Original article

Prefrontal coherence in the delta, theta, alpha, and beta frequency bands in response to cathodic high-definition transcranial direct current stimulation in professional basketball players during preparation for free-throw shooting bouts

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ABSTRACT | INTRODUCTION: Cathodic high-definition transcranial direct current stimulation (HD-tDCS) has been shown to modulate cerebral activity. **OBJECTIVES:** This study examined if cathodic high-definition transcranial direct current stimulation (HD-tDCS) could modulate cortical coherence during the preparation for free-throw shooting in professional female basketball players. **METHODS AND MATERIALS:** The cortical activity was measured using electroencephalography (EEG) and the spectral bands δ (0.5–≤4 Hz), theta θ (>4–≤8 Hz), alpha α (>8–≤13 Hz), and beta β (>13–≤30 Hz) were analyzed. Only successful free throws (n = 1,893) were considered. Multi-channel HD-tDCS (cathodic and sham) was applied for 20 minutes prior to bouts of shooting. **RESULTS AND CONCLUSION:** For FP1-F3 (channels) coherence, there was an interaction effect for delta ($F = 5.93$; $p = 0.03$), theta ($F = 11.38$; $p = 0.008$), alpha ($F = 15.33$; $p = 0.004$), but not for beta band ($F = 0.875$; $p = 0.37$). The post-hoc analysis revealed significant differences between post-cathodic HD-tDCS and pre-cathodic HD-tDCS, and post-cathodic HD-tDCS and post-sham HD-tDCS. These differences were due to increases in these spectral bands' coherence following the cathodic stimulation. No changes or differences in coherence were observed for other pairs of channels regardless of the HD-tDCS condition. These findings suggest that the effects are relatively focal, inducing changes primarily in the left pre-frontal hemisphere while preserving inter-hemispheric connectivity.

KEYWORDS: Neuromodulation. Functional Connectivity. Spectral Frequencies. Qualitative EEG. Team-sports.

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1. Introduction

In elite basketball, players generally execute a free throw within approximately one second, starting from receiving the ball to releasing it from their fingertips[1]. During this brief interval, the brain rapidly processes task-specific visual information and organizes the neural networks required to plan, initiate, and control the movement[2]. In sports, especially precision tasks such as basketball free-throw shooting, cognitive-motor preparation is critical, and brain oscillatory activity is thought to play a central role in optimizing performance[2,3].

The human cerebral cortex demonstrates distinct functional interconnection patterns that link diverse brain regions, from cell assemblies to individual cortical neurons[4]. These connections are neither entirely random nor fully organized, supporting both localized and distributed information processing[5]. Functional connectivity describes the temporal relationship of neuronal activity across different brain areas. Oscillatory activity between cortical regions within the same functional network, such as those involved in visual or motor processes, tends to be correlated[6,7].

Coherence is a widely used metric in electroencephalography (EEG) research for investigating brain connectivity and its role in enhancing athletic performance. Studies often employ EEG to assess coherence as an indicator of the interdependence or independence of activity between brain regions, with particular emphasis on interactions between the Fz electrode and other electrode sites across the scalp[8-11]. To further advance this knowledge within the field of sports science, spectral EEG coherence analysis may provide valuable insights into functional communication between cortical regions during physically and cognitively demanding tasks. Moreover, it can help characterize the integrative role of oscillatory brain rhythms in modulating motor behavior, attention, and decision-making processes during athletic performance.

Applying neuromodulation techniques in sports neuroscience has opened new avenues for understanding how brain activity can be modulated to enhance athletic performance[12-14]. One of the techniques gaining prominence is high-definition transcranial direct current stimulation (HD-tDCS), a non-invasive brain stimulation method known for its ability to modulate cortical excitability and network connectivity[15]. HD-tDCS has been reported to influence neural activity in brain regions linked to motor planning and execution in athletes[3]. It is proposed that cathodal stimulation targeting the left dorsolateral prefrontal cortex (DLPFC) may inhibit executive functions, such as working memory, thereby promoting a shift from explicit to implicit memory systems[15]. This transition could facilitate more automatic performance during tasks requiring precision.

In non-sporting contexts, research has explored how tDCS can drive neuroplastic changes by modifying functional cortical network connectivity. For instance, Polanía et al.[16] investigated this phenomenon in healthy participants by applying anodal tDCS to the primary motor cortex (M1) alongside inhibitory cathodal tDCS over the contralateral frontopolar cortex. Their findings revealed significant increases in functional connectivity within the premotor, motor, and sensorimotor regions of the stimulated hemisphere during motor activity, particularly in the 60–90 Hz frequency range. Moreover, connectivity alterations were observed both within and between hemispheres across all frequency bands, indicating that tDCS can influence brain synchronization and the functional network's organization. More recently, Claaß et al.[17] conducted a double-blind, within-subject study involving healthy individuals to assess tDCS effects on functional connectivity. By delivering anodal, cathodal, and sham tDCS to the DLPFC, they found that anodal stimulation reduced connectivity with the parietal cortex, thereby modifying network synchronization.

While tDCS has been demonstrated to improve functional connectivity between segregated cortical areas involved in motor tasks[16], the effects of tDCS on functional connectivity using EEG methods for analyze coherence in professional basketball players during the preparation phase of free-throw shooting remain under-explored. The present study, therefore, aimed to add to findings from Moscaleski et al.[3] who revealed that HD-tDCS induced changes in slow frontal frequency brain activity. Specifically, in that study it was demonstrated increases in spectral markers such as the power ratio index (PRI), delta/alpha ratio (DAR), and theta/beta ratio (TBR) following the cathodal condition, indicating enhanced slow frontal frequency brain activity. These alterations may be associated with neural mechanisms that enhance brain efficiency, enabling better regulation of negative thoughts and doubts that could interfere with the execution of precise motor tasks.

However, despite this intriguing finding, the effect on network connectivity and functional interconnection patterns remains incomplete. Further investigation into coherence within frontal channels could provide a deeper understanding of how HD-tDCS affects brain connectivity and offer new insights into potential changes in neural processing. By analyzing spectral EEG coherence data, this study aimed to build upon the work of Moscaleski et al.[3], exploring whether cathodal HD-tDCS can modulate cortical communication patterns critical for optimizing the preparation for free-throw shooting performance in professional female basketball players.

2. Methods

2.1 Participants

This study used data from Moscaleski et al.[3], in which twelve elite professional female basketball players from the same team (average age 33.5 ± 5.7 years; body mass 78.4 ± 10.8 kg; height 179 ± 8.5 cm) participated described previously[3]. The data were recorded from players who received full instructions on the study protocol and signed image rights agreements. The study was approved by the club and ethically cleared by the Ethics Committee of the ABC (CAAE: 08070819.1.0000.5594). Procedures adhered to the Declaration of Helsinki (2013) regarding human research ethics.

2.2 Experimental design

The data for the present study were obtained from a randomized, crossover, double-blind experimental design, as described previously[3]. Three sessions were conducted. The first session was dedicated to familiarizing participants with the testing protocol, where players received a detailed overview of the study, were accustomed to the EEG and HD-tDCS equipment and provided informed consent. During the two subsequent sessions, participants completed the experimental free-throw shooting protocol. Each session involved 200 free-throw shots from a distance of 4.23 meters (the official FIBA free-throw line). Players performed 100 shots initially (pre-HD-tDCS). Then, in a randomized order, participants received either a 20-minute session of cathodal HD-tDCS or an active sham tDCS, followed by another set of 100 shots (post-HD-tDCS). Each player experienced both conditions (cathodal and sham HD-tDCS) in alternating sessions. The cathodal stimulation, applied to the left dorsolateral prefrontal cortex (DLPFC) aimed to reduce the processing of irrelevant external stimuli, promoting a shift from external awareness to an internally focused state. Only successful free throws (n = 1,893) were considered in the analyses, aimed to explore and advance the understanding of how brain activity, specifically the oscillatory rhythms reflected in spectral frequency bands, might be affected by cathodal tDCS applied over the DLPFC during successful performance. By focusing exclusively on accurate shots, we sought to isolate brain patterns associated with optimal execution, thereby allowing us to identify neurophysiological signatures that may predict ideal performance states.

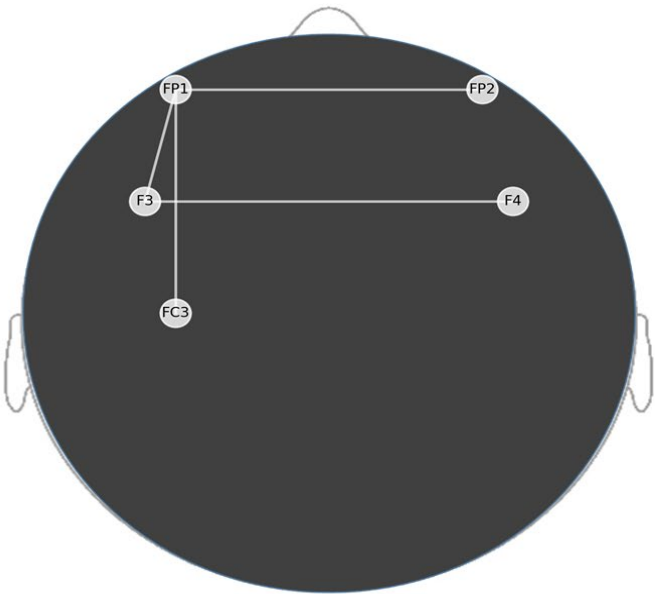
2.3 Electroencephalography (coherence), data processing, and analysis

Cortical electrical activity was measured using 64 active electrodes placed on the scalp surface, connected to a 24-bit BrainVision actiChamp amplifier from Brain Products, with a sampling rate of 1,000 Hz (BrainVision Analyzer toolbox, Version 2.3.0, Brain Products GmbH, Gilching, Germany). For the visualization of brain electrical activity during data collection, a band-pass filter of 1 to 100 Hz and a 60 Hz notch filter were employed. Impedance values were maintained below 10 kΩ at all electrode sites (ImpBox, Brain Products GmbH- impedance range of 10 kΩ to 300 kΩ).

The standard placement of electrodes for EEG recording followed the International 10/10 system, an extension of the International 10-20[18]. The electrode positioned at Fpz, located at the pre-frontal midline, was used to derive the average reference. For the assessment of inter-hemispheric functional coherence, spectral EEG coherence was analyzed between the following pairs of electrodes: Fp1-Fp2 and F3-F4. Fp1-Fp2 assessments were used to examine whether cathodal stimulation over the left DLPFC affects oscillatory synchronization between the bilateral prefrontal cortices during task preparation or execution. Moreover, F3–F4 electrode pair was selected because these electrodes are positioned directly over the left (F3) and right (F4) dorsolateral prefrontal cortices. Given that F3 is targeted during left cathodal DLPFC stimulation, coherence between F3 and F4 provides a direct measure of interhemispheric functional connectivity between homologous prefrontal areas involved in cognitive control, working memory, and attentional regulation.

For the assessment of intra-hemispheric cortical communication (left hemisphere), spectral EEG coherence was evaluated between the following pairs of electrodes: Fp1-F3 and Fp1-FC3. Fp1 captures activity from the most anterior part of the prefrontal cortex, and F3 is located directly over DLPFC, allowing for the assessment of local coherence changes within the left prefrontal cortex, between anterior prefrontal (frontopolar) and mid-lateral executive areas. FP1–FC3 electrode pair was selected to investigate how cathodal stimulation over the DLPFC may influence functional interactions between the frontopolar cortex (Fp1) and the dorsal premotor region (FC3) within the left hemisphere, which is therefore relevant in motor preparation and action planning tasks, such as free-throw shooting.

Figure 1. Set of electrodes analyzed for spectral EEG coherence. Inter-hemispheric coherence was evaluated between the following pairs of electrodes of interest: Fp1-Fp2 and F3-F4. Intra-hemispheric coherences (left hemisphere) were evaluated between the following pairs of electrodes: Fp1-F3 and FP1-FC3



Source: the authors (2025).

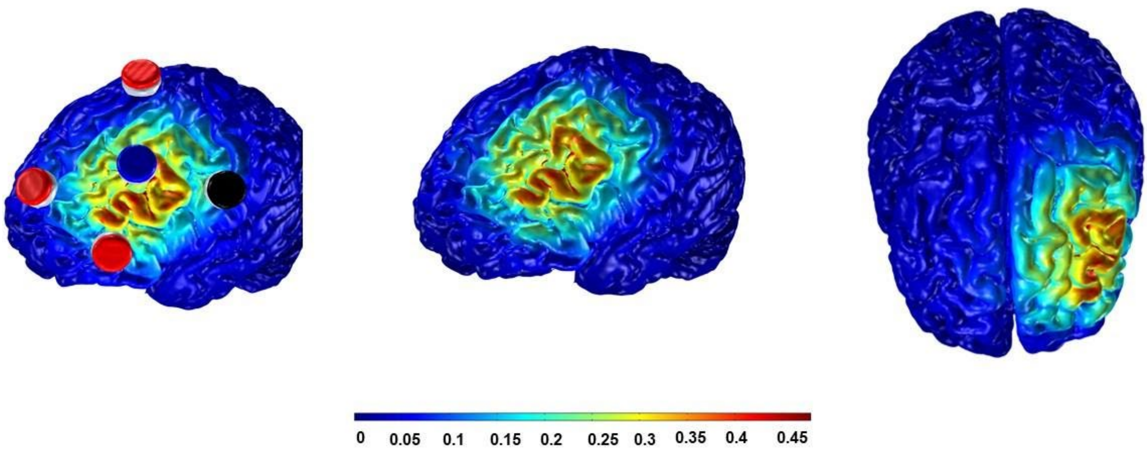
The BrainVision Analyzer toolbox (Version 2.3.0, Brain Products GmbH, Gilching, Germany) was used for EEG data pre-processing. EEG data were first pre-processed through filtering, artifact rejection, and segmentation into 1-second epochs of interest. This time window was determined from a frame-by-frame video analysis of each player's free-throw shot, conducted by three experienced basketball coaches, who observed that the time from the start of shot preparation to the moment the ball left the hand did not exceed 1 second. This protocol has previously been validated in professional basketball players' shots[1]. For all data, the sampling frequency was reduced to 500 Hz. A band-pass filter was applied based on the transformation of Infinite Impulse Response (IIR) filters, aimed at filtering or attenuating the unwanted frequency components present in the EEG data, that is, a low-frequency of 0.5Hz and high-frequency of 50Hz plus a 60Hz Notch filter.

The Notch filter was employed to attenuate electrical grid interference. Subsequently, for each player (each shotting attempt) in each session, Ocular correction ICA was applied semi-automatically to identify independent components and ocular artifacts. The semi-automatic approach was employed to prevent data omission. Following this, a Raw Data Inspection was conducted for all data in a semi-automatic mode across all channels to verify the EEG dataset for physical artifacts. During the inspection stage, the Gradient Check criterion - specifying the maximum allowable voltage difference between two data points - was set at 120 microvolts. Following Raw Data Inspection, the data were segmented into correct and incorrect throws. Complex Fourier coefficients were then calculated using FFT transformation. Subsequently, Coherence analysis was performed using the BrainVision Analyzer toolbox, using the "Coherence" transformation function, which applies a Fourier-based algorithm to estimate magnitude-squared coherence between selected channel pairs across predefined frequency bands. As a normalized, dimensionless measure, coherence ranges from zero (no correlation between signals) to one (linear dependence). Higher coherence indicates a stable, low-variability phase difference between signals at a given frequency. Conversely, high variability in phase difference across segments results in lower coherence values, approaching zero. The analysis yields a measure of the linear correlation between two signals in the frequency domain, reflecting the consistency of phase and amplitude relationships over time. Frequency bands of interest included delta (0.5–≤4 Hz), theta (>4–≤8 Hz), alpha (>8–≤13 Hz), and beta (>13–≤30 Hz).

2.4 HD-tDCS

High-definition transcranial direct current stimulation (HD-tDCS) was applied using Soterix Medical equipment (New York, NY) and was detailed previously[3]. Briefly, the DLPFC was targeted with both cathodal and sham stimulation, each lasting 20 minutes, with a 30-second ramp-up and ramp-down period (Figure 2). The HD-tDCS electrodes were fixed into a Brain Products EEG cap with 64 channels for simultaneous EEG-tDCS measurements. A conductive gel facilitated the electrode-skin interface. For the cathodal stimulation, specific electrode positions were utilized, and the current was set at -0.5 mA for FCC1h, AFF5h, and AFF1h, with FCC5 as the ground. In the sham condition, the current was briefly applied for 30 seconds at the beginning and end of the 20 minutes to simulate the ramp-up and ramp-down sensations. An auto-sham procedure generated the sham waveform based on the "real" waveform, ensuring similar experiences for the participants. There was a 72-hour interval between sessions to prevent any carry-over effects. Following each stimulation, participants completed a questionnaire to report sensations and intensity, following the Fertonani et al.[19] protocol, which was previously described[3].

Figure 2. Electrode's setup and voltage field simulation. Cathodal stimulation; gray matter electric field: 0.48 V/m.; Cathode (blue ring): FFC3h (-2 mA); Anode: FCC5h (ground; black ring), FCC1h, AFF5h, AFF1h (red rings) (0.5mA each)



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2.5 Statistical analysis

Data are reported as the mean and standard error of the mean (SEM). The Shapiro-Wilk test was used to test data normality, and Levene's test was used to verify the homoscedasticity (homogeneity of variances) across the conditions. A Two-Way ANOVA (condition [cathodal and sham] versus time-points [pre- and post-HD-tDCS]) with repeated measures on the time factor was used for each pair of electrodes (Fp1-F3, Fp1-FC3, Fp1-Fp2, and F3-F4) and spectral bands [(delta δ (0.5–≤4 Hz), theta θ (>4–≤8 Hz), alpha α (>8–≤13 Hz), and beta β (>13–≤30 Hz)]. Tukey post hoc test was used to identify possible differences. The effect sizes were calculated using partial eta square (ηp2), for which 0.01, 0.06, and 0.14 were considered as small, medium, and large effects, respectively. The significance level was set at $p \leq 0.05$.

3. Results

3.1 Intra-hemispheric coherence

3.1.1 FP1-F3 coherence

An interaction effect (condition versus time-point) was observed for FP1-F3 coherence analysis for delta (F = 5.93; p = 0.03; ηp2 = 0.39), theta (F= 11.38; p = 0.008; ηp2 = 0.55), alpha (F = 15.33; p = 0.004; ηp2 = 0.63), but not for beta band (F = 0.875; p = 0.37; ηp2 = 0.08). The post-hoc analysis revealed significant differences between pre-cathodic HD-tDCS and post-cathodic HD-tDCS (delta, p = 0.04; theta, p = 0.004; alpha, p = 0.001) and post-cathodic HD-tDCS and post-sham HD-tDCS (delta, p = 0.02; theta, p = 0.04; alpha, 0.02). These differences were due to increases in these spectral bands' coherence after the cathodic stimulation, while no changes were observed for the sham condition (Figure 3A). However, no condition effects were observed (delta, F = 2.37, p = 0.15; theta, F = 1.59, p = 0.23; alpha, F = 2.66, p = 0.13; beta, F = 3.24, p = 0.10).

3.1.1.1 Sample size and power considerations

Due to the limited availability of elite athletes, priori sample size calculation was not feasible. Instead, we conducted a post hoc power analysis for the significant Time × Condition interaction effects in the FP1–F3 electrode pair. The results showed medium to large effect sizes (partial η^2 ranging from 0.50 to 0.72), with observed statistical power ranging from 0.72 to 0.93. These findings suggest that the study had sufficient power to detect meaningful changes in spectral EEG coherence following HD-tDCS application.

3.1.2 Fp1-FC3 coherence

There were no significant differences between the pre-and post-coherence for Fp1-FC3 channels, regardless of the analyzed spectral band. (Figure 3B). No interaction effect neither condition or time effect was observed (*Interaction*: delta, F = 1.51, p = 0.25, ηp2 = 0.14; theta, F = 1.13, p = 0.31, ηp2 = 0.11; alpha, F = 0.45, p = 0.51, ηp2 = 0.04; beta, F = 0.56, p = 0.81, ηp2 = 0.006; *Condition*: delta, F = 0.75, p = 0.40; theta, F = 3.52, p = 0.09; alpha, F = 1.79, p = 0.21; beta, F = 1.39, p = 0.26; *Time*: delta, F = 0.01, p = 0.89; theta, F = 0.51, p = 0.49; alpha, F = 0.35, p = 0.56; beta, F = 0.20, p = 0.66).

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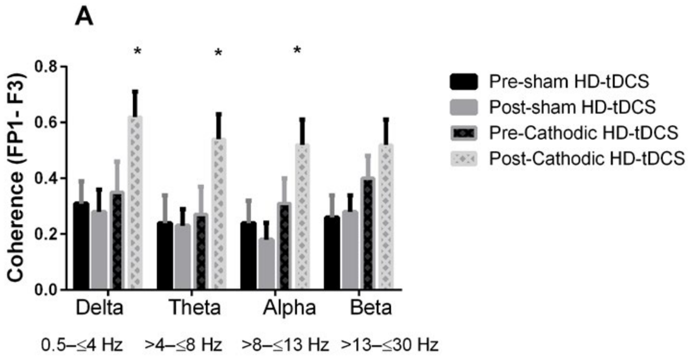
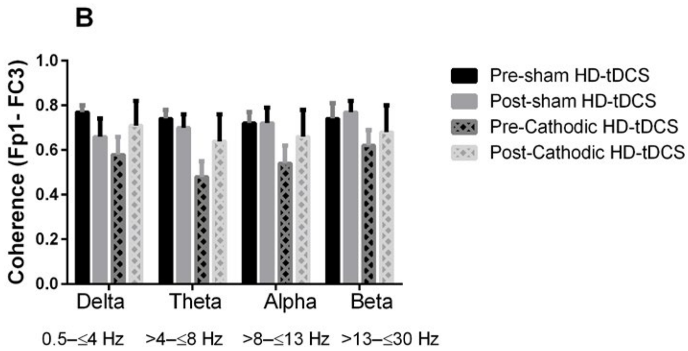
Figure 3. Fp1-F3 (A) and Fp1-FC3 (B) spectral EEG coherence analysis for delta, theta, alpha, and beta. Cathodic and sham conditions. * Significant difference between Pre-Cathodic HD-tDCS and Post-Cathodic HD-tDCS, and Post-Cathodic HD-tDCS and Post-sham HD-tDCS (Mean and SEM)





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3.2 Inter-hemispheric coherence

3.2.1 Fp1-FP2 coherence

No significant differences between the pre- and post-coherence for Fp1-Fp2 channels, in both conditions, regardless of the analyzed spectral band, were observed (Figure 4A). No interaction effect (condition [cathodic and sham] versus time (pre- and post-HD-tDCS), condition effect or time effect was observed (*Interaction*: delta, F = 0.00, p = 0.92, ηp2 = 0.0009; theta, F = 0.23, p = 0.63, ηp2 = 0.025; alpha, F = 0.00, p = 0.97, ηp2 = 0.0001; beta, F = 0.25, p = 0.62, ηp2 = 0.027; *Condition*: delta, F = 0.79, p = 0.39; theta, F = 0.83, p = 0.38; alpha, F = 0.93, p = 0.35; beta, F = 0.29, p = 0.12; *Time*: delta, F = 0.24, p = 0.63; theta, F = 0.18, p = 0.67; alpha, F = 0.53, p = 0.48; beta, F = 1.64, p = 0.23).

3.2.2 F3-F4 coherence

There were no significant differences between the pre- and post-coherence for F3-F4 channels, regardless of the analyzed spectral band (Figure 4B). No interaction effect neither condition or time effect was observed (*Interaction*: delta, F = 0.66, p = 0.80, ηp2 = 0.007; theta, F = 0.72, p = 0.41, ηp2 = 0.074; alpha, F = 0.01, p = 0.98, ηp2 = 0.00005; beta, F = 0.47, p = 0.51, ηp2 = 0.049; *Condition*: delta, F = 0.37, p = 0.55; theta, F = 0.54, p = 0.47; alpha, F = 0.61, p = 0.81; beta, F = 0.47, p = 0.90; *Time*: delta, F = 0.00, p = 0.99; theta, F = 0.14, p = 0.90; alpha, F = 2.09, p = 0.18; beta, F = 3.80, p = 0.08).

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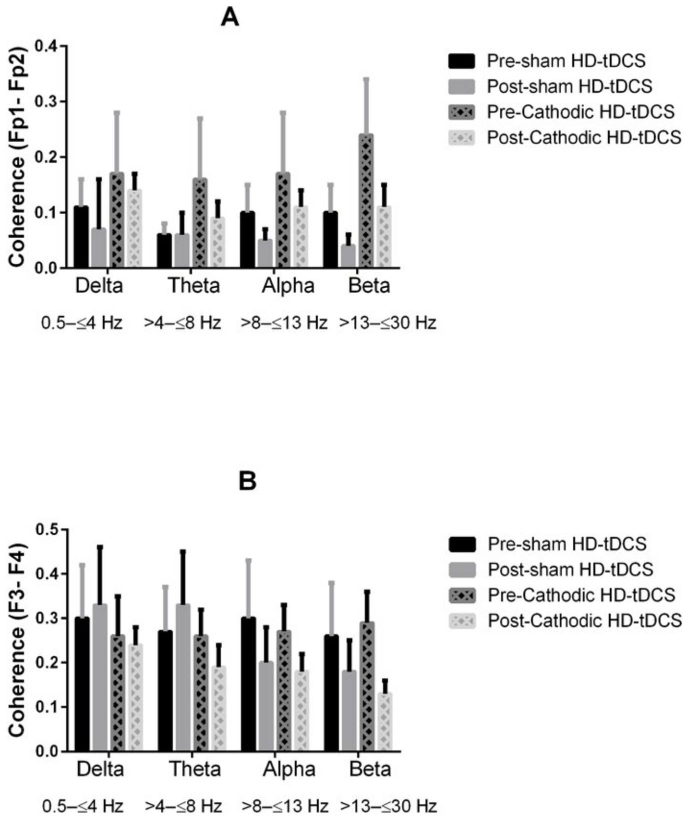
Figure 4. Fp1-Fp2 (A) and F3-F4 (B) spectral EEG coherence analysis for delta, theta, alpha, and beta. Cathodic and sham conditions (Mean and SEM)



Source: the authors (2025).

4. Discussion

The current study examined the impact of HD-tDCS on spectral coherence in elite female basketball players preparing for free-throw shooting. The main results showed an increase in delta, theta, and alpha coherence, but not statistically for beta, for FP1-F3 pairs channels. No significant changes were observed for other intra- or inter-hemispheric pairs of channels. The increases in delta, theta, and alpha FP1-F3 coherence suggest an important mechanism by which cathodal HD-tDCS over the left DLPFC may influence neural processes, notably, for frontal regions. This finding adds valuable information to the literature on the applications of this montage, potentially enhancing behaviors associated with free-throw preparation in professional female basketball players.

The FP1 and F3 EEG channels correspond to regions in the left pre-frontal cortex, aligning with key areas involved in cognitive and attentional processing. FP1 is generally thought to represent the left frontopolar cortex (Brodmann area 10), which is crucial for abstract reasoning, future planning, and decision-making. Studies indicate that this area supports processes requiring the management of multiple rules or the integration of relationships over time, highlighting its role in high-level cognitive functioning and emotional regulation[20].

F3 corresponds to the left DLPFC, particularly Brodmann areas 9 and 46. The DLPFC plays a key role in working memory, executive control, and attentional regulation, often being activated during tasks that require response inhibition, complex decision-making, and goal-oriented behavior. The DLPFC's connectivity, especially its structural and functional links to other prefrontal and parietal regions, allows it to function as a central hub for coordinating actions driven by higher-order cognitive demands[21]. Indeed, the DLPFC is widely interconnected with several brain regions, including subcortical areas like the thalamus and basal ganglia, as well as key structures

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involved in memory and associative processing, such as the hippocampus and parts of the posterior temporal and parietal cortices. These connections allow the DLPFC to integrate sensory, emotional, and cognitive data, which supports its involvement in complex behaviors and executive functions[22,23]. Together, these regions play a crucial role in managing attention and control during tasks that demand significant cognitive effort, such as motor planning in sports, making them particularly relevant to research on attention and coherence in athletes.

The choice of applying cathodal HD-tDCS was based on evidence showing that anodal tDCS characterized by inward current over the target area within specific dosages, typically enhance cortical excitability, while cathodal tDCS, involving outward current, generally reduces it[24-26]. The present study aimed to build on the findings of Moscaleski et al.[3], which demonstrated that cathodal HD-tDCS induced increases in slow-frequency frontal brain activity. Behaviorally, these spectral changes may relate to neural mechanisms that enable more efficient brain function, potentially supporting the regulation of negative thoughts and uncertainty regarding motor actions. The results of the current study contribute to understanding cathodal HD-tDCS's effects on network connectivity and spectral dynamics. The findings suggest that the effects are relatively focal, inducing changes primarily in the left prefrontal hemisphere while preserving inter-hemispheric connectivity from pre- to post-stimulation.

Moreover, the findings indicate that sham stimulation produced no significant change in spectral EEG coherence, supporting the notion that the observed increases with cathodal tDCS are not placebo-related but rather linked to neuromodulatory effects on coherence. Cathodal tDCS primarily affects low-frequency oscillations, as shown by increases in delta, theta, and alpha coherence. These results provide novel insights into possible changes in neural processing, highlighting cathodal HD-tDCS as a potential tool for modulating brain activity in targeted regions.

It is important to mention that studies examining spectral EEG coherence in sporting athletes have provided valuable insights, yet, contradictory, into the neural synchronization underlying motor performance and cognitive focus. For example, some studies have examined T7-Fz alpha coherence as a marker of expert performance in sports[27]. Cheng et al.[27] observed lower alpha coherence between T7 and Fz during best shooting performances compared to worst performances, and attributed this lower coherence to reduced sensorimotor processing, consistent with the concept of neural efficiency. Similarly, Wang et al.[28] compared elite and amateur golfers, concluding that lower alpha coherence between T7 and Fz is a hallmark of skilled motor performance and indicative of neural efficiency. In a recent meta-analytical review, Raman and Filho[29] reported that athletes had lower coherence in the T7-Fz brain pathway for alpha-band activation when performing better. The authors proposed that results may corroborate the notion that athletes become more "neuraly efficient" as the verbal and motor areas of the brain function more independently, i.e., the neural efficiency hypothesis. However, Parr, Gallicchio, and Wood[30] disagree with Raman and Filho[29], arguing that the evidence linking lower T7-Fz connectivity to superior motor performance remains inconclusive, with mixed findings across studies.

Despite this disagreement, it is important to highlight those other studies examining spectral EEG coherence in sports athletes have provided valuable insights into the neural synchronization underlying motor performance and cognitive focus. For example, Woo and Kim[11] found that interhemispheric coherence during aiming was higher during competition compared to practice. These authors suggested that competitive anxiety may reduce neural efficiency and regional cortical autonomy, although no differences in intrahemispheric EEG coherence were observed between competition and practice conditions. Indeed, Gu et al.[31] showed that compared with the expert archers, the elite archers had stronger functional coupling in beta1 and beta2 bands, and the difference was evident in the frontal and central regions.

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Additional functional connections at both sensor and source levels have been demonstrated[32]. This tDCS-induced changes in functional connectivity could potentially bias (i.e., activate or deactivate) specific neural networks[32]. The present findings contribute to this line of research, showing that HD-tDCS, specifically cathodal stimulation over the left DLPFC, altered intra-hemispheric spectral EEG coherence, increasing delta, theta, and alpha, FP1-F3 coherence. These results not only add to the existing literature but also extend insights into how tDCS shapes neural responses, with potential implications for practitioners working with high-performance athletes.

Previous research has provided evidence that tDCS can modulate cortical processing[16,33]. The targeted modulation of functional networks may explain the numerous positive effects of tDCS on neurological and psychiatric disorders[34,35]. Moreover, stimulation effects likely depend on the brain's current behavioral[36]. In the study of Kunze et al.[32], for example, it was assumed that the brain was resting (e.g., awake with eyes closed) during stimulation[37]. However, in the present study, players were actively engaged in a task, making it reasonable to assume a vigilant state, which should be considered when considering the present results. Additionally, the current findings, notably, the changes induced by methodical stimulation, for FP1-F3 coherence, may relate to the effects of tDCS, increasing coherence (FP1-F3) due to synaptic plasticity[38]. Previously, Polanía et al.[16] suggested that the cathodal electrode placed over the frontopolar area may have generated a consistent negative electric field during stimulation, potentially causing neuron hyperpolarization. This hyperpolarization, in turn, may have led to an increased synchronization of spontaneous activity within the cathodal-stimulated region. This suggested mechanism may aid in explaining the results of the present study.

Despite the unique and promising findings of this study, certain limitations should be highlighted. This study is a preliminary attempt to examine the effect of HD-tDCS on spectral band coherence in frontal channels, both intra- and inter-hemispherically, during the free-throw shooting preparation stage. Although brain connectivity methods are used for a thorough analysis, a precise scientific explanation for all significant complex connections remains incomplete. This may partly be due to the limited sample size, which is frequently stated in research examining top-level professional athletes. Additionally, the sample comprises of only one team, making this a case study of professional female basketball players rather than a universally applicable study and thus the generalization of these findings must be cautious. Future research could incorporate network parameters based on graph theory, as well as using approaches such as multidimensional arrays (tensors), multimodal analysis, and deep learning to enable a more comprehensive understanding of brain network characteristics during basketball free-throw shooting. Nonetheless, despite these limitations, it is important to highlight that this study is unique, as it was conducted with top-level professional female basketball players. It offers new insights into the mechanisms involved in HD-tDCS response within this population and is the first to explore spectral EEG coherence analysis with HD-tDCS in this context.

5. Conclusion

In conclusion, the main findings of this study indicate that cathodal HD-tDCS stimulation can increase delta, theta, and alpha coherence in the FP1-F3 channels, and that this effect does not appear to be associated with any placebo effects, as no changes in spectral EEG coherence were observed under the sham stimulation. These results contribute significantly to the neural mechanisms underlying tDCS effects in top-level professional female basketball players during preparation for free-throw shooting. The findings support the hypothesis that cathodal HD-tDCS induces significant coherence changes in the preparation phase, suggesting that increases in delta, theta, and alpha coherence at FP1-F3 may reflect a key mechanism by which cathodal HD-tDCS over the left DLPFC influences neural processes.

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Authors' contributions

The authors declared that they have made substantial contributions to the work in terms of the conception or design of the research; the acquisition, analysis or interpretation of data for the work; and the writing or critical review for relevant intellectual content. All authors approved the final version to be published and agreed to take public responsibility for all aspects of the study.

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Competing interests

No financial, legal, or political conflicts involving third parties (government, private companies, and foundations, etc.) were declared for any aspect of the submitted work (including but not limited to grants and funding, advisory board participation, study design, manuscript preparation, statistical analysis, etc.).

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