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Effects of QEEG-Guided Low-Intensity Transcranial Magnetic Stimulation on Executive Network Function in an Athlete with Chronic Traumatic Brain Injury

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Case Report

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Abstract

Background

Traumatic brain injury (TBI) can cause persistent executive dysfunction, critically affecting athletes' cognitive control and decision-making. Personalized neuromodulation, guided by quantitative electroencephalography (QEEG), may enhance network function.

Methods

In this case study, a 33-year-old male athlete with chronic TBI underwent a 12-session individualized low-intensity transcranial magnetic stimulation (Li-TMS) protocol guided by quantitative electroencephalography (QEEG). Stimulation targeted Pz, F4, and F3 using sequential low-delta, infra-low frequency, and sensorimotor rhythm protocols. Resting-state QEEG was recorded before and after the intervention.

Results

Post-intervention QEEG showed reduced slow-wave activity and normalization of alpha, beta, and sensorimotor rhythm oscillations in frontal and central regions. Connectivity analyses revealed improved intra- and inter-hemispheric organization and enhanced functional integration within executive control networks.

Conclusions

This case provides preliminary evidence that individualized, QEEG-guided low-intensity TMS may support restoration of executive network organization in chronic TBI. The findings highlight the potential of precision neuromodulation as a targeted rehabilitation strategy for athletes with persistent cognitive impairment.

1. Introduction

Traumatic brain injury (TBI) is one of the leading causes of persistent cognitive impairment in young and physically active populations and poses a particular challenge for athletes due to its impact on both daily functioning and professional performance. Even in cases where structural neuroimaging findings appear mild or focal, long-lasting functional alterations within large-scale brain networks may persist and contribute to higher-order cognitive deficits (1). Among the cognitive sequelae of TBI, executive dysfunction occupies a central role, as executive functions are essential for goal-directed behavior, adaptive decision-making, and cognitive flexibility (2, 3).

Executive functions comprise a set of higher order cognitive processes including sustained attention, working memory, response inhibition, cognitive flexibility, and planning, which are primarily mediated by distributed front parietal networks (2). Damage to frontal brain regions, commonly observed in acceleration and deceleration injuries and motor vehicle accidents, can disrupt the efficiency of these networks and result in slowed cognitive processing, impaired cognitive control, and deficits in decision making (3). These impairments are particularly detrimental for athletes, for whom optimal executive functioning is critical for rapid reactions, motor planning, and behavioral adaptation under high pressure conditions. Consistent with this, a systematic review by Kohler and colleagues demonstrated that athletes with traumatic brain injury perform more poorly in attention, memory, processing speed, and executive function compared with healthy individuals (4, 5). Despite substantial progress in the acute management of traumatic brain injury, the rehabilitation of persistent cognitive impairments remains a significant clinical challenge. Conventional cognitive rehabilitation approaches have shown variable effectiveness and are often limited by prolonged intervention periods, dependence on active patient engagement, and heterogeneous treatment outcomes (6). As a result, recent research has increasingly focused on non-invasive neuromodulation techniques, particularly transcranial magnetic stimulation, as potential tools for modulating dysfunctional neural activity and supporting cognitive recovery (7). Accumulating evidence suggests that transcranial magnetic stimulation can influence cortical excitability and neural oscillatory dynamics, thereby modulating the activity of networks involved in cognitive control.

Neural oscillations in frontal regions, especially within the beta frequency range, play a critical role in executive control, working memory, and response inhibition. Alterations in alpha and beta power and instability of dominant oscillatory frequencies have been consistently reported following traumatic brain injury and are associated with impaired executive functioning (8). In recent years, low intensity brain stimulation approaches have received growing attention due to their favorable safety profile and higher tolerability. Preliminary findings indicate that low intensity magnetic stimulation may enhance neural efficiency without inducing excessive cortical excitation, making it particularly suitable for individuals with chronic traumatic brain injury (9–11). In this regard, Quantitative electroencephalography (QEEG) provides an objective and sensitive method for identifying functional brain alterations following traumatic brain injury and for monitoring treatment related neurophysiological changes. Reduced stability and abnormal distribution of beta activity in frontal regions have been reported as neurophysiological markers of executive dysfunction after brain injury, whereas increased organization and normalization of these oscillatory patterns are associated with improved executive control. Furthermore, integrating quantitative electroencephalography data with structural neuroimaging findings such as computed tomography enables a more comprehensive understanding of the relationship between structural injury, functional brain reorganization, and cognitive outcomes (12).

Given the limited clinical evidence regarding the effects of low intensity transcranial magnetic stimulation in athletes with chronic traumatic brain injury, detailed case studies that simultaneously examine neurophysiological and cognitive changes are of considerable clinical importance. Therefore, the present study aimed to investigate the effects of a quantitative electroencephalography guided and

individualized low intensity transcranial magnetic stimulation protocol on executive function related neurophysiological markers in an athlete with chronic traumatic brain injury. By integrating clinical findings, structural imaging data, and pre and post intervention quantitative electroencephalography assessments, this study seeks to provide preliminary evidence supporting biomarker informed neuromodulation approaches in cognitive rehabilitation following traumatic brain injury.

1.1. Case history

The patient was a 33 year old male athlete who sustained a traumatic brain injury following a motor vehicle accident. After the injury, he experienced persistent neurological and vestibular symptoms, including intermittent headaches, positional dizziness, impaired concentration, and short term memory difficulties. These symptoms persisted despite the absence of severe structural abnormalities requiring surgical intervention. Initial computed tomography imaging revealed a left frontotemporal subdural hematoma measuring 5.6 mm in thickness, a left frontal epidural hematoma measuring 6.7 mm, and mild cerebral contusion hemorrhage in the left front parietal region. Additional findings included a left parietal sub periosteal hematoma, fracture of the right lateral pterygoid process, and signs of skull base trauma with air fluid levels in the bilateral sphenoid sinuses. No midline shift was observed, indicating the absence of significant mass effect. Vestibular assessment demonstrated abnormalities consistent with bilateral vestibular dysfunction, including head shaking nystagmus and impaired semicircular canal function. Two years after the injury, the patient continued to report balance instability during dynamic movements, cognitive fatigue, attentional deficits, and reduced working memory capacity, consistent with chronic post traumatic cognitive and vestibular dysfunction. Given the persistence of these symptoms, the patient underwent quantitative electroencephalography evaluation followed by a targeted neuromodulation intervention.

2. Methods

2.1. Study Design

This study was conducted using a single-case; quasi-experimental pre–post design to examine within-subject neurophysiological changes associated with an individualized, QEEG-guided low-intensity transcranial magnetic stimulation (Li-TMS) intervention. Given the exploratory nature of the study and the single-participant design, the analysis focused on descriptive evaluation of pre- and post-intervention changes rather than population-level statistical inference.

2.2. Participant

The participant was a 33-year-old male competitive athlete who sustained a traumatic brain injury (TBI) following a motor vehicle accident. At the time of intervention, the participant was approximately two years post-injury and continued to experience persistent cognitive and vestibular symptoms, including impaired attention, reduced working memory, cognitive fatigue, headaches, dizziness, and balance

instability during dynamic movements. Structural neuroimaging revealed focal frontotemporal and front parietal injuries without midline shift or indications for surgical intervention.

2.3. Neurophysiological Assessment (QEEG)

Quantitative electroencephalography (QEEG) was recorded before and after the intervention using standardized resting-state EEG acquisition procedures under eyes-closed conditions. Spectral power was computed for delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–25 Hz), sensorimotor rhythm (SMR; 12–15 Hz), and high beta frequency bands. EEG data were transformed into Z-scores relative to age-matched normative databases to identify deviations from typical neural activity patterns. Baseline QEEG assessment demonstrated elevated slow-wave activity, frontal oscillatory dysregulation, hemispheric asymmetries, and disrupted front parietal functional connectivity, consistent with executive dysfunction associated with chronic TBI.

2.4. Intervention Protocol

An individualized neuromodulation protocol was developed based on baseline QEEG findings. The intervention consisted of 12 sessions of low-intensity magnetic stimulation delivered using the Beta One device. This system applies subthreshold magnetic fields that differ fundamentally from conventional high-intensity repetitive TMS (rTMS) and is therefore classified as low-intensity TMS in accordance with emerging neuromodulation literature. Stimulation was administered sequentially across three cortical targets:

- **Pz** (Sessions 1–4): Low Delta protocol aimed at reducing excessive slow-wave activity and improving large-scale cortical network efficiency.
- **F3** (Sessions 5–8): Sensorimotor Rhythm (SMR) protocol designed to enhance frontal executive control, attentional regulation, and sensorimotor integration.
- **F4** (Sessions 9–12): Infra-Low Frequency (ILF) protocol targeting frontal regulatory networks associated with cognitive load, emotional regulation, and executive balance.

All sessions were conducted under standardized conditions, with stimulation parameters individually adjusted based on neurophysiological response and participant tolerability.

2.5. Data Analysis

Given the single-case design, data analysis was descriptive and within-subject in nature. Pre- and post-intervention QEEG measures were compared to characterize changes in spectral power, Z-score deviations, and functional connectivity patterns across targeted cortical regions. Emphasis was placed on the direction and magnitude of neurophysiological changes relative to normative reference values, rather than inferential statistical testing. Topographic Z-score maps and connectivity visualizations were used to assess intra- and inter-hemispheric network organization and to illustrate intervention-associated modulation of executive function–related neural circuits.

2.6. Ethical Considerations

This study was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from the participant prior to participation and the publication of anonymized data. The study protocol was reviewed and approved by the Ethics Committee of the Faculty .of Sport Sciences and Health, University of Tehran

3. Results

Descriptive within-subject comparisons of pre- and post-intervention quantitative electroencephalography (QEEG) measures revealed marked neurophysiological modulation following the 12-session individualized low-intensity transcranial magnetic stimulation (Li-TMS) protocol. At baseline, the participant exhibited prominent abnormalities across multiple frequency bands, characterized by elevated slow-wave activity (delta and theta), reduced alpha and beta power in frontal regions, hemispheric asymmetries, and disrupted front parietal and frontotemporal network organization.

3.1. Spectral Power Modulation

Following the intervention, QEEG analysis demonstrated a clear reduction in excessive slow-wave activity, particularly within central and front parietal regions. Delta (1–4 Hz) and theta (4–8 Hz) power at Pz showed normalization toward age-matched reference ranges, indicating reduced cortical slowing and improved large-scale network efficiency. In frontal regions, especially at F3, alpha (8–12 Hz) and beta (12–25 Hz) activity increased and exhibited greater stability relative to baseline. Sensorimotor rhythm (SMR; 12–15 Hz) power at F3 also showed marked normalization, reflecting improved frontal executive regulation, attentional control, and sensorimotor integration. At F4, elevated high beta activity observed at baseline was reduced post-intervention, suggesting decreased cognitive load and improved .emotional–executive balance

3.2. Topographic Organization

Post-intervention Z-score topographic maps revealed substantial normalization of previously focal abnormalities. Regions that initially demonstrated pronounced delta and theta elevations showed reduced deviation from normative values and a more homogeneous spatial distribution. Faster frequency bands (alpha and beta) exhibited increased symmetry and more coherent topographic .organization across frontal and central areas, consistent with enhanced neurophysiological stability

3.3. Functional Connectivity and Hemispheric Integration

Connectivity analyses indicated improved intra- and inter-hemispheric network organization following Li-TMS. Baseline assessments revealed disrupted connectivity within front parietal and frontotemporal networks, particularly in the right hemisphere, accompanied by marked hemispheric asymmetries. Post-intervention, Z-score deviations in homologous inter-hemispheric connections were reduced, with most connections approaching normative ranges. Within-network connectivity in executive control–related

circuits demonstrated increased coherence across alpha and beta frequency bands, while excessive slow-wave coupling in delta and theta bands was attenuated. These changes suggest improved integration and coordination of neural activity within distributed cortical networks underlying executive .function

3.4. Summary of Neurophysiological Changes

Collectively, the observed QEEG changes indicate that the individualized, QEEG-guided Li-TMS protocol was associated with normalization of oscillatory dynamics, reduced hemispheric asymmetry, and enhanced functional organization of executive control networks. The spatial and frequency-specific nature of these changes corresponded closely with the targeted stimulation sites (Pz, F4, and F3), supporting the physiological specificity of the intervention (Figure 2).

4. Discussion

This case study investigated the neurophysiological effects of an individualized, QEEG-guided low-intensity transcranial magnetic stimulation (Li-TMS) protocol on executive control networks in a competitive athlete with chronic traumatic brain injury (TBI). The findings indicate consistent modulation of oscillatory activity and functional network organization following intervention, particularly within frontal, front parietal, and frontotemporal circuits known to support executive function and cognitive control.

One of the primary observations was the reduction of excessive slow-wave activity (delta and theta) alongside increased stability and normalization of faster oscillations, including alpha, beta, and sensorimotor rhythm (SMR). In chronic TBI, elevated slow-wave power is widely interpreted as a marker of cortical inefficiency, disrupted large-scale network integration, and increased cognitive load. Conversely, normalization of oscillatory balance reflects improved excitatory–inhibitory regulation and more efficient information processing across distributed cortical systems (13, 14). The frequency-specific changes observed in this case align with network neuroscience models emphasizing the role of coordinated neural oscillations in supporting higher-order cognitive functions (15–17). Importantly, the spatial distribution of neurophysiological changes corresponded closely to the targeted stimulation sites (Pz, F3, and F4), supporting the physiological specificity of the QEEG-guided intervention. Increases in alpha and beta organization within left frontal regions and enhanced SMR stability are consistent with improved executive regulation, attentional control, and sensorimotor integration. Additionally, the reduction of elevated high beta activity in right frontal regions suggests decreased cognitive strain and improved emotional–executive balance, a pattern frequently disrupted following frontal and frontotemporal injury (16, 17).

Beyond spectral power modulation, connectivity analyses revealed meaningful reorganization of intra- and inter-hemispheric networks. Baseline QEEG demonstrated fragmented connectivity and hemispheric asymmetry within executive control networks, particularly involving front parietal and frontotemporal circuits. Following Li-TMS, these abnormalities were attenuated, with post-intervention connectivity

patterns approaching normative organization. Such improvements in network-level integration are increasingly recognized as key neurophysiological substrates of executive function and cognitive flexibility (18). In particular, normalization of theta- and alpha-band connectivity may reflect improved coordination between prefrontal control regions and distributed cortical areas supporting goal-directed behavior (19).

The analytic approach adopted in this study emphasizes coherent patterns of oscillatory regulation and network organization rather than isolated numerical changes. In single-case neuromodulation research, especially when guided by individualized QEEG biomarkers, descriptive and network-oriented analyses provide clinically meaningful insight into functional brain reorganization (12, 20). This approach aligns with prior EEG- and QEEG-based studies in which normalization of Z-score distributions, hemispheric symmetry, and connectivity patterns were interpreted as indicators of improved neural efficiency and functional integration (19–21). By focusing on convergence across frequency bands, cortical regions, and network-level measures, the present findings support interpretation of intervention-related modulation without reliance on inferential statistical comparisons. These results are consistent with emerging evidence supporting the use of non-invasive brain stimulation techniques to enhance cognitive function and executive control in neurological populations (22, 23). Low-intensity neuromodulation approaches, in particular, may offer advantages in terms of tolerability and safety while still facilitating neuroplasticity changes in oscillatory dynamics and functional connectivity (10, 11). For athlete populations, in whom efficient executive network integration is critical for performance under high cognitive and physical demands; such individualized, biomarker-informed interventions may be especially relevant. From a network neuroscience perspective, athletes rely on efficient integration of executive, attentional, and sensorimotor networks to support rapid adaptation and goal-directed behavior. Traumatic brain injury–related disruption of these networks may therefore be particularly salient in athletic populations.

Several limitations should be acknowledged. The single-case design limits generalizability and precludes causal inference. The absence of concurrent standardized neuropsychological assessments restricts interpretation of functional behavioral outcomes, and spontaneous recovery or non-specific intervention effects cannot be entirely excluded. Additionally, the lack of longitudinal follow-up prevents evaluation of the durability of observed neurophysiological changes. Future studies should incorporate randomized controlled designs, multimodal outcome measures, and longitudinal assessments to validate these preliminary findings and further elucidate underlying mechanisms.

5. Conclusion

This case study provides preliminary evidence that individualized, QEEG-guided low-intensity transcranial magnetic stimulation (Li-TMS) may modulate neural networks underlying executive control in an athlete with chronic traumatic brain injury. The intervention was associated with improved oscillatory regulation and enhanced functional connectivity across frontal and front parietal networks, suggesting more efficient coordination among cortical systems supporting cognitive control and goal-directed behavior.

These neurophysiological changes indicate that personalized neuromodulation approaches may influence large-scale brain networks implicated in executive functioning following traumatic brain injury.

Despite these promising findings, the results should be interpreted with caution due to the single-case design and the absence of a control condition, which limit causal inference and generalizability. Moreover, while changes in neural connectivity and oscillatory dynamics were observed, the direct functional significance of these alterations remains to be fully established. Future studies should integrate standardized executive function measures to directly link neurophysiological changes to behavioral performance, thereby clarifying the clinical relevance of observed neural modulation.

To strengthen the evidence base, future research should employ randomized controlled designs with larger samples, incorporate comprehensive neuropsychological and behavioral outcome measures, and include longitudinal follow-up assessments to evaluate the durability and functional impact of stimulation-related effects. Continued investigation of personalized, QEEG-guided neuromodulation protocols may help elucidate underlying mechanisms and refine precision-based rehabilitation strategies, particularly for athlete populations and other individuals requiring recovery of executive function following traumatic brain injury.

Declarations

Data Availability Statement

All data supporting the findings of this study are available within the paper and its Supplementary Information.

Funding Declaration

No funding was received for this study.

Clinical Trial Number

Not applicable.

Human Ethics and Consent to Participate

This study was approved by the Research Ethics Committee of Tehran University, in accordance with the ethical code IR.UT.SPORT.REC.1404.196, and relevant guidelines and regulations of the Research Ethics Committee of Tehran University. Informed consent was obtained from the participant for participation in this study

Consent to Publish

Written informed consent for publication was obtained from the participant.

Authors' contributions

A.N. wrote the main manuscript, performed Li-TMS, and analyzed data. M.G.N. conceptualized the study, supervised the project, and reviewed the manuscript. M.A.J. performed QEEG recording and analysis, prepared the figures, and assisted with writing. All authors reviewed and approved the final manuscript.

Conflict of Interest

The authors had no conflicts of interest.

Statement on Use of Artificial Intelligence

The authors are non-native English speakers. An AI-based language model (ChatGPT, OpenAI) was used to assist with English language editing and stylistic refinement of the manuscript. The authors take full responsibility for the scientific content, interpretation, and integrity of the work.

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Figures



Figure 1

Experimental setup for QEEG-guided low-intensity transcranial magnetic stimulation (Li-TMS).

The image illustrates the neuromodulation configuration used during the intervention sessions, including the low-intensity stimulation device and head-mounted applicator. Written informed consent was obtained from the participant for publication of this image.

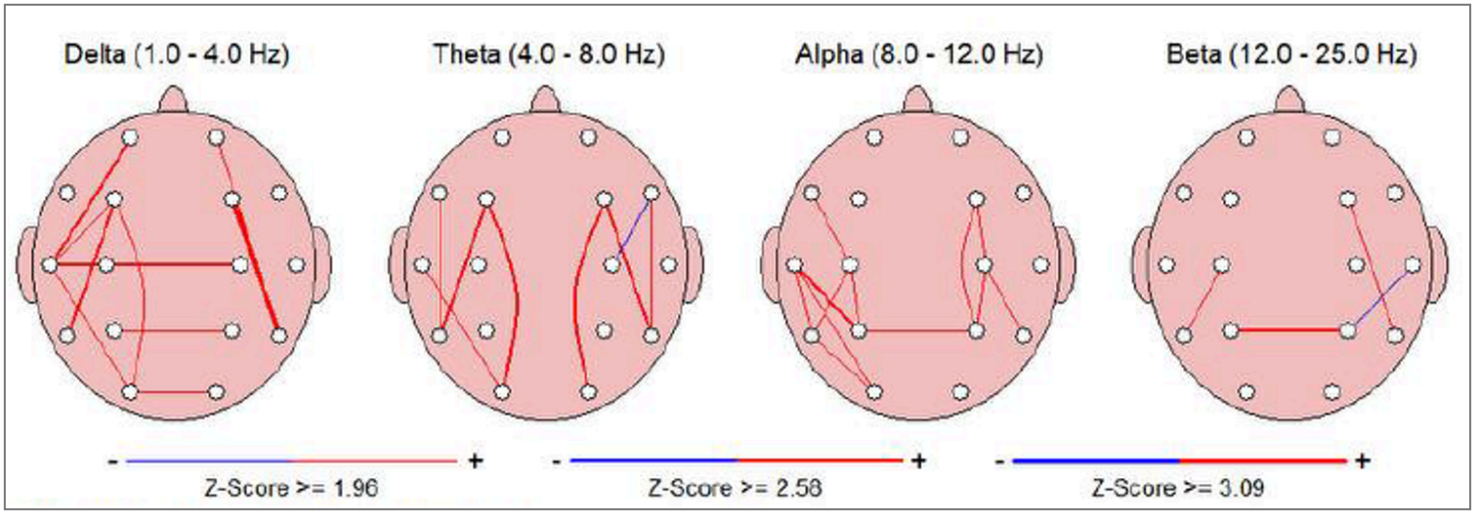


Figure 2

Post-intervention Z-score topographic maps of QEEG activity across frequency bands.

Delta (1–4 Hz), Theta (4–8 Hz), Alpha (8–12 Hz), and Beta (12–25 Hz) bands demonstrate normalization of intra- and inter-hemispheric connectivity, with reduced slow-wave deviations and more homogeneous faster-wave patterns, indicating improved neurophysiological organization and functional connectivity following targeted neurotherapy

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Beforeintervention.pdf
- Afterintervention.pdf
- CAREChecklist.pdf