 (4.45)	55.60 (2.41)
Sham	Dominant	52.20 (3.51)	53.40 (3.91)
	Non-Dominant	51.13 (4.05)	52.60 (3.48)

Prior to analysis, model assumptions were evaluated. Box's M test for homogeneity of covariance matrices was non-significant (Box's $M = 19.47$, $F(10, 3748.21) = 1.64$, $p = .088$). Mauchly's test of sphericity was not applicable due to only two levels for each within-subject factor; therefore, sphericity was assumed. A 2 (Time: Pre-test, Post-test) × 2 (Leg: Dominant, Non-dominant) × 2 (Group: tDCS, Sham) repeated-measures ANOVA was conducted to assess the effects of the intervention.

The ANOVA revealed a significant main effect of Time, $F(1, 28) = 22.27$, $p < .001$, partial $\eta^2 = 0.443$, 95% CI [0.18, 0.62], indicating that kicking force increased significantly from pre-test to post-test across all participants. A significant main effect of Leg was also observed, $F_{(1, 28)} = 5.61$,

p = 0.025, partial η^2 = 0.167, 95% CI [0.00, 0.38], with the dominant leg generating greater force than the non-dominant leg overall.

Most importantly, a significant Time × Group interaction was found, $F_{(1, 28)}$ = 4.78, p = 0.037, partial η^2 = 0.146, 95% CI [0.00, 0.36]. This result indicates that the rate of improvement from pre-test to post-test was significantly greater for the tDCS group compared to the Sham group. The effect size is considered medium according to Cohen's conventions.

No other effects reached statistical significance. The Leg × Group interaction ($F_{(1, 28)}$ = 0.002, p = 0.967, partial η^2 < .001), the Time × Leg interaction ($F_{(1, 28)}$ = 2.22, p = 0.148, partial η^2 = 0.073), and the three-way Time × Leg × Group interaction ($F_{(1, 28)}$ = 1.16, p = 0.290, partial η^2 = 0.040) were all non-significant. The between-subjects main effect of Group was also non-significant, $F_{(1, 28)}$ = 2.34, p = 0.137, partial η^2 = 0.077 (Table 10).

Table 10. Repeated-Measures ANOVA (Within-Subjects Effects) for Head Kicking Force

Source	Type III Sum of Squares	df	Mean Square	*F*	Sig.	Partial η^2	95% CI for Partial η^2
Time	185.008	1	185.008	22.274	<0.001	0.443	[0.18, 0.62]
Time × Group	39.675	1	39.675	4.777	0.037	0.146	[0.00, 0.36]
Error(Time)	232.567	28	8.306				
Leg	27.075	1	27.075	5.609	0.025	0.167	[0.00, 0.38]
Leg × Group	0.008	1	0.008	0.002	0.967	< .001	[0.00, 0.00]
Error(Leg)	135.167	28	4.827				
Time × Leg	7.008	1	7.008	2.216	0.148	0.073	[0.00, 0.27]
Time × Leg × Group	3.675	1	3.675	1.162	0.290	0.040	[0.00, 0.22]
Error(Time×Leg)	88.567	28	3.163				

To quantify the magnitude of pre- to post-test changes, Cohen's d was calculated for each leg within each group. The tDCS group demonstrated large improvements for both the dominant leg (d = 0.73, 95% CI [0.12, 1.33]) and the non-dominant leg (d = 0.92, 95% CI [0.30, 1.53]). In contrast, the Sham group exhibited smaller, small-to-moderate improvements (Dominant leg: d = 0.35, 95% CI [-0.25, 0.94]; Non-dominant leg: d = 0.40, 95% CI [-0.20, 0.99]). Furthermore, an examination of parameter estimates from the model indicated that at post-test, the tDCS group significantly outperformed the Sham group for kicks with both the dominant leg (B = 2.33, p = .046) and the non-dominant leg (B = 3.00, p = .010).

In summary, while both groups improved their head-target kicking force overtime and the dominant leg was consistently superior, the active tDCS intervention yielded a significantly greater improvement compared to the sham procedure, as evidenced by the significant Time × Group interaction. This beneficial effect was consistent across both legs (non-significant three-way interaction) and was associated with large within-group effect sizes in the tDCS condition. These results demonstrate the efficacy of multi-session cerebellar anodal tDCS for enhancing high-accuracy kicking performance in trained taekwondo athletes (Figure 5).

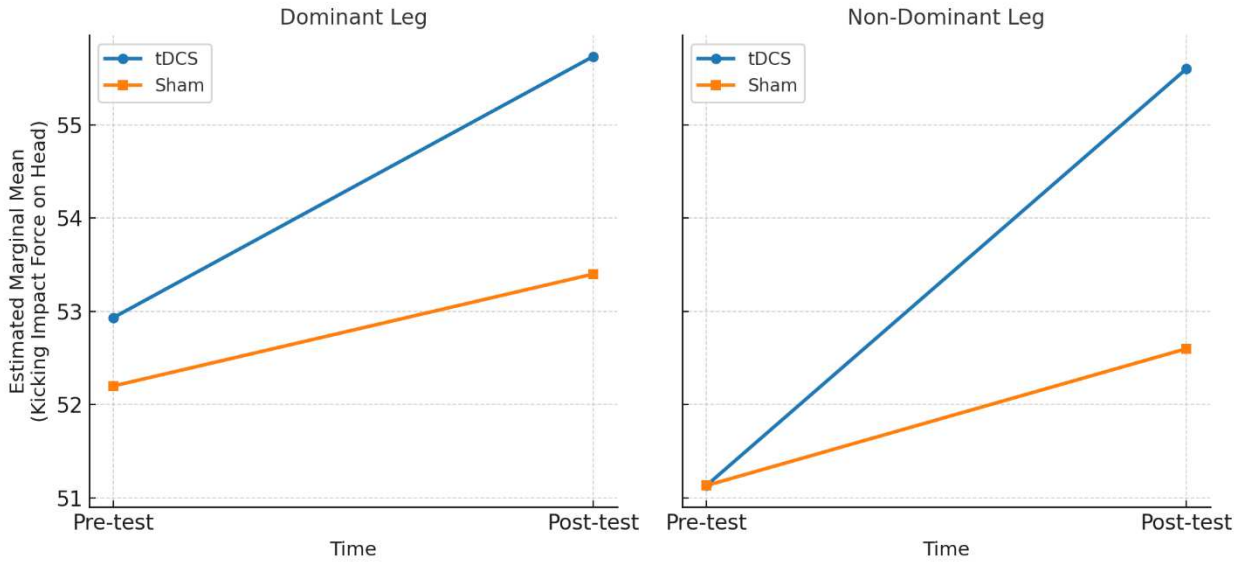


Figure 5. Pre and Post-Test Comparison of Kicking Impact Force on head by Group and Leg Dominance

Discussion

This randomized, sham-controlled study demonstrated that a five-day course of anodal transcranial direct current stimulation (tDCS) over the fronto-central motor area (FCz) significantly enhanced lower-limb explosive power (standing long jump) and sport-specific kicking impact force in trained taekwondo athletes, compared to sham stimulation. These findings indicate that multi-session tDCS can induce functional neuromuscular adaptations relevant to complex, ballistic movements. The consistent pattern of a significant Time × Group interaction across all primary and secondary outcomes (standing long jump, torso kicking force, and head kicking force) provides robust evidence that the multi-session anodal tDCS protocol was effective in enhancing lower-body explosive performance.

The observed enhancements in lower-limb explosive power and sport-specific kicking performance are likely underpinned by cumulative neuroplastic changes within the supplementary motor area (SMA) and its corticospinal projections to lower-limb muscles. Repeated anodal tDCS over the fronto-central motor area (FCz), which targets the SMA and adjacent premotor regions, may facilitate longer-lasting potentiation of synaptic efficacy, increase corticospinal excitability, and modulate intracortical inhibition. These neurophysiological effects can improve motor coordination, optimize the timing of muscle activation across the trunk and lower limbs, and stabilize the execution of complex, ballistic movements. This mechanistic framework is particularly relevant for trained athletes, who may exhibit a ceiling effect due to high baseline neural efficiency; multi-session stimulation can progressively modulate SMA–M1 networks to overcome these limits, thereby promoting measurable functional gains in both general explosive power and sport-specific actions [27,25]. The FCz electrode site, targeting the SMA and adjacent premotor regions, is supported by neuroimaging studies showing its involvement in planning and executing coordinated lower-limb tasks [28,29].

These findings are consistent with meta-analytic evidence highlighting the synergistic effects of tDCS combined with physical training on lower-limb performance. Specifically, a recent meta-analysis reported that tDCS paired with resistance or sport-specific training significantly enhances strength and explosive power outcomes compared to sham-controlled training alone [20]. This synergy likely arises from tDCS priming the supplementary motor area (SMA) and adjacent premotor regions, facilitating training-induced adaptations such as optimized motor unit recruitment, increased rate of force development, and refined inter-muscular coordination—all factors directly relevant to explosive jumping and kicking [30,31]. Supporting this notion, studies employing tDCS montages targeting lower-limb kinetics have observed improvements in countermovement jump height and joint power, indicative of enhanced kinetic chain efficiency [10].

The significant improvements in both the sport-specific kicking tasks and the general explosive power test suggest that multi-session tDCS over FCz can enhance a range of lower-limb ballistic performances. The complex, multi-joint nature of taekwondo kicks, which require precise inter-segmental coordination, may particularly benefit from the hypothesized tDCS-induced optimization of SMA-mediated motor planning and execution [11]. Taekwondo kicks are high-velocity, multi-joint movements that require precise proximal-to-distal sequencing and inter-

segmental coordination. Repeated tDCS may enhance corticospinal drive and reduce intracortical inhibition, improving the synchronization of muscle activation across the trunk and lower limbs. This likely leads to more effective force summation during ballistic actions [11]. Such observations align with prior evidence indicating that tDCS more effectively improves complex motor skills than simple strength tasks, likely by increasing the efficiency of distributed motor networks [32].

It is important to contextualize these positive findings within the broader literature, which demonstrates heterogeneous effects of tDCS on athletic performance. A recent meta-analysis reported that anodal tDCS significantly enhances sport-specific performance with a moderate overall effect size (standardized mean difference ≈ 0.39), particularly when stimulation is paired with appropriate intensity (1.6–2.0 mA) and duration (16–20 min) [33]. Subgroup analyses in this review also noted that stimulation of primary motor and prefrontal regions tended to yield more consistent improvements across multiple performance domains (e.g., endurance, skill tasks) than other targets [33].

Systematic reviews suggest that single-session tDCS outcomes in athletes are variable, with many studies showing mixed or minimal effects on sport-specific performance when stimulation is not integrated with repeated task practice or training [19]. For example, heterogeneous results, including improvements in strength or endurance in some studies but limited effects in sport-specific tasks, have been reported, indicating that baseline neural efficiency and task complexity influence responsiveness to tDCS [19].

The present study observed meaningful improvements in both lower-limb explosive power and sport-specific kicking performance following multi-session anodal tDCS over FCz. The intervention produced moderate-to-large practical effects, indicating that the observed gains are not only statistically significant but also relevant for athletic performance. Three-way interactions (Leg × Time × Group) were not significant, suggesting that the improvements occurred across both dominant and non-dominant limbs, without a differential effect based on limb specialization. Overall, the magnitude of enhancement supports the practical utility of repeated tDCS sessions for boosting general explosive power and ballistic sport-specific skills. It is important to note that no serious adverse effects were reported, and the sham protocol was well-tolerated, suggesting a favorable benefit-risk profile for this intervention protocol in healthy athletes.

Moreover, the consistent improvements in both dominant and non-dominant limbs indicate that stimulation at FCz may enhance bilateral neuromuscular coordination and skill transfer, rather than producing only unilateral or strength-specific changes. This pattern aligns with evidence suggesting that tDCS can modulate broader motor networks involved in coordination and timing, particularly when repeated sessions and task-specific activity are employed [33].

The generalisability (external validity) of our findings is necessarily constrained to populations similar to our sample: competitive, adolescent-to-young adult male taekwondo athletes with substantial training experience. Whether similar effects would be observed in females, in athletes from different sports requiring lower-body explosiveness, or in untrained individuals is an important question for future research.

Limitations and Future Directions

Despite the positive outcomes, several limitations of this study should be acknowledged. First, the underlying neural mechanisms remain inferential due to the lack of concomitant neurophysiological measures (e.g., transcranial magnetic stimulation to assess corticospinal excitability and inhibition, or high-density electromyography to evaluate muscle activation patterns). Future studies should integrate such measures to directly link tDCS-induced neuroplasticity with performance improvements.

Second, the durability of observed enhancements beyond the immediate post-intervention period is unknown. Follow-up assessments are needed to determine whether these gains are maintained, decay over time, or require periodic "booster" sessions. Third, while the FCz montage was selected to target the supplementary motor area (SMA) and adjacent premotor regions, alternative montages (e.g., bilateral M1, cerebellar, or prefrontal cortex stimulation for cognitive-motor aspects) may elicit differential or synergistic effects, warranting systematic comparison [17]. Finally, our sample consisted exclusively of trained taekwondo athletes; the efficacy and potential for larger relative gains in novice populations or other sports disciplines remain to be explored.

Furthermore, the moderate sample size may limit the precision of our effect estimates. Although we employed standard analytical methods for repeated measures, the number of statistical tests performed warrants caution in interpreting the findings, and the results should be considered exploratory until replicated in larger trials.

Conclusion and Practical Implications

This study demonstrates that a five-day multi-session anodal tDCS protocol over the fronto-central motor area (FCz) enhances both lower-limb explosive power (standing long jump) and sport-specific kicking performance in trained taekwondo athletes. These findings support the use of tDCS as a neuromodulatory adjunct to athletic training, particularly for improving complex, coordinated motor skills that rely on precise corticospinal timing and inter-muscular coordination.

Multi-session anodal tDCS at FCz can serve as a potentiation tool during preparatory or intensified training phases. Key recommendations for application and future research include:

- Incorporate neurophysiological assessments (e.g., TMS, HD-EMG) to clarify underlying mechanisms of tDCS-induced improvements.
- Extend intervention periods (e.g., 2–4 weeks) and include follow-up assessments to evaluate the durability of gains.
- Explore alternative stimulation montages (e.g., bilateral M1, cerebellar-M1) to optimize performance outcomes.
- Integrate tDCS with sport-specific drills to maximize transfer to athletic performance.

References

1 Bridge, C., McNaughton, L. R., Close, G. L. & Drust, B. Taekwondo exercise protocols do not recreate the physiological responses of championship combat. *International journal of sports medicine* **34**, 573-581 (2013).

2 Kazemi, M., Perri, G. & Soave, D. A profile of 2008 Olympic Taekwondo competitors. *The journal of the Canadian chiropractic association* **54**, 243 (2010).

3 Nielsen, J. B. & Cohen, L. G. The Olympic brain. Does corticospinal plasticity play a role in acquisition of skills required for high-performance sports? *The Journal of physiology* **586**, 65-70 (2008).

4 Taylor, J. L., Amann, M., Duchateau, J., Meeusen, R. & Rice, C. L. Neural contributions to muscle fatigue: from the brain to the muscle and back again. *Medicine and science in sports and exercise* **48**, 2294 (2016).

5 Polanía, R., Paulus, W., Antal, A. & Nitsche, M. A. Introducing graph theory to track for neuroplastic alterations in the resting human brain: a transcranial direct current stimulation study. *Neuroimage* **54**, 2287-2296 (2011).

6 Landi, S. M., Baguear, F. & Della-Maggiore, V. One week of motor adaptation induces structural changes in primary motor cortex that predict long-term memory one year later. *Journal of Neuroscience* **31**, 11808-11813 (2011).

7 Nitsche, M. A. & Paulus, W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of physiology* **527**, 633 (2000).

8 Stagg, C. J. & Nitsche, M. A. Physiological basis of transcranial direct current stimulation. *The Neuroscientist* **17**, 37-53 (2011).

9 Esmaeilpour, Z. *et al.* Incomplete evidence that increasing current intensity of tDCS boosts outcomes. *Brain stimulation* **11**, 310-321 (2018).
10 Zhiqiang, Z., Wei, W., Yunqi, T. & Yu, L. Effects of bilateral extracephalic transcranial direct current stimulation on lower limb kinetics in countermovement jumps. *International Journal of Environmental Research and Public Health* **20**, 2241 (2023).
11 Park, S.-B., Han, D. H., Hong, J. & Lee, J.-W. Transcranial direct current stimulation of motor cortex enhances spike performances of professional female volleyball players. *Journal of Motor Behavior* **55**, 18-30 (2023).
12 Rocha, J. V. D. S. *et al.* Effects of bi-hemispheric anodal transcranial direct current stimulation on soccer player performance: a triple-blinded, controlled, and randomized study. *Frontiers in Sports and Active Living* **6**, 1350660 (2024).
13 Romero-Arenas, S. *et al.* Transcranial direct current stimulation does not improve countermovement jump performance in young healthy men. *The Journal of Strength & Conditioning Research* **35**, 2918-2921 (2021).
14 Jung, J. *et al.* Effect of tDCS combined with physical training on physical performance in a healthy population. *Research Quarterly for Exercise and Sport* **95**, 149-156 (2024).
15 Halakoo, S., Ehsani, F., Hosnian, M., Zoghi, M. & Jaberzadeh, S. The comparative effects of unilateral and bilateral transcranial direct current stimulation on motor learning and motor performance: A systematic review of literature and meta-analysis. *Journal of Clinical Neuroscience* **72**, 8-14 (2020).
16 Ehsani, F., Jayedi, A., Motaharinezhad, F. & Jaberzadeh, S. The effects of transcranial direct current stimulation montages on motor learning across various brain regions: A systematic review and network meta-analysis. *Neuroscience* **569**, 32-42 (2025).
17 Alves-Lobão, T. *et al.* The effects of Transcranial Direct Current Stimulation on psychomotor performance of athletes: a systematic review and meta-analysis. *Motricidade* **18**, 458-466 (2022).
18 Lewis, A., Rattray, B. & Flood, A. Optimising transcranial direct current stimulation application for the enhancement of exercise performance: a review. *Frontiers in Physiology* **16**, 1672603 (2025).
19 Yu, Y., Zhang, X., Nitsche, M. A., Vicario, C. M. & Qi, F. Does a single session of transcranial direct current stimulation enhance both physical and psychological performance in national-or international-level athletes? A systematic review. *Frontiers in Physiology* **15**, 1365530 (2024).
20 Wang, B., Xiao, S., Yu, C., Zhou, J. & Fu, W. 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 (2021).
21 Dumel, G. *et al.* Motor learning improvement remains 3 months after a multisession anodal tDCS intervention in an aging population. *Frontiers in aging neuroscience* **10**, 335 (2018).
22 Kim, Y. K., Kim, Y. H. & Im, S. J. Inter-joint coordination in producing kicking velocity of Taekwondo kicks. *Journal of sports science & medicine* **10**, 31 (2011).
23 Liu, T.-T., Lin, Y.-C., Tang, W.-T., Hamill, J. & Chang, J.-S. Lower-limb kinematic characteristics of Taekwondo kicks at different attack angles. *International Journal of Performance Analysis in Sport* **21**, 519-531 (2021).

24 Faul F, Erdfelder E, Lang AG, Buchner A. G Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior research methods, **39**(2):175-91 (2007).
25 Machado, D. G. d. S. *et al.* Effect of transcranial direct current stimulation on exercise performance: a systematic review and meta-analysis. *Brain stimulation* **12**, 593-605 (2019).
26 Grandperrin Y, Grosprêtre S, Nicolier M, Gimenez P, Vidal C, Haffen E, et al. Effect of transcranial direct current stimulation on sports performance for two profiles of athletes (power and endurance)(COMPETE): A protocol for a randomised, crossover, double blind, controlled exploratory trial. Trials, **21**(1):461 (2020).
27 Rostami, M. *et al.* Multi-session anodal transcranial direct current stimulation enhances lower extremity functional performance in healthy older adults. *Experimental brain research* **238**, 1925-1936 (2020).
28 Mihara, M., Miyai, I., Hatakenaka, M., Kubota, K. & Sakoda, S. Role of the prefrontal cortex in human balance control. *Neuroimage* **43**, 329-336 (2008).
29 Sahyoun, C., Floyer-Lea, A., Johansen-Berg, H. & Matthews, P. M. Towards an understanding of gait control: brain activation during the anticipation, preparation and execution of foot movements. *Neuroimage* **21**, 568-575 (2004).
30 Angius, L., Hopker, J. G., Marcora, S. M. & Mauger, A. R. The effect of transcranial direct current stimulation of the motor cortex on exercise-induced pain. *European journal of applied physiology* **115**, 2311-2319 (2015).
31 Hendy, A. M. & Kidgell, D. J. Anodal tDCS applied during strength training enhances motor cortical plasticity. *Medicine and science in sports and exercise* **45**, 1721-1729 (2013).
32 Summers, J. J., Kang, N. & Cauraugh, J. H. Does transcranial direct current stimulation enhance cognitive and motor functions in the ageing brain? A systematic review and meta-analysis. *Ageing research reviews* **25**, 42-54 (2016).
33 Jiang, M., Liu, Y. & Gao, X. Meta-analysis of the acute effects of anodal transcranial direct current stimulation on athletic performance. *Frontiers in Physiology* **16**, 1631905 (2025).

Acknowledgment

The authors would like to sincerely thank all the athletes who participated in this study for their time, effort, and dedication. We also acknowledge the support of the coaching staff, the technical team, and the Taekwondo Association of Zanjan Province for their assistance in the training sessions and data collection. This research was conducted without external funding. The authors declare no conflicts of interest.

Ethical Considerations

The study protocol was reviewed and approved by the Zanjan Taekwondo Federation and the Ethics Committee of University of Zanjan (approval code: IR.ZNU.REC.1403.031). All experimental procedures were conducted in accordance with relevant guidelines and regulations,

including the Declaration of Helsinki. Prior to participation, all athletes were provided with detailed information regarding the study objectives, procedures, and potential risks, and written informed consent was obtained from each participant. Participants were explicitly informed of their right to withdraw from the study at any time without any penalty. This trial has been registered retrospectively in the Iranian Registry of Clinical Trials (IRCT) under registration number IRCT20260119068612N1 (registration date: 2026-03-16).

Author Contributions

Ahmad Fallahi conceptualized and designed the study, supervised data collection, performed statistical analyses, and drafted the manuscript. Jaber Alizadehgoradel contributed to study design, experimental planning, and interpretation of psychological aspects. Mina Shiri-Yekta, Mahshid Saboorinia, and Roma Ghorbanlu assisted with data collection, preprocessing, literature review, and administrative coordination. All authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Data Availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The author(s) declare no competing interests.

Funding

The author received **No Funding** for this work.