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Neurophysiological Impact of Physical Activity: EEG Differences Between Sedentary, Individual Athletes, and Team Athletes

Fiziksel Aktivitenin Nörofizyolojik Etkisi: Sedanterler, Bireysel Sporcular ve Takım Sporcuları Arasındaki EEG Farklılıkları

Research Article / Araştırma Makalesi

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Abstract

Resting-state EEG oscillations provide insights into neurophysiological adaptations associated with physical activity and sport specialization. This study examined spectral power density (PSD), peak alpha frequency (PAF), and phase slope index (PSI) differences among sedentary individuals, individual sport athletes, and team sport athletes under eyes-open (EO) and eyes-closed (EC) conditions. EEG data were collected from Fp1, Fp2, T7, T8, O1, O2, and Pz locations, focusing on theta, alpha, and beta frequency bands. Results indicated no significant differences in PAF across groups ($p > .05$). However, PSD analyses revealed group-specific modulations: individual athletes exhibited elevated theta power at temporal ($p = .002$; $\eta^2 = .2988$) and parietal ($p = .0024$; $\eta^2 = .3244$) sites compared to sedentary, while team athletes showed reduced theta power at frontal ($p = .028$; $\eta^2 = .1834$) and occipital ($p = .019$; $\eta^2 = .1978$) regions. Alpha power was higher in sedentary participants at temporal and parietal sites during EC ($p < .01$; $\eta^2 = .3753$-$\eta^2 = .2219$), whereas team athletes demonstrated increased frontal and occipital alpha power during EO ($p < .05$; $\eta^2 = .1935$). Beta power was consistently lower in athlete groups relative to sedentary across frontal, occipital, and parietal areas ($p < .001$). PSI analysis revealed altered directed connectivity patterns, with beta-band fronto-occipital connections differentiating sedentary from team athletes ($p = .038$; $\eta^2 = 0.18$) and alpha-band connectivity distinguishing all groups during EC ($p < .05$; $\eta^2 = 0.22$-0.34). These findings suggest sport-specific neuroplasticity characterized by altered oscillatory power and functional connectivity in resting-state brain networks. Future research should explore longitudinal designs to elucidate the causal mechanisms underlying these sport-related neural adaptations and their behavioral correlates.

Keywords: Brain oscillations, Connectivity, Neuromodulation, Relative power

Öz

Dinlenik durum EEG salınımları, fiziksel aktivite ve spor uzmanlığı ile ilişkili nörofizyolojik adaptasyonlar hakkında bilgi sağlamaktadır. Bu çalışmada, sedanterler, bireysel sporcular ve takım sporcuları arasında spektral güç yoğunluğu (SGY), tepe alfa frekansı (TAF) ve faz eğim indeksi (FEİ) farklılıklarının incelenmesi amaçlanmıştır. EEG verileri Fp1, Fp2, T7, T8, O1, O2 ve Pz bölgelerinden elde edilmiş; teta, alfa ve beta frekans bantlarına odaklanılmıştır. Sonuç olarak TAF skorlarında gruplar arası anlamlı farklılık olmadığı gözlemlenmiştir ($p > .05$). SGY skorlarında, bireysel sporcular, sedanterlere kıyasla temporal ($p = .002$; $\eta^2 = .2988$) ve parietal ($p = .0024$; $\eta^2 = .3244$) bölgelerde artmış teta gücü gösterirken, takım sporcuları frontal ($p = .028$; $\eta^2 = .1834$) ve oksipital ($p = .019\eta^2 = .1978$) bölgelerde azalmış teta gücü sergilemiştir. Alfa gücü, sedanter katılımcılarda göz kapalı koşulda temporal ve parietal bölgelerde daha yüksekken ($p < .01$; $\eta^2 = .3753$-$\eta^2 = .2219$), takım sporcuları göz açık koşulda frontal ve oksipital bölgelerde artmış alfa gücü göstermiştir ($p < .05$; $\eta^2 = .1935$). Beta gücü, frontal, oksipital ve parietal alanlarda sporcu gruplarında sedanterlere göre daha düşük olarak gözlemlenmiştir. ($p < .001$). FEİ skorlarında gruplar arası yönlü bağlantısallık desenlerinde anlamlı farklılıklar gözlemlenmiştir. Beta frekansında fronto-oksipital bağlantıda sedanter ve takım sporcuları arasında anlamlı farklılıklar gözlemlenirken ($p = .038$; $\eta^2 = 0.18$), alfa frekansında göz kapalı koşulda gruplar arası anlamlı farklılıklar gözlemlenmiştir ($p < .05$; $\eta^2 = 0.22$-0.34). Bu bulgular, dinlenme halindeki beyin ağlarında salınımsal güç ve fonksiyonel bağlantının değişmesi ile karakterize olarak spora özgü nöroplastisiteyi işaret etmektedir. Gelecekteki araştırmalarda sporla ilgili nöral adaptasyonların altında yatan nedensel mekanizmaları ve bunların davranışsal ilişkilerini aydınlatmak için boylamsal tasarımlar kullanılmalıdır.

Anahtar Kelimeler: Bağlantısallık, Beyin salınımları, Nöromodülasyon, Bağıl güç

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Introduction

Long-term and regular physical training has been shown to exert significant effects not only on physical health but also on the structural and functional characteristics of the brain, as demonstrated by numerous recent neuroscientific studies (Batouli and Saba, 2017; Erickson et al., 2015; Li et al., 2024). Neuroplasticity mechanisms, which support high-level cognitive processes such as motor learning, attention, executive functions, and sensorimotor integration, are known to be enhanced particularly through repetitive and disciplined physical activity (Chang et al., 2012). Structurally, individuals who have participated in various sports disciplines over extended periods exhibit increased gray matter volume, especially in brain regions such as the motor cortex, premotor areas, and cerebellum (Schlaffke et al., 2014). Furthermore, it has been indicated that regular physical exercise induces significant alterations in the functional architecture of the brain. In particular, the interactions among brain regions associated with attention, motor control, and executive functions have been shown to be enhanced. In this context, functional measurement techniques allow for a detailed examination of the temporal and spatial dynamics of brain activity, thereby facilitating a better understanding of the effects of exercise on the brain.

Techniques such as functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), functional near-infrared spectroscopy (fNIRS), and electroencephalography (EEG) are widely employed to assess brain functions at different scales (Bullmore and Sporns, 2009). Among these, EEG stands out as a crucial tool for real-time monitoring of brain electrical activity due to its high temporal resolution. Quantitative analyses of EEG data, including event-related potentials (ERP), event-related oscillations (ERO), connectivity patterns, and spectral evaluations, reveal various dimensions of neural activity (Zhang et al., 2023). Connectivity and spectral analyses are among the most commonly utilized methods. In functional brain studies, connectivity methods are critical for assessing neural interactions and information flow between distinct brain regions. These approaches elucidate the dynamic operation of neural networks, thereby enhancing our understanding of the integrated function of brain networks underlying cognitive and motor functions (Sakkalis, 2011). Metrics such as the Phase Slope Index (PSI) are used to quantify the direction of information flow between brain regions based on phase differences across frequencies (Nolte et al., 2008). Unlike measures that only capture the strength of synchronization, PSI indicates whether one region is leading or driving another. This directional connectivity can provide critical insights into the hierarchical organization and causal interactions underlying cognitive processes. On the other hand, power spectral density (PSD) analysis characterizes the distribution of energy across the frequency components of the EEG signal. Increases or decreases in power within specific frequency bands of brain waves are associated with cognitive states and attention levels. Following PSD analysis, peak alpha frequency (PAF) emerges as a key parameter for detailed examination of alpha band activity. PAF represents the frequency at which an individual's alpha rhythm exhibits maximal power and is considered an indicator of cognitive performance (Ismail and Karwowski, 2020), attentional state (Kaushik et al., 2022), and neurological health (Alvi et al., 2022).

Evaluations of brain functions are conducted not only during task-based conditions but also in resting-state paradigms. Task-based assessments allow for the examination of neural responses associated with specific cognitive or motor demands, providing insight into functional brain organization under active engagement (Gramkow et al., 2020). Conversely, resting-state evaluations capture the brain's intrinsic functional architecture in the absence of explicit task performance, reflecting baseline patterns and spontaneous neural activity. Together, these approaches offer complementary perspectives that contribute to a comprehensive understanding of brain function and its modulation under various physiological and pathological states (Newson and Thiagarajan, 2019).

In the field of sports sciences, approaches such as functional connectivity, PSD, and PAF have been widely employed to assess athletes' cognitive and motor performance, fatigue levels, cognitive abilities, and to investigate differences between elite and novice athletes (Phan et al., 2025; Del Percio et al., 2009). For instance, in a study by Babiloni et al. (2010), the amplitude of parietal and occipital alpha 1 sources was found to be significantly higher in elite karate athletes compared to amateur athletes and non-athletes, suggesting enhanced neural synchronization during resting-state conditions in elite performers. In another study, Gu and colleagues (2022) investigated the connectivity patterns related to shooting in archers of different skill levels. Their results demonstrated that, compared to expert archers, elite archers exhibited stronger functional coupling in the beta1 and beta2 frequency bands, particularly in the frontal and central brain regions. In another study, Gutmann et al. (2018) aimed to examine the effects of different intensities of acute physical exercise on PAF. Their results showed that PAF significantly increased only after high-intensity or exhaustive exercise, and this effect lasted for approximately 30 minutes post-exercise. These findings provide important insights into how brain functions vary across different levels of performance and physical states within the field of sports sciences. Although various methods were used in sport-related neural modulations, such as PLV, PSD, or PAF, studies have used directional connectivity patterns, such as the Phase Slope Index (PSI) are limited.

This study aims to examine the effects of different types of physical activity on brain functions by comparing the resting-state PSI, PSD, and PAF parameters of sedentary individuals with those of team and individual athletes. In line with this aim, we hypothesized that sedentary individuals would exhibit

higher spectral power—particularly within the beta frequency band—whereas individual and team sport athletes would demonstrate distinct theta- and alpha-band power patterns across frontal, temporo-parietal, and occipital regions under both eyes-open and eyes-closed conditions. Moreover, we anticipated that directional connectivity (PSI) in the alpha and beta bands would differ among the groups, reflecting variations in the direction and magnitude of information flow between frontal–occipital and temporo-parietal electrode sites, while peak alpha frequency (PAF) would not show substantial group differences across conditions. The findings are expected to expand the existing literature on the neurophysiological effects of exercise and contribute to a more comprehensive understanding of the neural mechanisms associated with cognitive functions.

Method

Participants

A total of 40 individuals voluntarily participated in the present study. Participants were between the ages of 18 and 30 years and were divided into three groups: sedentary (n= 14), team athletes (n= 14), and individual athletes (n= 12). The mean age of the sedentary group was 23.57 ± 2.43 years, the team athletes' group was 22.45 ± 1.57 years, and the individual athletes' group was 21.12 ± 1.13 years. The gender distribution was as follows: the team athletes group consisted of 10 males and 4 females, the individual athletes group included 7 males and 5 females, and the sedentary group comprised 9 males and 5 females. The team athletes were actively engaged in sports such as soccer, basketball, and volleyball, whereas the individual athletes participated in disciplines including tennis, swimming, and track and field athletes. Participants were included if they were sedentary with no history of regular engagement in structured physical activities, or athletes with at least 5 years of active participation in national and international competitions. All participants reported having no history of neurological or psychological disorders that could interfere with the outcomes of the study. Additionally, none of the participants had any ophthalmologic condition that might affect visual processing. Prior to the experimental procedures, participants were instructed to abstain from consuming alcohol, caffeine, and other stimulant beverages for at least 24 hours (Lithari et al., 2012). They were also advised to refrain from using any neuroactive medications or supplements that could influence cognitive or sensory performance.

Ethical Statement

All participants were thoroughly informed about the nature, procedures, potential risks, and benefits of the study. Following the briefing, written informed consent was obtained from each participant. The study protocol was approved by the Lokman Hekim University Scientific Research Ethics Committee (No: 2025198) and was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki.

Experimental Procedures

All experimental procedures were carried out in a laboratory environment under controlled conditions. The room was dimly lit, and the ambient temperature was maintained at a constant 23°C throughout the sessions. Participants were seated in a comfortable chair that provided sufficient postural support and minimized physical discomfort or movement. Before the EEG recordings began, participants were instructed to remain as still as possible and were explicitly advised not to move, take deep breaths, clench their jaw, or make eye movements during the sessions in order to minimize physiological artifacts. The experimental protocol consisted of two consecutive sessions: a 3-minute eyes open (EO) condition followed by a 3-minute eyes closed (EC) condition. A one-minute resting interval was provided between the two sessions to minimize cognitive and sensory carry-over effects. The sequence of conditions was kept consistent for all participants, with the EO session always preceding the EC session. During the EO condition, participants were instructed to focus their gaze on a fixation cross ("+") displayed on a screen placed approximately 100 centimeters in front of them. In the EC condition, participants were asked to close their eyes and remain still and relaxed without engaging in any specific mental activity.

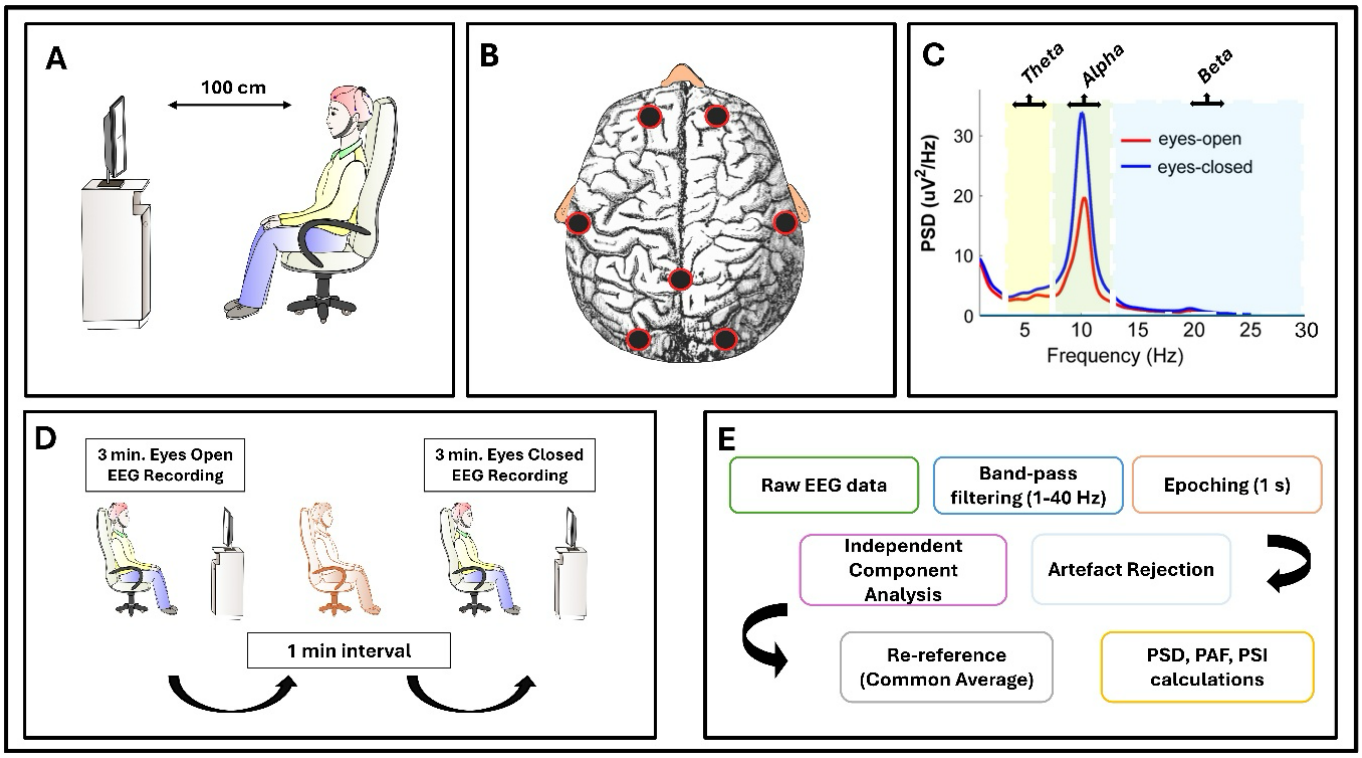
EEG Data Acquisition

EEG data were recorded using the Mentalab Explore EEG system, a wireless and wearable device with a sampling rate of 500 Hz. A total of seven scalp electrodes (Fp1, Fp2, T7, T8, O1, O2, and Pz) were positioned according to the international 10–20 system, with the left mastoid used as the reference site. The scalp areas corresponding to electrode placements were prepared using an abrasive skin prepping gel (Nuprep, Weaver and Co., Aurora, CO) to reduce skin–electrode impedance and improve signal quality. An EEG cap appropriate for each participant's head shape and size was used to ensure secure and consistent electrode contact. Electrode impedance levels were checked prior to each session and maintained below 10 kΩ. EEG signals were acquired using Mentalab Explore software, which allowed real-time visualization and signal quality monitoring. Online filtering was applied during data acquisition, including a 0.5–50 Hz bandpass filter to attenuate low-frequency drifts and high-frequency noise, and a 50 Hz notch filter to suppress electrical line noise. EEG signals were wirelessly transmitted and visually monitored throughout the recordings to ensure signal stability and minimize artifacts.

Signal Processing

EEG signal processing was conducted using MATLAB (MathWorks Inc., Natick, MA) and the EEGLAB toolbox (Delorme and Makeig, 2004). Offline IIR Butterworth filter (8^{th}-order, 48db/oct) filtering between 1 and 40 Hz was applied to improve

signal quality and ensure consistency across datasets, particularly to address potential limitations of real-time (online) filtering during data acquisition. The filtered signals were then segmented into 1-second epochs, and segments contaminated by gross artifacts (e.g., muscle activity, movement) were visually identified and excluded. To further eliminate ocular artifacts, particularly those caused by eye blinks, Independent Component Analysis (ICA) was applied, and relevant components were removed. After artifact correction, data were re-referenced using the common average reference (CAR) method to enhance spatial uniformity. Power spectral density (PSD) was estimated using Welch's method implemented in a custom MATLAB script, with a 2-second Hanning window and 1-second overlap between segments. Relative power was then calculated for each frequency band as theta (4–7 Hz), alpha (7–13 Hz), and beta (13–30 Hz) by dividing the power in each band by the total power in the 1–30 Hz range. Relative power values were log-transformed to improve the normality of the data distribution prior to statistical analysis. Prior to the analysis of PSI, epoched EEG data were transformed using Fisher's Z transformation to stabilize variance and to approximate a normal distribution, thereby ensuring the appropriateness of subsequent statistical evaluations. PAF was calculated using the centre of gravity (COG) method within the alpha band (Klimesch, 1997). This approach provides a more precise estimation of the alpha peak frequency by considering the distribution of power across the alpha band rather than only the single maximum power frequency. The experimental design and data processing steps are summarized in Figure 1.



Note. Panel (A) shows the seating arrangement of the participants during the EEG recording. Panel (B) depicts the electrode placement, with black circles indicating the precise positions of the electrodes according to the standardized montage used in the study. Panel (C) presents the separation of the EEG frequency bands into theta, alpha, and beta ranges. Panel (D) outlines the timeline of the experimental protocol, which consisted of 3 minutes of eyes-open recording, followed by 1 minute of rest, and then 3 minutes of eyes-closed recording. Panel (E) provides a schematic overview of the signal processing steps applied to the recorded EEG data.

Figure 1. Experimental procedure and data processing workflow.

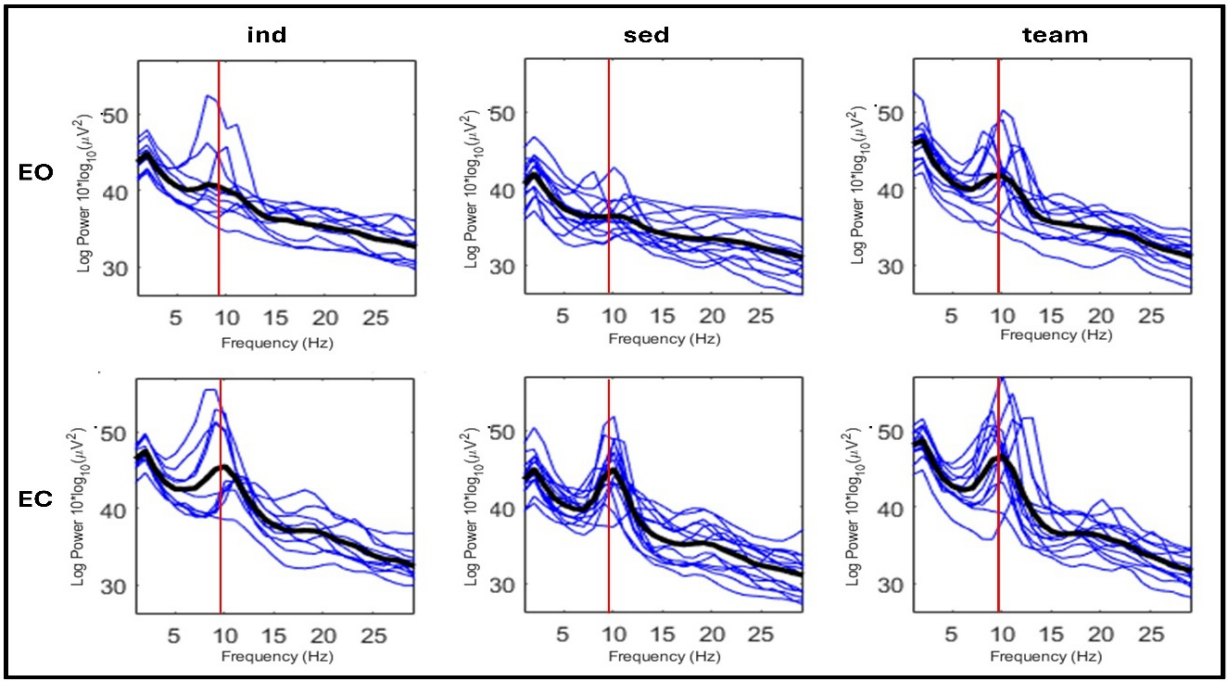
Statistical Analysis

All statistical analyses were conducted using R software (version 4.3.0). EEG values from each electrode site and electrode pairs served as the dependent variables, while group membership (sedentary, individual athletes, team athletes) was the independent variable. One-way ANOVA was performed to assess group differences for each electrode and frequency band separately. The assumptions of normality and homogeneity of variances were checked using the Shapiro–Wilk test and Levene's test, respectively, with all models meeting these assumptions ($p > 0.05$). Effect sizes for the ANOVA were reported using eta squared (η^2) to indicate the proportion of variance explained by group membership. Following significant ANOVA results, Bonferroni-corrected post hoc comparisons were conducted to identify specific group differences, with Cohen's d calculated to estimate the magnitude of pairwise differences. Since each analysis (PSI, PSD, and PAF) involved multiple dependent

variables, false discovery rate (FDR) correction was applied to control for Type I error. Statistical significance was determined at an alpha level of 0.05.

Results

Statistical results revealed significant group differences in PSD and PSI among sedentary, individual athletes, and team sport athletes across theta, alpha, and beta frequency bands under both eyes-open (EO) and eyes-closed (EC) conditions in various electrode regions. In addition, PAF scores showed that there were no significant differences among sedentary, individual, and team athletes under EO and EC conditions in all electrode sites. The grand-average PAF data are presented in Figure 2.



Note. The top row shows the eyes-open condition, and the bottom row shows the eyes-closed condition; columns correspond, from left to right, to individual athletes, sedentary, and team athletes. The red line represents the grand-average PAF scores.

Figure 2. Grand-average peak alpha frequency (PAF) data displayed for eyes-open and eyes-closed conditions across three groups.

Power Spectral Density

PSD analyses revealed significant differences among groups (Figure 3). These differences were examined in detail across the Theta, Alpha, and Beta frequency bands, which are presented below as separate subsections.

Theta frequency

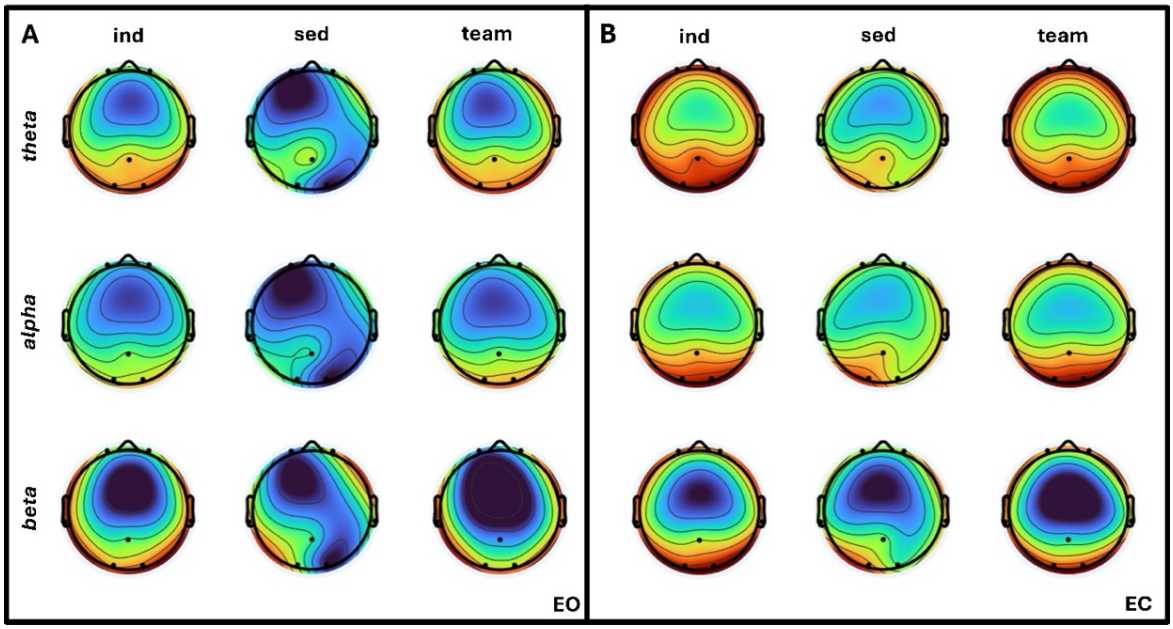
In the EC condition, significant group differences were observed at several electrode sites. At Fp2, the main effect of group was significant ($F(2, 34)= 3.82$, $p= .0319$, $\eta^2= .1834$). Post-hoc comparisons revealed a significant difference between the sedentary and team groups ($p= .0282$, $d= 0.96$), with the team group exhibiting lower theta power compared to the sedentary group. No significant differences were found between the individual group and the other groups at this electrode. At T8, the group effect was highly significant ($F(2, 34)= 7.24$, $p= .0024$, $\eta^2= .2988$). Post-hoc tests showed that the individual group had significantly higher theta power than the sedentary group ($p= .0025$, $d= 1.43$). Furthermore, a significant difference was found between the sedentary and team groups ($p= .0446$, $d= –0.93$), with the team group showing higher theta power than the sedentary group. At O2, a significant group effect was observed ($F(2, 34)= 4.19$, $p= .0236$, $\eta^2= .1978$). Post-hoc analyses revealed a significant difference between sedentary and team groups ($p= .0197$, $d= 1.01$), with the team group showing lower theta power compared to the sedentary group. No significant differences were detected between the individual group and the other groups. At Pz, a significant group effect was also found ($F(2, 34)= 8.16$, $p= .0013$, $\eta^2= .3244$). Post-hoc comparisons indicated that the individual group had significantly higher theta power than the sedentary group ($p= .0024$, $d= 1.50$). Additionally, the team group demonstrated significantly higher theta power than the sedentary group ($p= .0108$, $d= –1.12$). In the EO condition, a significant group effect was observed at O2 ($F(2, 34)= 3.47$, $p= .0427$, $\eta^2= .1693$). Post-hoc analyses revealed a significant difference between sedentary and team groups ($p= .0421$, $d= 0.92$), with the team group showing lower theta power compared to the sedentary group. No significant differences were observed between the individual group and the others.

Alpha frequency

In the EO condition, significant group differences were observed at the Fp1 electrode ($F(2, 34)= 4.08$, $p= .0259$, $\eta^2= .1935$). Post-hoc comparisons indicated a significant difference between the sedentary and team groups at Fp1 ($p= .0218$, $d= –1.20$), with the team group demonstrating higher alpha power than the sedentary group. In the EC condition, significant group differences emerged at the T8 ($F(2, 34)= 10.22$, $p< .001$, $\eta^2= .3753$) and Pz ($F(2, 34)= 4.85$, $p= .0140$, $\eta^2= .2219$) electrodes. At T8, post-hoc analyses revealed significant differences between the individual and sedentary groups ($p= .0021$, $d= –1.52$), as well as between the sedentary and team groups ($p= .0011$, $d= 1.56$). The sedentary group showed notably higher alpha power compared to both individual and team groups. At Pz, a significant difference was found between the individual and sedentary groups ($p= .0172$, $d= –1.28$), with the sedentary group exhibiting higher alpha power than the individual group.

Beta frequency

In the EC condition, a significant group effect was found at the Fp2 electrode ($F(2, 34)= 10.53$, $p= .0003$, $\eta^2= .3824$). Post-hoc comparisons revealed that the individual group exhibited significantly lower beta power than the sedentary group ($p= .0145$, $d= –1.42$). Additionally, the team group showed significantly lower beta power than the sedentary group ($p= .0003$, $d= 1.67$). No significant difference was observed between the individual and team groups. In the EO condition, significant group differences were observed across multiple electrode sites. At Fp1, the group effect was significant ($F(2, 34)= 9.48$, $p= .0005$, $\eta^2= .358$). Post-hoc tests revealed a significant difference between the sedentary and team groups ($p= .0004$, $d= 1.96$), with the team group showing lower beta power compared to the sedentary group. No significant differences were found between the individual group and other groups at this electrode. At Fp2, significant group differences were also observed ($F(2, 34)= 8.71$, $p= .0009$, $\eta^2= .3388$). The sedentary group showed significantly higher beta power than the team group ($p= .0006$, $d= 1.79$), while differences involving the individual group were not significant. At O1, the group effect was significant ($F(2, 34)= 6.21$, $p= .0050$, $\eta^2= .2676$). Post-hoc analyses revealed a significant difference between sedentary and team groups ($p= .0038$, $d= 1.49$), with the team group showing lower beta power compared to the sedentary group. No significant differences were detected between the individual group and others. At O2, a significant group effect was present ($F(2, 34)= 3.71$, $p= .0349$, $\eta^2= .1791$). Post-hoc comparisons showed that the team group had significantly lower beta power than the sedentary group ($p= .0424$, $d= 1.09$). Differences involving the individual group were not significant. At Pz, the significant group effect was observed ($F(2, 34)= 15.26$, $p< .0001$, $\eta^2= .473$). Post-hoc tests revealed that the sedentary group had significantly higher beta power compared to both the individual group ($p= .0068$, $d= –1.21$) and the team group ($p< .0001$, $d= 2.39$). No significant difference was found between the individual and team groups.



Note. Panel (A) depicts the eyes-open condition, while panel (B) shows the eyes-closed condition. Within each panel, the top row represents the theta frequency band, the middle row the alpha band, and the bottom row the beta band. Columns correspond to the three groups: individual athletes, sedentary, and team athletes, from left to right. These maps provide a spatial representation of PSD distribution across the scalp for each frequency band and group under both experimental conditions.

Figure 3. Topographic maps of power spectral density (PSD) scores across different frequency bands and participant groups.

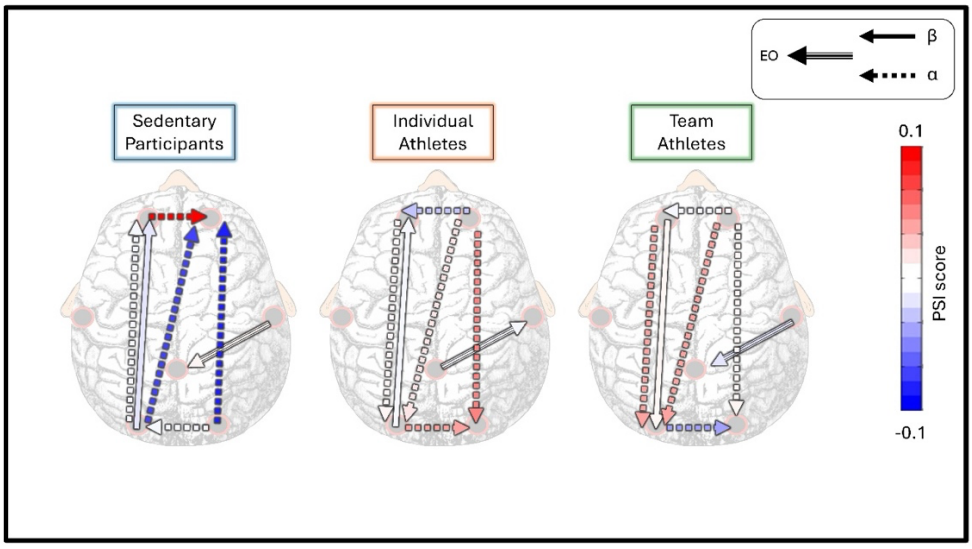
Table 1. Significant power spectral density differences

Frequency	*Condition*	*Electrode*	*F*	*p*	*eta²*	*Comparison*	*d*
Theta	EC	Fp2	3,82	0,0319	0,1834	Sedentary vs Team	0,96
Theta	EC	T8	7,24	0,0024	0,2988	Individual vs Sedentary	1,43
Theta	EC	T8	7,24	0,0024	0,2988	Sedentary vs Team	-0,93
Theta	EC	O2	4,19	0,0236	0,1978	Sedentary vs Team	1,01
Theta	EC	Pz	8,16	0,0013	0,3244	Individual vs Sedentary	1,5
Theta	EC	Pz	8,16	0,0013	0,3244	Team vs Sedentary	-1,12
Theta	EO	O2	3,47	0,0427	0,1693	Sedentary vs Team	0,92
Alpha	EO	Fp1	4,08	0,0259	0,1935	Sedentary vs Team	-1,2
Alpha	EC	T8	10,22	0,001	0,3753	Individual vs Sedentary	-1,52
Alpha	EC	T8	10,22	0,001	0,3753	Sedentary vs Team	1,56
Alpha	EC	Pz	4,85	0,014	0,2219	Individual vs Sedentary	-1,28
Beta	EC	Fp2	10,53	0,0003	0,3824	Individual vs Sedentary	-1,42
Beta	EC	Fp2	10,53	0,0003	0,3824	Team vs Sedentary	1,67
Beta	EO	Fp1	9,48	0,0005	0,358	Sedentary vs Team	1,96
Beta	EO	Fp2	8,71	0,0009	0,3388	Sedentary vs Team	1,79
Beta	EO	O1	6,21	0,005	0,2676	Sedentary vs Team	1,49
Beta	EO	O2	3,71	0,0349	0,1791	Sedentary vs Team	1,09
Beta	EO	Pz	15,26	0,0001	0,473	Sedentary vs Individual	-1,21
Beta	EO	Pz	15,26	0,0001	0,473	Sedentary vs Team	2,39

Frequency: EEG frequency band (Theta, Alpha, Beta); Condition: Eye condition: EC= Eyes Closed, EO= Eyes Open; Electrode: Electrode location; Comparison: Groups compared in post-hoc analysis

Phase Slope Index

Significant group differences were observed in the beta band during the EC condition at the Fp1O1 electrode pair ($F(2,34)= 3.61$, $p= 0.038$, $\eta^2= 0.18$), with post-hoc analyses revealing a difference between the sedentary and team athletes' groups ($p= 0.041$, $d= -0.958$). In the beta band during the EO condition, the T8Pz site showed a pronounced group effect ($F(2,34)= 6.34$, $p= 0.005$, $\eta^2= 0.27$), particularly between the individual athletes and team athletes' groups ($p= 0.003$, $d= -1.407$). Within the alpha band under the EC condition, significant differences were detected at multiple electrode pairs, including Fp1Fp2 ($F(2,34)= 5.64$, $p= 0.008$, $\eta^2= 0.25$), Fp1O1 ($F(2,34)= 3.89$, $p= 0.030$, $\eta^2= 0.19$), Fp2O1 ($F(2,34)= 8.59$, $p= 0.001$, $\eta^2= 0.34$), Fp2O2 ($F(2,34)= 4.67$, $p= 0.016$, $\eta^2= 0.22$), and O1O2 ($F(2,34)= 5.38$, $p= 0.009$, $\eta^2= 0.24$). Post-hoc tests for the alpha EC condition revealed significant differences between the individual athletes and sedentary groups at Fp1Fp2 ($p= 0.015$, $d= -1.10$) and Fp2O1 ($p= 0.015$, $d= 1.14$). Significant differences were also found between the sedentary and team athletes' groups at Fp1Fp2 ($p= 0.032$, $d= 0.93$), Fp1O1 ($p= 0.031$, $d= -1.06$), Fp2O1 ($p= 0.001$, $d= -1.39$), and Fp2O2 ($p= 0.072$, $d= -0.82$). Additionally, the individual and team athlete groups differed significantly at O1O2 ($p= 0.007$, $d= 1.29$). The direction and magnitude of these group differences are illustrated in Figure 4.



Note. Dashed lines represent connections in the alpha frequency band, solid lines correspond to the beta frequency band, and striped lines (T8-Pz) indicate eyes-open conditions. Arrows on the lines indicate the directionality of the connections, while the colours represent the strength of the PSI values.

Figure 4. Connectivity patterns and directions of significant differences in electrode pairs in PSI scores.

Table 2. Significant phase slope index differences

Frequency	*Condition*	*Electrode Pair*	*F*	*p*	*eta²*	*Comparison*	*d*
Beta	EC	Fp1-O1	3,61	0,038	0,18	Sedentary vs Team	-0,958
Beta	EO	T8-Pz	6,34	0,005	0,27	Individual vs Team	-1,407
Alpha	EC	Fp1-Fp2	5,64	0,008	0,25	Individual vs Sedentary	-1,1
Alpha	EC	Fp1-Fp2	5,64	0,008	0,25	Sedentary vs Team	0,93
Alpha	EC	Fp1-O1	3,89	0,03	0,19	Sedentary vs Team	-1,06
Alpha	EC	Fp2-O1	8,59	0,001	0,34	Individual vs Sedentary	1,14
Alpha	EC	Fp2-O1	8,59	0,001	0,34	Sedentary vs Team	-1,39
Alpha	EC	Fp2-O2	4,67	0,016	0,22	Sedentary vs Team	-0,82
Alpha	EC	O1-O2	5,38	0,009	0,24	Individual vs Team	1,29

Frequency: EEG frequency band (Alpha, Beta); Condition: Eye condition: EC= Eyes Closed, EO= Eyes Open; Electrode Pair: Pair of electrodes; Comparison: Groups compared in post-hoc analysis

Discussion

This study investigated resting-state EEG activity by comparing PSD, PAF, and PSI across sedentary, individual sport athletes, and team sport athletes. Measurements were taken under both EO and EC conditions. The findings demonstrated distinct group-related modulations in oscillatory brain activity within the theta, alpha, and beta frequency bands, while PAF values did not differ significantly among the groups.

Peak Alpha Frequency Differences

In contrast to the robust differences observed in PSD and PSI, PAF did not differ significantly among sedentary, individual sport athletes, and team sport athletes under either EO or EC conditions. PAF is generally regarded as a stable neurophysiological trait linked to cognitive processing speed, attentional capacity, and overall brain efficiency (Grandy et al., 2013). Previous research in sport contexts has shown that PAF—or its closely related measure, PAF can be higher in elite athletes and may correlate with specific cognitive abilities such as sustained attention. For example, Zhang et al. (2021) reported that elite ice hockey players displayed higher PAF than intermediate players, and that higher PAF was associated with better performance in a multiple object tracking task. Similarly, studies in precision sports have suggested that pre-performance PAF reflects enduring individual traits, while post-task changes may capture transient state fluctuations (Christie et al., 2017). However, other work (Hülsdünker and Mierau, 2021) has found no association between PAF and visuomotor speed, indicating that its predictive value may be domain-specific. Taken together, these findings suggest that while PAF may be sensitive to certain aspects of expertise or cognitive capacity, it remains largely resistant to short-term experiential influences and is shaped primarily by stable neurobiological factors. Consistent with this perspective, the present study found no significant differences in PAF between sedentary, individual athletes, and team athletes, indicating that sport participation at least within the scope and sample of this study does not appear to alter the alpha peak frequency.

Power Spectral Density Differences

This study investigated resting-state EEG spectral power differences across sedentary individuals, individual athletes, and team athletes, focusing on Theta, Alpha, and Beta frequency bands during EC and EO conditions. Our findings reveal distinct modulation patterns in neural oscillations associated with physical activity types, highlighting potential neurophysiological adaptations related to sport participation. Significant group differences in Theta power were observed at multiple electrode sites during the EC condition. Specifically, individual athletes demonstrated higher Theta power at temporal (T8) and parietal (Pz) electrodes compared to sedentary individuals, while team athletes showed lower Theta power at frontal (Fp2) and occipital (O2) sites relative to sedentary participants. The elevated Theta in individual athletes aligns with prior research linking Theta oscillations to enhanced cognitive control, working memory, and task-related attentional processes (Cavanagh and Frank, 2014). These results suggest that individual sports may selectively enhance cognitive networks reflected in increased Theta power. Conversely, the reduced Theta power in team athletes at frontal and occipital sites may reflect more efficient cortical processing and neural inhibition mechanisms during rest, possibly due to the high demands of dynamic visuomotor coordination in team sports (Klimesch, 2012). During the EO condition, Theta power differences were primarily limited to occipital sites, with team athletes exhibiting lower Theta than sedentary individuals, consistent with greater visual attention and processing efficiency in athletes (Li and Smith, 2021). Alpha power analyses revealed that sedentary participants generally exhibited higher Alpha activity at temporal (T8) and parietal (Pz) sites during EC compared to both athlete groups, indicating relatively greater cortical idling or reduced engagement of attention-related networks (Klimesch, 1999). The suppression of Alpha power in athletes aligns with evidence that Alpha desynchronization reflects enhanced cortical excitability and information processing efficiency, particularly relevant in sports requiring sustained attention and sensorimotor integration (Bazanova and Vernon, 2014). Interestingly, during the EO condition, team athletes showed significantly higher Alpha power at frontal (Fp1)

compared to sedentary individuals, possibly reflecting enhanced top-down inhibitory control mechanisms that facilitate selective attention in complex environments (Bazanova and Vernon, 2014; Sauseng et al., 2005). This dynamic modulation of Alpha suggests that team sports may foster flexible neural inhibition strategies. In both EC and EO conditions, sedentary individuals consistently showed higher Beta power across frontal (Fp1, Fp2), occipital (O1, O2), and parietal (Pz) electrodes compared to athlete groups, with team athletes generally demonstrating the lowest Beta power. Elevated Beta power in resting states is often interpreted as increased cortical excitability or arousal but can also indicate inefficient motor cortical inhibition (Engel and Fries, 2010). The reduced Beta power in athletes may represent refined sensorimotor processing and motor inhibition mechanisms, potentially resulting from extensive motor training and neuroplasticity associated with sport participation (Neuper and Pfurtscheller, 2001). The notably lower Beta power in individual and team athletes compared to sedentary participants, especially in frontal and parietal areas, supports the hypothesis that regular physical activity leads to more efficient neural functioning and greater motor control at rest (Rossiter et al., 2014).

Phase Slope Index Differences

PSI analyses revealed sport-related reconfigurations of directed functional connectivity, primarily within the alpha and beta bands, indicating that regular athletic engagement is associated not only with amplitude changes (PSD) but with altered information flow across cortical networks. These directed-connectivity differences were spatially specific in our data: beta-band fronto-occipital (Fp1–O1) PSI distinguished sedentary from team athletes under eyes-closed conditions, whereas beta T8–Pz PSI during eyes-open conditions separated individual from team athletes; alpha-band PSI under eyes-closed conditions produced a widespread pattern of group differences across frontal, fronto-occipital and occipital electrode pairs (Fp1–Fp2, Fp1–O1, Fp2–O1, Fp2–O2, O1–O2). These results indicate that different types of sport practice may sculpt both the directionality and locus of interregional communication in resting networks.

The directionality of the observed fronto-occipital effects is consistent with prior work showing that top-down control and frontally-driven modulation of posterior sensory regions are important substrates of skilled sensorimotor performance; resting-state investigations that relate motor imagery and motor activation to large-scale network interactions further implicate fronto-posterior pathways in motor planning and imagery processes. In this respect, studies of resting-state functional connectivity and motor-imagery have documented fronto-occipital/fronto-parietal coupling that supports task-relevant information routing, suggesting that the Fp1–O1 beta-PSI differences in our sample may reflect sport-dependent tuning of top-down control circuitry (Saiote et al., 2016). The broader pattern of alpha-band PSI differences across frontal and occipital pairs aligns with recent sport-specific EEG findings showing that athletes exhibit distinct resting connectivity topologies when compared to non-athletes, and that high-level athletes often demonstrate stronger or more extensive functional connections in task-relevant networks. Such large-scale connectivity differences have been related to “neural efficiency” and enhanced sensorimotor integration in athletic populations, which provides a plausible functional interpretation for the multiple alpha-band PSI effects observed in our EC data (Gong et al., 2019; Ramyarangsi et al., 2024). Complementary high-resolution resting EEG work further supports the idea that amplitude and connectivity remodeling coexist in athletes: resting-state spectral differences (e.g., alpha/beta modulations) reported in elite samples co-occur with altered connectivity metrics, pointing to experience-dependent neuroplasticity in both local oscillatory power and network-level organization. Our PSI findings dovetail with this literature by showing that the direction of information transfer — not only its strength — is sensitive to athletic specialization (Babiloni et al., 2010). Methodologically, PSI is particularly appropriate for interpreting these results because it estimates directed interactions while being relatively robust to spurious coupling generated by volume conduction and source mixing; both the original PSI formulation and subsequent simulation/validation studies demonstrate that PSI provides meaningful estimates of information flow and is less likely than many alternative metrics to report artifactual directionality in EEG/MEG data. This methodological property increases confidence that the group differences we observe reflect genuine sport-related reorganization of directed cortical interactions rather than measurement confounds (Ewald et al., 2013).

Taken together, the beta-band Fp1–O1 and T8–Pz PSI differences point to sport-specific adaptations in circuits supporting top-down control, sensorimotor integration, and context-dependent attentional allocation: team sports—characterized by high demands on rapid, externally-directed attention and dynamic interpersonal coordination—may foster particular fronto-occipital beta-directionality at rest, whereas individual-sport demands leave a different PSI fingerprint. These directed-connectivity signatures may underlie the behavioural advantages frequently reported in athlete populations and suggest testable hypotheses for interventional and longitudinal work.

Limitations

While the study offers significant insights, certain limitations should be acknowledged. First, the EEG data were collected using a limited number of electrodes, which restricts the comprehensive examination of cortical activity and brain networks, particularly in relation to deep brain structures and large-scale functional networks. Future research employing high-density electrode arrays may overcome this limitation and enable more detailed topographic analyses. Second, the focus on resting-state EEG alone may be insufficient to capture the dynamic cognitive and motor processes underlying athletic performance.

Third, the relatively limited sample size may reduce the statistical power of the analyses and limit the generalizability of the findings. Therefore, combining resting-state data with EEG recordings obtained during specific motor and cognitive tasks could provide a better understanding of the causal relationships between neural efficiency and motor performance.

Conclusion

This study highlights that different forms of sport participation are linked to specific resting-state EEG alterations. Although peak alpha frequency showed no group differences, significant variations in power spectral density and phase slope index were evident among sedentary individuals, individual athletes, and team athletes. These results indicate that athletic training shapes neural oscillations and directed connectivity, reflecting adaptations in cognitive control, sensorimotor processing, and attentional networks. The distinct neural profiles observed between individual and team sports underscore the role of sport-specific demands in modulating brain function. However, future studies with larger sample sizes are needed to confirm these findings and increase the generalizability of the results. Future longitudinal studies are necessary to establish causal links and to explore how these neurophysiological changes may enhance performance and inform tailored training strategies.

Practical Implications

The present findings suggest that regular participation in individual and team sports is associated with distinct neural adaptations in oscillatory activity, particularly within theta, alpha, and beta frequency bands, which are linked to attention and cognitive control. These results indicate that structured sport engagement may enhance neurocognitive functioning compared to sedentary lifestyles, with team athletes showing advantages in collective coordination and attentional processes, while individual athletes exhibit patterns associated with sustained focus and self-regulation. Although no differences were observed in peak alpha frequency, suggesting that general cognitive speed remains comparable across groups, the observed PSD and PSI differences highlight sport-specific neural benefits. Practically, these insights may guide coaches, sport psychologists, and educators in developing tailored mental training, neurofeedback interventions, and exercise-based programs to optimize performance, cognitive resilience, and mental well-being in both athletic and non-athletic populations.

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Conflict of Interest

There is no conflict of interest among the authors related to publication of this article.

Author Contributions

Research idea: MD, AS, BG; Research design: MD, BG; Analysis of data: MD, BG; Manuscript writing: MD, AS; Critical review: BG

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