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Applications of Functional Near-Infrared Spectroscopy (fNIRS) in Sport Sciences: A Systematic Review

Spor Bilimlerinde Fonksiyonel Yakın Kızılötesi Spektroskopi (fNIRS) Uygulamaları: Sistematik Derleme

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ABSTRACT: With advancing technological capabilities, neuroimaging techniques that analyze brain activity play a critical role in optimizing athletes' cognitive and physical performance. In this context, functional near-infrared spectroscopy (fNIRS), with its ability to provide real-time measurements, emerges as an innovative tool bridging the fields of sport sciences and neuroscience. This systematic review aims to examine the use of fNIRS technology in sport sciences and identify its contributions to evaluating athletes' cognitive performance and neurophysiological responses. Using the keywords "fNIRS," "sports," and "athletes," a systematic search was conducted in the Web of Science database to identify relevant peer-reviewed articles published between 2017 and 2024. A total of 35 studies were included based on their focus on cognitive performance, executive functions, and neurophysiological outcomes related to exercise or participation in sports. The reviewed studies demonstrate that fNIRS is an effective tool for enhancing cognitive performance, observing neurological adaptations, and understanding the acute and chronic effects of exercise. In conclusion, fNIRS stands out as an innovative technology in understanding cognitive and neurophysiological processes in sport sciences. Its portability and usability under field conditions offer extensive applications for improving athletes' performance and preserving their neurological health. In the future, broader use of this technology in sport sciences—particularly in field-based testing, rehabilitation processes, and assessments involving young or elite athletes—and its integration with other neuroimaging techniques are expected to yield more comprehensive and context-specific findings.

Keywords: Brain Activation, Cognitive Performance, Executive Function, Exercise Neuroscience, Functional Near-Infrared Spectroscopy (fNIRS).

ÖZ: Gelişen teknolojik imkanlar dahilinde beyin aktivitesini analiz eden nöro-görüntüleme teknikleri, sporcuların bilişsel ve fiziksel performansını optimize etmede kritik bir rol oynamaktadır. Bu bağlamda, gerçek zamanlı ölçümler yapabilme özelliği ile İşlevsel Yakın Kızılötesi Spektroskopi (fNIRS), spor bilimleri ve nörobilim arasındaki köprüyü oluşturan yenilikçi bir araç olarak öne çıkmaktadır. Bu sistematik derlemenin amacı, spor bilimleri alanında fNIRS teknolojisinin kullanımını incelemek ve sporcuların bilişsel performansları ile nörofizyolojik tepkilerini değerlendirmede sağladığı katkıları belirlemektir. Araştırmada, "fNIRS", "sports" ve "athletes" anahtar kelimeleri kullanılarak Web of Science veri tabanında sistematik bir tarama gerçekleştirilmiştir. 2017 ile 2024 yılları arasında yayımlanmış hakemli makaleler arasından, egzersiz ya da spora katılım ile ilişkili bilişsel performans, yürütücü işlevler ve nörofizyolojik çıktılara odaklanan toplam 35 çalışma incelemeye dahil edilmiştir. İncelenen çalışmalar, fNIRS teknolojisinin bilişsel performansı artırma, nörolojik adaptasyonları gözlemleme ve egzersizin akut/kronik etkilerini anlama konularında etkili bir araç olduğunu göstermektedir. Sonuç olarak fNIRS'ın spor bilimlerinde bilişsel ve nöro-fizyolojik süreçlerin anlaşılmasında yenilikçi bir teknoloji olarak kendini gösterdiği, taşınabilirliği ve saha koşullarında kullanılabilirliği ile sporcuların performansını artırmak ve nörolojik sağlıklarını korumak için geniş uygulama alanları sunduğu görülmektedir. Gelecekte, bu teknolojinin spor bilimlerinde (özellikle saha tabanlı testlerde, rehabilitasyon süreçlerinde ve genç veya elit sporcuları içeren değerlendirmelerde) daha geniş kullanımının ve diğer nörogörüntüleme teknikleriyle entegrasyonunun daha kapsamlı ve bağlama özgü bulgular sağlaması beklenmektedir.

Anahtar Kelimeler: Beyin Aktivasyonu, Bilişsel Performans, Yürütücü İşlev, Egzersiz Nörobilimi, Fonksiyonel Yakın Kızılötesi Spektroskopi (fNIRS).

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1. INTRODUCTION

Traditional performance metrics such as heart rate, VO_2max, and lactate threshold provide valuable insights into athletes' physiological states. However, these indicators fall short in capturing cognitive readiness, mental fatigue, and decision-making under pressure. In modern sports, optimal performance requires not only physical competence but also mental preparedness and efficient cognitive functioning (*Thompson et al., 2008*). As a result, athletes strive not only to be faster or stronger but also to become cognitively sharper.

During physical performance, multiple physiological mechanisms function simultaneously, with the brain and central nervous system playing a central regulatory role. Consequently, brain research has become increasingly in-depth and widespread. Neuroscience studies, in particular, focus on how the brain responds to various physical and cognitive demands, moving beyond behavioral or self-reported outcomes to explore quantifiable electrophysiological, metabolic, and hemodynamic changes (*Lucas et al., 2015; Smith & Ainslie, 2017*).

One of the most significant advancements enabling this shift is functional near-infrared spectroscopy (fNIRS). This non-invasive neuroimaging technique uses near-infrared light applied to the scalp to measure changes in oxygenated (HbO_2) and deoxygenated hemoglobin (deoxyHb) concentrations in cortical brain tissue, approximately 2–2.5 cm deep (*Tam & Zouridakis, 2014*). Due to its high temporal resolution and ability to capture signals from hairless scalp regions, fNIRS is particularly effective for observing the prefrontal and, to some extent, frontal cortex. Its portability and relatively low cost have led to increasing adoption not only by neuroscientists but also by researchers in applied fields such as sports sciences (*Ayaz et al., 2013*).

In recent years, fNIRS has been widely used in sports science to examine cerebral blood flow under various exercise and environmental conditions, including before, during, and after physical activity (*Monroe et al., 2016*). This technique allows for the investigation of neural mechanisms underlying cognitive processes such as attention, executive function, motor planning, fatigue, and decision-making under exercise-induced stress (*Byun et al., 2016; Chang et al., 2017; Mandolesi et al., 2018*). Its applicability in field settings and compatibility with dynamic movement tasks make it a promising tool for sport-specific research.

Despite the growing interest in using fNIRS for cognitive assessment in sport science, there remains a lack of comprehensive synthesis examining how this technology has been applied across different athletic disciplines. The aim of this systematic review is to explore the use of fNIRS in sports sciences, particularly in relation to the evaluation of cognitive efficiency and neurophysiological adaptations under exercise conditions, and to highlight its potential for enhancing athletic performance.

1.1. Brain and Blood Flow

The brain requires energy to function similarly to a machine. During energy exchange, the demand for oxygen increases proportionally with the level of activity. The primary source supplying the fluid that contains energy is recognized as blood circulation (*Özgören, 2008*). Accordingly, the percentage of 'blood flow' in the brain region increases during any activity. The first studies in this area were conducted in 1881 by Angelo Mosso (*Tetik, 2012*).

Mosso developed a manometric mechanism on a cranial opening in the patient he used during the experiment. Through this mechanism, he identified changes in pressure fluctuations resulting from stimuli and emotional states. In another study conducted by Mosso, it was demonstrated that when the level of blood flow in the brain of a subject lying balanced on a sensitive table changed, the balance shifted toward the head. Cerebral blood flow measurements were carried out using a cerebral thermometer (*Dror, 2001*).

From Mosso's research, where cerebral blood flow was measured using a cerebral thermometer, to the present day, the methods used to study this topic have evolved significantly. The most recent techniques include Transcranial Doppler, MRI, Near-Infrared Spectroscopy (NIRS/fNIRS), and functional MRI (fMRI). The MRI technique generates images based on the movement and density of hydrogen atoms in tissues. Functional MRI (fMRI) enables the visualization of brain function and relies on differences in the magnetic properties of deoxyhemoglobin and oxyhemoglobin in the blood. For this reason, the fMRI signal is referred to as the Blood-Oxygenation-Level-Dependent (BOLD) signal. Positron Emission Tomography (PET) is a proven effective imaging method that reveals differences in the function and metabolism of tissues and organs along with anatomical details. Single-Photon Emission Computed Tomography (SPECT) provides information about brain tissue perfusion (blood flow) through sectional imaging. Electroencephalography (EEG) is defined as the imaging of electrical activity in the brain. Historically, neuroimaging methods have followed a progression, starting with EEG and subsequently advancing to PET, SPECT, MEG, and fMRI. In studies focusing on superficial measurements, NIRS has emerged as a neuroimaging technique employing optical scattering technology to measure surface tissue areas (*Bozkurt & Onaral, 2004; Kleinschmidt et al., 1996*).

1.2. Historical Development of NIRS and fNIRS Devices

From a historical perspective, the development of NIRS began with Jöbsis (*1977*), who was the first to apply the in vivo NIRS technique to animal cells. Using infrared light within the 700–1000 nm range, Jöbsis achieved penetration in animal cells. In his study, he identified changes in cortical oxygenation during hyperventilation, demonstrating that stimulated cerebral differences could be visualized using NIRS (*Jöbsis, 1999; Reynolds et al., 1988*).

Delpy (*1988*), who initiated the development of multiple NIRS devices, conducted the first quantitative measurements of deoxyhemoglobin (Hb), oxyhemoglobin (HbO_2), total hemoglobin (tHb = Hb + HbO_2), cerebral blood flow, and cerebral blood volume in neonatal patients after a three-year process. Additionally, Ferrari et al. (*1985*) and Brazy et al. (*1985*) presented the first clinical applications of NIRS in neonatal and adult patients with cerebrovascular conditions.

The fNIRS device was developed based on the principles of NIRS. The first fNIRS study was conducted by Chance (*1991*), followed by Hoshi and Tamura (*1993*), who examined regional changes using a five-channel device.

1.3. Features of fNIRS Technology

fNIRS enables the acquisition of information about brain activity using the technique of infrared light absorption and scattering. This technology allows for spectroscopic data collection from tissue samples through light-based sampling, as well as the detection of hemoglobin concentrations, including deoxyhemoglobin and oxyhemoglobin (*Strangman et al., 2002*).

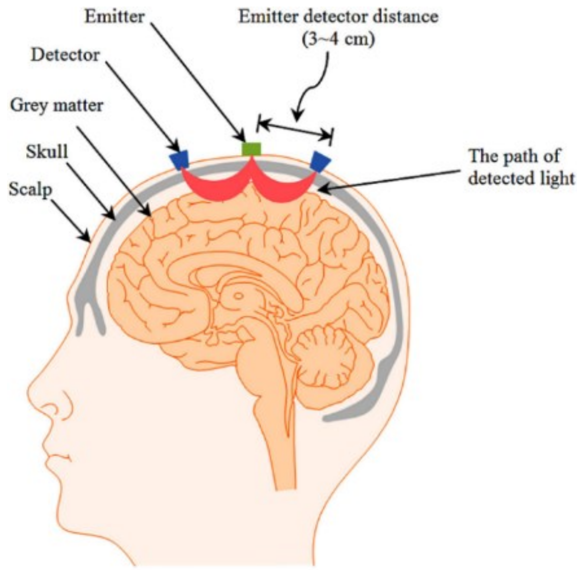

Figure 1

Source-Detector Pair and Light Propagation (Naseer & Hong, 2015)

fNIRS is a neuroimaging technique used to map cortical functions, based on the principles of NIRS. Compared to NIRS, which typically operates with only 2 channels, fNIRS offers a functional advantage with multi-channel capability (16 channels). While NIRS measures total hemoglobin using wavelength-based methods, fNIRS quantifies it as the sum of oxyhemoglobin (HbO_2) and deoxyhemoglobin (Hb) concentrations (*Cope & Delpy, 1988; Strangman et al., 2002*). There are three main fNIRS methods: the Continuous Wave (CW) method measures light attenuation under continuous light stimulation, the Frequency-Domain method analyzes both light attenuation and phase delay, and the Time-Domain method utilizes short light pulses to detect and analyze scattering patterns in tissues (*Kumar et al., 2017*). Among these, the CW method is most commonly used in neuroscience research (*Xu et al., 2014*). Measurements performed with CW devices are calculated as relative oxygenation differences using the Modified Beer-Lambert Law, with units such as micromolar*cm or millimolar*mm (*Ferrari & Quaresima, 2012; Sassaroli & Fantini, 2004*).

In fNIRS, optical fibers that generate light are referred to as sources, while other optical fibers collect photons and transfer them to the detector. Each source-detector pair constitutes a measurement area, which is referred to as a channel (*Naseer & Hong, 2015*). Currently, multi-channel fNIRS devices have become the standard method (*Duman, 2019*).

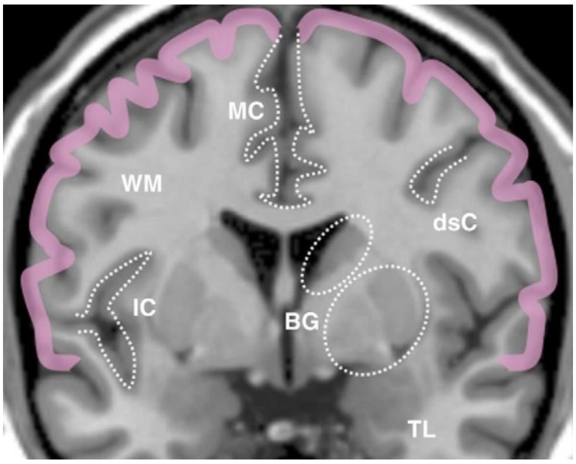

Figure 2

Brain Regions Measurable Using the fNIRS Method (Obrig, 2014)

The brain regions measurable using the fNIRS method are highlighted in pink. TL represents the temporal lobe, dsC denotes the deep sulcus cortex, BG refers to the basal ganglia, IC indicates the insular cortex, WM signifies white matter, and MC corresponds to the mesial cortex (*Obrig, 2014*).

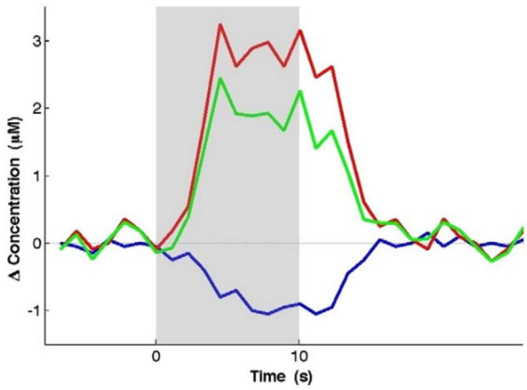

Figure 3

Typical fNIRS Signal Recording (Ferrari & Quaresima, 2012)

The green lines represent changes in total hemoglobin (total-Hb), the blue lines indicate changes in deoxyhemoglobin (deoxy-Hb), and the red lines show changes in oxyhemoglobin (oxy-Hb) concentrations (*Ferrari & Quaresima, 2012*).

1.4. Comparison of fNIRS with Other Neuroimaging Methods

There are numerous neuroimaging methods available, with approaches examining the metabolic (fMRI, PET) and electrophysiological (EEG, MEG) properties of neuronal activity being commonly preferred in neuroscience research. Among these, the fNIRS method, which has gained increasing prominence in recent studies, offers certain advantages and disadvantages when compared to other brain imaging techniques. Its advantages include ease of application, ecological validity due to its ability to be conducted in natural settings, suitability for recording data from bedridden or non-compliant individuals, quiet operation, affordability, and good temporal resolution (*Kumar et al., 2017*). However, its primary disadvantages are its limitation to cortical recordings and relatively low spatial resolution (*Obrig, 2014*).

1.5. Applications of fNIRS and Its Role in Neuroscience Research

The fNIRS method is increasingly being utilized in neuroscience research (*Boas et al., 2014*). It has been applied in various studies to analyze resting states, visual processing, language, attention, memory, emotions, executive functions, somatosensory activity, and motor activity (*Adorni et al., 2016*). Additionally, it holds significant potential for monitoring rehabilitation responses and addressing neurological conditions such as brain injuries, epilepsy, and cerebrovascular diseases. Recent years have also seen growing optimism regarding its use in psychiatric disorders. The application of fNIRS has exponentially increased over the past decade and continues to expand. Research exploring its use in conditions like Alzheimer's disease, autism, attention deficit hyperactivity disorder (ADHD), depression, substance use disorders, bipolar disorder, and schizophrenia is ongoing. Furthermore, studies investigating cortical activity relationships, psychiatric symptoms, genetic factors, and the effects and efficacy of treatments offer promising insights (*Boas et al., 2014; Kumar et al., 2017*).

2. METHOD

This study was designed as a systematic review in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The purpose of the review is to examine the use of functional near-infrared spectroscopy (fNIRS) technology in sports sciences, with a focus on evaluating athletes' cognitive performance and neurophysiological responses.

A comprehensive literature search was conducted in the Web of Science database between January 1 and January 31, 2025, using the keywords "fNIRS," "sports," and "athletes". Boolean operators (AND/OR) were used to ensure relevant combinations and maximize search coverage. The search was limited to peer-reviewed articles published between 2017 and 2024.

Inclusion criteria were as follows:

• Studies that applied fNIRS in sports science contexts,

• Studies focusing on cognitive performance, executive function, or neurophysiological outcomes,

• Articles published in English,

• Original research articles with empirical data.

Exclusion criteria included:

• Reviews, conference abstracts, or commentaries,

• Studies conducted outside of a sport or exercise context,

• Articles not involving human participants.

All studies were screened by both authors independently. Any disagreement regarding inclusion was resolved through discussion and consensus, ensuring reliability in the selection process. Ultimately, 35 articles meeting the criteria were included in the review.

3. RESULTS

Table 1

Studies Included in the Review Based on the Search Results Using the Keywords "fNIRS," "Sports," "Athletes" in the Web of Science Database

Study	Type of Sport	Participant Characteristics	Test Details	Brain Regions (Cortex)
Liu et al. (*2024*)	Orienteering	49 Athletes	Spatial memory, Mental rotation	Prefrontal
Sathe et al. (*2024*)	Taekwondo, Karate, Judo	35 Athletes 35 Non-athletes	Clinical test of sensory interaction on balance (CTSIB)	Oksipito-parietal, Prefrontal, Temporo-parietal
Song et al. (*2024*)	Badminton	22 Athletes 30 Non-athletes	N-back task	Frontoparietal, Dorsolateral prefrontal, Ventrolateral prefrontal
Lai et al. (*2023*)	Swimming	13 Athletes	Schulte grid test (SGT) Trail-making test (TMT) Digit span test (DST)	Frontoparietal, Dorsolateral prefrontal
Grijalva et al. (*2023*)	Soccer	20 Athletes	Upper extremity dual-task (UEF)	Prefrontal, Motor
Xiang et al. (*2023*)	Shooting	33 Athletes	2-back, Task-switching, Stroop test	Prefrontal
Gao & Zhang (*2023*)	Shooting	78 Athletes	Eye-gaze indicator	Dorsolateral prefrontal
Jain et al. (*2023*)	Soccer	12 Athletes	King-devick (K-D) Complex tandem gait (CTG)	Prefrontal
Li et al. (*2023*)	Fitness	20 Athletes 20 Non-athletes	Resting state functional connectivity (RSFC)	Motor
Wang et al. (*2023*)	Basketball, Football, Table tennis, Badminton, Track and field, Aerobics, Boxing	48 Athletes 48 Non-athletes	Trust game (TG)	Frontal pole, Dorsolateral prefrontal
Shao et al. (*2023*)	-	42 Athletes	Stroop task, Simon task, High-intensity interval training (HIIT), Tabata training	Dorsolateral prefrontal, Ventrolateral prefrontal
Schmaderer et al.	Soccer	39 Athletes	General and sport-specific cognitive tasks	Prefrontal

(*2023*)				
Carius et al. (*2023*)	Table tennis	35 Athletes	Two table tennis strokes (forehand and backhand), Randomized combination	Sensorimotor
Trbovich et al. (*2023*)	American football, Soccer, Ice hockey, Volleyball, Lacrosse	20 Athletes	Ruff 2 & 7 selective attention test	Right hemisphere, Left hemisphere
Yu et al. (*2023*)	Ice hockey	38 Athletes	Revised lateralized attention network test	Dorsolateral prefrontal, Inferior frontal gyrus
Liu et al. (*2022*)	Orienteering	30 Athletes	Spatial memory tasks	Prefrontal, Dorsolateral prefrontal, Ventrolateral prefrontal
Li et al. (*2022*)	Aerial skiing	32 Athletes	Go/No-go task	Dorsolateral prefrontal, Ventrolateral prefrontal, Orbitofrontal
Sun et al. (*2022*)	Taekwondo	10 Athletes	Eriksen flanker test (EFT), Stroop test, Rapid visual information processing test	Prefrontal
Wang & Lu (*2022*)	Tai chi chuan	13 Athletes 11 Controls	Resting and exercise state	Prefrontal, Sensorimotor zone
Köyağasıoğlu et al. (*2022*)	-	57 Healthy adults	Stabilometry, Star excursion balance test (SEBT)	Prefrontal
Zhu et al. (*2022*)	Soccer	17 Athletes	Stroop task, Corsi-block tapping task	Prefrontal
Moriarty et al. (*2022*)	-	9 Participants	Piano task	Motor
Seidel-Marzi et al. (*2021*)	Slacklining	16 Athletes	Standing (ST), Walking (WA)	Primary motor, Premotor, Supplementary motor
Mancı et al. (*2021*)	Basketball	12 Athletes 9 Non-athletes	Sprint interval training (SIT), Recovery periods	Prefrontal
Park & Kim (*2020*)	Archery	10 Athletes 10 Non-athletes	Visual-simulation task	Prefrontal, Dorsolateral prefrontal
Yu & Liu (*2021*)	Interceptive sports (Table tennis, Badminton, Tennis) Strategic sports (Basketball, Volleyball, Soccer)	26 Interceptive sports athletes 26 strategic sports athletes	Revised lateralized attention network test (LANT-R)	Dorsolateral prefrontal, Inferior frontal gyrus
Slutter et al. (*2021*)	Soccer	22 Participants	Penalty kicks	Prefrontal, Motor, Temporal
Sharma et al. (*2020*)	Rugby	21 Retired rugby athletes 23 Non-athletes	Neurovascular coupling (NVC) test	Middle frontal gyrus

Helmich et al. (*2020*)	American Football, Ice hockey, Rugby, Boxing, Handball, Soccer	62 Athletes	During postural control	Frontopolar
Carius et al. (*2020*)	Bouldering	13 Athletes	Boulder performance	Sensorimotor zone
Seidel et al. (*2019*)	Triathlon, Cycling, Cross-country skiing	22 Athletes 20 Controls	Cycling test	Primary motor, Premotor
Wolff et al. (*2019*)	Track and field	33 Athletes	Sprint start sequences (Ready-Set-Go)	Prefrontal
Zhang et al. (*2019*)	Race walking	4 Athletes 20 Controls	Action observation, Motor imagery, Motor execution	Frontal, Parietal
Giles et al. (*2018*)	Long-distance running	36 Athletes	Stroop test, Cognitive reappraisal task (CRT)	Prefrontal
Kenville et al. (*2017*)	-	10 Participants	Barbell squat	Superior parietal lobe

Liu et al. (*2024*) investigated the impact of sports experience on cognitive performance in orienteering athletes, focusing on prefrontal cortex (PFC) dynamics. The study included 49 participants divided into two groups: high-experience and low-experience athletes. The high-experience group comprised athletes who ranked highly in national orienteering championships, while the low-experience group consisted of athletes from university teams. Cognitive performance was assessed using spatial memory and mental rotation tasks, with motor experience evaluated both within and between groups. During testing, participants' accuracy rates and reaction times were recorded using the "E-Prime 3.0" software, and brain oxygenation levels were measured with an fNIRS device. The results revealed that the high-experience group demonstrated neurological efficiency with lower brain activation, whereas the low-experience group performed better on spatial memory tasks. The study provided significant insights into the relationship between motor experience and cognitive performance in orienteering athletes.

Sathe et al. (*2024*) aimed to investigate differences in cerebral cortex activation during static balance tasks between active athletes and sedentary individuals. The study included 70 participants aged 18–30, with the active athlete group comprising individuals engaged in sports such as taekwondo, karate, and judo. Participants were assessed using the Clinical Test of Sensory Interaction on Balance (CTSIB), and HbO_2 and deoxyHb concentrations were recorded using fNIRS. The results indicated that the active athlete group exhibited better balance performance compared to the sedentary group, alongside differences in activation in the occipito-parietal, prefrontal, and temporo-parietal cortex regions. The study concluded that regular participation in sports activities contributes to improved balance control and enhanced cerebral cortex activation.

Song et al. (*2024*) examined brain activation and performance during working memory tasks in badminton athletes and sedentary individuals. The study included 22 badminton players and 30 sedentary participants. Behavioral performance and HbO_2 levels in the prefrontal cortex were assessed using fNIRS. Participants completed 1-back, 2-back, and 3-back tasks. The results showed no significant differences in behavioral performance between athletes and sedentary individuals in the n-back tasks. However, in the 3-back task, significant brain activation differences were observed in the left frontoparietal, right dorsolateral prefrontal cortex, and left ventrolateral prefrontal cortex regions. The findings indicate that longer training durations are associated with better performance in working memory tasks.

Lai et al. (*2023*) investigated the effects of a 1500-meter freestyle race at maximum speed on athletes' cognitive functions. The study included 13 male swimmers who were assessed using cognitive tests before and after the race, while prefrontal cortex oxygenation was measured using fNIRS. The results revealed a significant decline in cognitive functions (SGT, TMT, DST) and notable changes in HbO_2 concentrations in the right frontal cortex, right dorsolateral prefrontal cortex, and middle dorsolateral prefrontal cortex. The observed cognitive decline suggests that these changes are linked to alterations in activation and functional connectivity in specific regions of the prefrontal cortex.

Grijalva et al. (*2023*) aimed to examine the immediate effects of sub-concussive impacts from soccer headers on brain function. The study included 20 university-level soccer players who were exposed to an average peak linear acceleration of 30.7 g and a peak angular velocity of 7.2 rad/s during 10 consecutive headers performed in a natural setting. Measurements were conducted using fNIRS. The results showed an increase in HbO_2 levels in the left prefrontal cortex and left motor cortex, along with a rise in signal entropy in the right and left motor cortices observed through time-series analysis. Despite these changes, no alterations in balance or neurocognitive functions were detected following the headers, indicating that the impacts were mild in severity.

Xiang et al. (*2023*) aimed to evaluate the effects of combined physical and cognitive training (CPCT) on executive function performance and brain oxygenation in adolescent shooting athletes, comparing it with cognitive-only training (CCT). The study included 33 adolescent athletes who were randomly assigned to two groups (17 in CPCT and 16 in CCT). Following a 6-week training program, both groups were assessed using the 2-back, task-switching, and Stroop tests. During these tasks, HbO_2 levels in the prefrontal cortex were monitored using fNIRS. The results indicated that both groups improved their accuracy rates and updating functions similarly in the 2-back task. However, participants in the CPCT group showed a significant increase in accuracy in the task-switching test, while no such improvement was observed in the CCT group. In the Stroop test, which assessed inhibition functions, neither group demonstrated behavioral performance improvements. Notably, the CPCT group exhibited a marked increase in HbO_2 levels in the prefrontal cortex during all three cognitive tasks, whereas no changes were observed in the CCT group. These findings suggest that CPCT is more effective than CCT in enhancing task-switching performance and increasing brain oxygenation.

Gao and Zhang (*2023*) investigated whether 20 minutes of mindfulness meditation (MM) improves pre-competition attention control in athletes and whether it leads to changes in the activity of brain regions associated with attention control. The study compared eye movement indicators and fNIRS parameters of 78 university athletes after 20 minutes of MM and 20 minutes of mind-wandering (MW) during a virtual reality shooting competition. The results showed that in the MM group, the average fixation durations (AFD) on task-relevant targets were significantly longer, while the number of fixations (AFC) on task-irrelevant information (ranking screen) was significantly lower compared to the MW group. Additionally, the MM group exhibited stronger activation in the left and right dorsolateral prefrontal cortex, increased HbO_2 levels, and greater functional connectivity in the right dorsolateral prefrontal cortex. Furthermore, the shooting performance of the MM group was significantly better than that of the MW group. The findings suggest that 20 minutes of mindfulness meditation immediately before competition enhances focus and improves athletic performance.

Jain et al. (*2023*) conducted a study on the relationship between repeated head impact exposure (RHIE) and neurophysiological dysfunction in adolescents. The study included 12 high school football players (5 female), who completed the King-Devick (K-D) and Complex Tandem Gait (CTG) tests both pre-season and post-season while wearing an fNIRS sensor. For each athlete, the average head impact load (AHIL) was standardized and determined through video-verified head impact sensor data. No differences were observed in K-D and CTG performance between the pre-season and post-season assessments. However, higher AHIL was associated with increased cortical activation in the most challenging conditions of the K-D test and during the CTG post-season. This finding indicates that greater RHIE necessitates increased cortical activation to achieve the same level of performance on the more demanding components of these assessments.

Li et al. (*2023*) examined differences in resting-state functional connectivity (RSFC) of the motor cortex and the test-retest reliability of these connections between athletes and sedentary university students. The study included 20 athlete students and 20 sedentary individuals as a control group. fNIRS measurements were used to assess motor cortical blood oxygen signals. The results revealed significant differences in RSFC (HbO_2 signals) between the athlete and sedentary groups. These findings suggest that RSFC strength in the motor cortex is influenced by physical fitness levels, and such variables could serve as potential biomarkers for assessing physical fitness levels.

Wang et al. (*2023*) conducted a simultaneous fNIRS study using the Trust Game (TG) to evaluate trust behaviors and capture neural synchronization related to interpersonal trust (INS) in athletes and sedentary university students. The results revealed that male athletes exhibited higher trust behaviors and greater INS values in the left dorsolateral prefrontal cortex compared to female athletes. Additionally, the athlete group demonstrated significantly higher trust behaviors and INS values in the left frontal pole and left dorsolateral prefrontal cortex compared to the sedentary group. These findings suggest that athletes exhibit better trust behaviors, likely due to increased INS values in the left dorsolateral prefrontal cortex.

Shao et al. (*2023*) aimed to identify the potential neural mechanisms underlying high-intensity interval training (HIIT) and Tabata training. The study included 42 young adults (21 female) with an average age of 19.36. Participants completed Stroop and Simon tasks before and after acute HIIT, Tabata training, and a control session. Cortical hemodynamic changes in the prefrontal cortex during these tasks were monitored using fNIRS. The HIIT and Tabata sessions lasted 12 minutes each. HIIT participants cycled on an ergometer at 80% of their maximum aerobic power and a speed of 90–100 rpm, while the Tabata participants performed eight high-intensity activities such as high knees, jumping, and heel kicks without equipment, maintaining their heart rates at 80–95% of their maximum. Control group participants remained sedentary, watching sports videos. The results showed that both the HIIT and Tabata groups exhibited reduced reaction times post-intervention, along with changes in activation patterns in the dorsolateral and ventrolateral prefrontal cortex. These findings suggest that both training methods enhance cognitive performance and influence prefrontal cortex activity.

Schmaderer et al. (*2023*) aimed to analyze prefrontal activity during general and sport-specific cognitive tasks in football players. A total of 39 semi-professional football players completed four perceptual-cognitive tests, including two general cognitive and two sport-specific cognitive tasks. Given the high movement demands of football, two of the tests were conducted while participants were in motion. Prefrontal activity during the cognitive tests was recorded using fNIRS. The results showed that prefrontal activity was significantly higher during general cognitive tests compared to sport-specific cognitive tests. This finding highlights differences in neural engagement depending on the cognitive demands of the tasks.

Carius et al. (*2023*) investigated how expertise levels and task complexity influence cortical hemodynamics in table tennis players. The study included 35 right-handed participants, 17 of whom were experts and 18 novices. Participants performed forehand and backhand strokes as well as random combinations of these strokes. Cortical hemodynamics were assessed using fNIRS, and stroke performance was evaluated through video recordings. The results showed that expert players exhibited higher target accuracy across all conditions compared to novices. Novice players demonstrated greater activation in extensive brain regions associated with sensorimotor and multisensory integration. These findings support the neural efficiency hypothesis, suggesting that expert table tennis players utilize fewer cortical resources to achieve superior performance compared to novices.

Trbovich et al. (*2023*) investigated brain activation using fNIRS in 20 adolescent athletes following sports-related concussions (SRC). The study compared athletes who continued playing after SRC (PLAYED group) with those who were immediately removed from play (REMOVED group). Athletes in the PLAYED group demonstrated worse clinical outcomes compared to those in the REMOVED group. A linear mixed-effects model revealed that the PLAYED group showed an increase in HbO_2 in the left hemisphere during the initial visit, whereas the REMOVED group experienced a decrease in HbO_2 in the right hemisphere during clinical recovery. Additionally, the PLAYED group exhibited a greater increase in HbO_2 in the left hemisphere compared to the REMOVED group during the initial visit, although no significant differences were observed during recovery. The findings suggest that athletes who continued playing after SRC exhibited more pronounced hyperactivation in the left hemisphere, which may be associated with poorer clinical recovery outcomes.

Yu et al. (*2023*) examined brain activity associated with the executive control attention network in novice, expert, and elite-level female ice hockey players. The results showed that elite players had faster reaction times compared to novices, and experts demonstrated higher accuracy rates than novices. The influence of the executive network on reaction time was greater in novices but reduced in elite players. Moreover, elite players exhibited more efficient executive control in the right dorsolateral prefrontal cortex and right inferior frontal gyrus. The findings suggest that elite players outperform expert and novice female ice hockey players in terms of cognitive performance and neural efficiency.

Liu et al. (*2022*) evaluated the map recognition and spatial memory abilities of orienteering athletes at various difficulty levels while analyzing brain activation. Using fNIRS, the study monitored oxygenation levels and performance in the prefrontal cortex, right dorsolateral prefrontal cortex, and right ventrolateral prefrontal cortex of expert and novice orienteering athletes. The results showed no significant differences between the two groups during simple tasks. However, as task difficulty increased, both groups exhibited longer reaction times, decreased behavioral performance, and increased brain oxygenation. Expert athletes demonstrated more efficient cognitive performance during complex tasks, characterized by higher accuracy rates and lower brain oxygenation levels, particularly in the right dorsolateral and ventrolateral prefrontal cortices. These findings suggest that expert athletes possess a cognitive advantage in map recognition and memory tasks.

Li et al. (*2022*) investigated the effects of summer and winter training conditions on executive control and their neural mechanisms in freestyle skiing aerial athletes. The study included 32 athletes who performed a rapid event-related go/no-go task under different training conditions. Changes in HbO_2 concentrations in the prefrontal cortex were monitored using fNIRS. The results revealed that athletes demonstrated lower accuracy in behavioral control during summer training conditions compared to the control condition. Additionally, both summer and winter training conditions were associated with longer reaction times compared to the control condition. Significant differences in activation were observed in the left and right dorsolateral prefrontal cortex and orbitofrontal cortex during executive control tasks across training conditions. Moreover, interactions between training conditions and behavioral control were noted in the activation of the left and right ventrolateral prefrontal cortex as well as the left dorsolateral prefrontal cortex. These findings suggest that different training conditions in freestyle skiing aerial athletes may lead to reductions in executive control abilities and decreases in activation in the right and left ventrolateral prefrontal cortex and orbitofrontal cortex.

Sun et al. (*2022*) examined the effects of caffeine consumption on simulated match performance and Wingate Anaerobic Test (WAnT) performance in elite taekwondo athletes, alongside changes in cognitive functions. The study included 10 elite-level taekwondo athletes from Hong Kong. Participants consumed either a caffeinated beverage (CAF) or a placebo beverage (PLA) one hour before performing two simulated taekwondo matches, followed by the WAnT. Cognitive functions were assessed before and after exercise using the Eriksen Flanker Test (EFT), Stroop Test, and Rapid Visual Information Processing Test, while fNIRS data were recorded. The results showed that caffeine intake enhanced anaerobic power, reduced reaction times in the EFT, and improved certain aspects of cognitive function. However, the fNIRS data were inconsistent with the observed cognitive changes. Additionally, no significant effect of caffeine on simulated match performance was observed.

Wang and Lu (*2022*) aimed to investigate the characteristics of multiloop brain synergy in elite Tai Chi Chuan athletes during rest and exercise. The study compared brain activities between professional Tai Chi Chuan athletes and novice practitioners using fNIRS, focusing on functional connectivity between the prefrontal lobe and the sensorimotor region. During rest, the functional connectivity between the right sensorimotor region and the left prefrontal lobe was significantly lower in the professional group compared to the novices. During exercise, the professional group exhibited significantly lower functional connectivity patterns among the right sensorimotor region, left prefrontal lobe, left sensorimotor region, right prefrontal lobe, and between the left and right sensorimotor regions compared to the novices. However, during the transition from rest to exercise, the professional group showed a greater increase in functional connectivity between the left prefrontal cortex, right sensorimotor region, and between the left and right sensorimotor regions. These findings suggest that professional Tai Chi Chuan athletes demonstrate distinct functional connectivity patterns and greater adaptability in transitioning between rest and exercise states.

Köyağasıoğlu et al. (*2022*) investigated the effects of mental training programs on balance skills and prefrontal cortex hemodynamic responses. The study included 57 healthy adults (28 women and 29 men) aged 18–25, who were randomly assigned to three groups: virtual reality mental training (VRMT), conventional mental training (CMT), and a control group. The training program incorporated action observation and motor imagery exercises via balance exercise videos. Over four weeks, participants in the VRMT group trained with a virtual reality headset, while the CMT group used a computer screen, each for 30 minutes, three times per week. Balance levels were assessed at the start and end of the training period using the Stabilometry and Star Excursion Balance Test (SEBT). fNIRS was used to measure HbO_2 levels in the prefrontal cortex during balance tests. The results showed that in the stabilometry test, at least one variable significantly improved in both the VRMT and CMT groups, while no improvement was observed in the control group. In the SEBT, composite reach distances increased in the VRMT and CMT groups but decreased in the control group. Both mental training groups showed increased reach distances in the posterolateral and posteromedial directions for the non-dominant leg and the posterolateral direction for the dominant leg. Notably, the posteromedial score for the non-dominant leg significantly improved only in the VRMT group. Between-group comparisons revealed that improvements in posteromedial and posterolateral scores for the dominant leg were significantly higher in both mental training groups compared to the control group. While no significant changes in oxygenation levels were observed during stabilometry tests, SEBT results showed a decrease in oxygenation levels in the control group. The findings suggest that both VRMT and CMT can significantly enhance balance performance, with VRMT providing additional benefits for specific balance parameters.

Zhu et al. (*2022*) investigated the acute effects of a mindfulness-based intervention (MBI) on cognitive functions in football players following a 45-minute laboratory-based football protocol. Seventeen male football players participated in two main trials: an MBI trial and a control trial. After the 45-minute exercise, participants in the MBI trial underwent a short mindfulness-based intervention, while those in the control trial listened to an audio recording about travel. Cognitive function (Stroop Test, Corsi Block Tapping Test), salivary cortisol, blood lactate levels, and mental fatigue were measured at baseline (pre-test) and after the intervention (post-test). Brain oxygenation levels during the cognitive tests were assessed using fNIRS. The results demonstrated that the short MBI improved working memory performance in terms of both reaction time and accuracy, supported by an increase in HbO_2 concentration in the prefrontal cortex. These findings highlight the positive effects of MBI on working memory and suggest its implementation during halftime in football matches to enhance cognitive performance.

Moriarty et al. (*2022*) aimed to compare whole-body motor skill performance following moderate-intensity exercise (MIT) and high-intensity interval training (HIIT) using a piano task and to determine whether motor cortex activation was associated with these performance changes. The study included nine participants (seven women and two men) who completed MIT and HIIT trials before performing a piano task. Motor cortex activation during post-exercise piano performance was assessed using fNIRS to measure changes in HbO_2 and hemoglobin difference (Hbdiff). The results indicated that piano performance scores were higher after the MIT trial compared to the control trial, whereas no improvement was observed following the HIIT trial. Motor cortex activation significantly increased after the HIIT trial. When data from all trials (MIT, HIIT, and control) were combined, a positive relationship between motor cortex activation and piano performance was identified. These findings suggest that improvements in complex motor skill performance are driven by acute moderate-intensity exercise, while high-intensity exercise enhances motor cortex activation. The study concludes that acute aerobic exercise can enhance fine motor skills and alter motor cortex activation, with the effects differing based on exercise intensity.

Seidel-Marzi et al. (*2021*) investigated brain activity during balance maintenance on a slackline, a task requiring high balance skills and often used as complementary training in various sports. The study measured hemodynamic responses in sensorimotor brain regions using fNIRS in 16 advanced slackliners during standing (ST) and walking (WA) conditions on the slackline. The results revealed changes in hemodynamic responses in sensorimotor brain regions, including the primary motor cortex, premotor cortex, and supplementary motor cortex, during both conditions. However, no significant differences were observed between the ST and WA conditions, and no relationship was found between cortical activity and slacklining experience. These findings suggest that while slacklining engages key sensorimotor brain regions, the level of cortical activation is similar across different balance tasks, and experience level does not appear to influence neural responses in this context.

Mancı et al. (*2021*) compared hemodynamic changes in the prefrontal cortex during sprint interval training (SIT) and recovery periods between athletes and sedentary individuals. The study involved 21 male participants (12 athletes and 9 sedentary) performing SIT on a cycle ergometer, with hemodynamic changes in the prefrontal cortex recorded using fNIRS throughout the protocol. The results showed significant increases in HbO_2 levels in both groups, while power outputs during repeated Wingate anaerobic tests (WAnTs) decreased over time. The sedentary group exhibited higher HbO_2 levels compared to the athlete group. Despite increasing intensity, athletes demonstrated better performance with lower HbO_2

levels and faster recovery of prefrontal HbO_2 levels during recovery periods. These findings suggest that athletes are more efficient in maintaining performance with lower prefrontal activation and recover more rapidly, highlighting differences in prefrontal hemodynamic responses between trained and untrained individuals during high-intensity exercise.

Park and Kim (*2020*) investigated hemodynamic responses during a stress-inducing visual simulation task using fNIRS. The study included 10 archers and 10 sedentary university students. Participants reported their perceived stress levels using a visual analog scale before and after the task. Average HbO_2, deoxyHb, and total hemoglobin (HbT) levels were calculated to compare neural efficiency between the groups. The results showed increased stress levels in both groups following the simulation task. No significant group differences were observed in average hemodynamic responses in the prefrontal cortex or dorsolateral prefrontal cortex. However, while the average hemodynamic response levels were similar between the groups, the archer group exhibited more stable patterns in their hemodynamic responses compared to the sedentary group. These findings suggest that although stress affected both groups similarly in terms of average hemodynamic responses, archers demonstrated greater stability in their neural responses, potentially reflecting better adaptation to stress.

Yu and Liu (*2021*) examined differences in executive attention network and blood oxygen levels in the right frontal-parietal brain regions between interceptive and strategic sport athletes. The results showed that strategic athletes demonstrated higher accuracy rates and longer reaction times compared to interceptive athletes. Additionally, in invalid cue conditions, strategic athletes exhibited more pronounced activation in the dorsolateral prefrontal cortex and inferior frontal gyrus, indicating a dominance of top-down control strategies. These findings suggest that the observed differences in brain activation, as measured by fNIRS, are associated with the cognitive advantages inherent to specific sports disciplines.

Slutter et al. (*2021*) investigated the effects of anxiety and pressure, common causes of errors in penalty kicks in football, using fNIRS. The study included 22 participants who performed 15 penalty kicks under three pressure conditions: no goalkeeper, team goalkeeper, and opposing goalkeeper. Brain activation was compared across sessions with and without reported anxiety, as well as between successful and missed penalty attempts for experienced and inexperienced participants. The results revealed that the motor cortex was more active when participants did not experience anxiety. Experienced players showed increased activation in the left temporal cortex when feeling anxious, whereas inexperienced players exhibited higher left temporal cortex activation when scoring goals. This study demonstrated that fNIRS can provide neurological insights into anxiety and performance, supporting its use for ecologically valid investigations in field settings.

Sharma et al. (*2020*) investigated brain hemodynamic responses to a neurovascular coupling (NVC) test in retired contact sport athletes with a history of mild traumatic brain injury (mTBI) and in a control group without mTBI. The study included 21 retired rugby players with a history of three or more concussions and 23 controls with no history of mTBI. fNIRS was used to assess brain hemodynamic changes during the NVC test. The results showed significantly reduced HbO_2 levels and lower brain hemodynamic responses in the mTBI group compared to the controls during the NVC test. Additionally, in the mTBI group, a decrease in HbO_2 levels and an increase in deoxyHb levels were observed in the left middle frontal gyrus. This study represents the first to examine brain hemodynamic changes in response to an NVC test in retired rugby players, highlighting the potential long-term effects of repeated mTBI on neurovascular function.

Helmich et al. (*2020*) compared brain oxygenation patterns in the frontal cortices of symptomatic and asymptomatic athletes with a history of sports-related concussions (SRC). The study included 62 athletes, 31 symptomatic and 31 asymptomatic, who were assessed during four different postural control tasks involving eyes-closed, eyes-open, stable, and unstable surface conditions. Brain oxygenation was recorded using fNIRS from the frontopolar cortex of both hemispheres. The results showed that symptomatic athletes exhibited greater postural sway compared to asymptomatic athletes, particularly under eyes-closed and unstable surface conditions. HbO_2 changes in the left hemispheric frontopolar cortex were significantly reduced in symptomatic athletes during eyes-closed conditions compared to asymptomatic athletes. Self-reported post-concussion symptoms, such as headaches and sadness, were predictive of reduced brain oxygenation during eyes-closed postural control. Symptomatic athletes, especially under eyes-closed conditions, were characterized by increased postural sway and reduced frontopolar brain oxygenation during postural control tasks. These findings suggest that athletes with post-concussion symptoms may experience difficulties coordinating postural adjustments in conditions with reduced sensory input.

Carius et al. (*2020*) investigated neural activities during climbing in bouldering athletes. Hemodynamic response changes were recorded using fNIRS in 13 advanced climbers while performing bouldering tasks. Participants' cortical activation levels were compared between simple and moderate climbing routes. The results revealed that climbing activated nearly all sensorimotor system regions, including the bilateral premotor cortex, supplementary motor cortex, bilateral primary motor cortex, bilateral supramarginal gyrus, and somatosensory cortex. This activation was observed across both simple and complex climbing routes. However, task complexity did not significantly affect cortical activity levels. Additionally, a negative relationship was found between expertise level and hemodynamic response in the supplementary motor area, suggesting that reduced activation in secondary motor regions with increased expertise reflects motor automaticity. This study provides the first conceptual evidence using fNIRS to assess hemodynamic response changes during complex climbing movements, highlighting its potential for evaluating motor function in sports like bouldering.

Seidel et al. (*2019*) examined the effects of endurance exercise at different intensity levels on brain function and structure using fNIRS. Data were collected from trained endurance athletes (EA) and active control participants (ACP) during a cycling test. Participants performed an incremental cycling test (ICT) to assess cardiorespiratory parameters, including maximum heart rate (HRmax), oxygen consumption volume (VO_2max), and peak power output (PPO). Participants cycled at intensities of 20%, 40%, and 60% PPO, during which cardiorespiratory responses and neurovascular coupling were measured. The results revealed decreases in deoxyHb levels in motor-related brain regions during exercise. However, no significant differences in brain activation were found between the EA and ACP groups. These findings suggest that while endurance exercise induces specific hemodynamic responses in motor-related brain regions, the effects on brain activation may not differ significantly between trained endurance athletes and active controls at varying exercise intensities.

Wolff et al. (*2019*) aimed to investigate the neural basis of brain oxygenation in the lateral prefrontal cortex during the initiation of sprint performance using fNIRS. The study included 33 male participants, each completing three different sprint start sequences (Ready-Set-Go) performed 10 times. The results showed an increase in brain oxygenation following the "Set" signal. This study is the first to examine oxygenation changes in cortical regions during sprint start performance, providing valuable insights into the neural mechanisms underlying high-intensity athletic actions.

Zhang et al. (*2019*) investigated the hemodynamic responses in the fronto-parietal cortex of 4 elite race walkers (EG) and 20 university students (CG) using fNIRS during action observation, motor imagery, and motor execution tasks. The results showed that during motor execution and action observation tasks, elite race walkers exhibited significantly lower activation levels in the inferior frontal gyrus pars triangularis, dorsolateral prefrontal cortex, premotor cortex, supplementary motor cortex, and primary somatosensory cortex compared to university students. Furthermore, during motor execution tasks, primary motor cortex activation was significantly lower in elite race walkers than in university students. In contrast, during motor imagery tasks, activation intensities in the dorsolateral prefrontal cortex, premotor cortex, supplementary motor cortex, and primary motor cortex were significantly higher in elite race walkers compared to university students. These findings suggest distinct neural activation patterns in elite athletes, reflecting their advanced motor skills and expertise in specific tasks.

Giles et al. (*2018*) examined the effects of acute endurance exercise on cognitive control. The study included 36 endurance athletes (21 women, 15 men) aged 18–30, all running at least 30 miles per week. Participants performed two exercise sessions on separate days: walking at 51–63% of age-adjusted maximum heart rate (HRmax) and running at 70% HRmax (range 64–76%) for 90 minutes. Participants completed the Stroop Test before exercise, every 30 minutes during exercise, and 30 minutes after exercise. Additionally, a Cognitive Reappraisal Task (CRT) was performed post-exercise. Throughout the sessions, changes in HbO_2 and deoxyHb levels in the prefrontal cortex were recorded using fNIRS. The results indicated that task-related reductions in prefrontal cortex oxygenation did not impair cognitive control. These findings suggest that cognitive control processes remain intact despite decreases in prefrontal oxygenation during endurance exercise.

Kenville et al. (*2017*) investigated how brain activity changes during barbell squat (BS) exercises at varying barbell weights using fNIRS. The study employed a crossover design with 10 healthy male participants. While fNIRS recordings were taken, participants performed BS tasks at random barbell load levels: 0% 1RM (one-repetition maximum), 20% 1RM, and 40% 1RM. The results showed that HbO_2 changes in the superior parietal lobe region were influenced by the barbell load levels. This study highlights the relationship between physical load intensity and brain activity in the superior parietal lobe during resistance exercises like barbell squats.

Collectively, the reviewed studies reflect a growing body of empirical evidence highlighting the nuanced relationships between physical activity, cognitive performance, and cortical activation patterns. While methodologies and target populations vary, several overarching themes emerge. First, expertise level often correlates with neural efficiency, with trained athletes exhibiting more targeted and less diffuse activation patterns during cognitive and motor tasks. Second, interventions such as mindfulness, cognitive-motor dual tasks, and varying exercise intensities appear to acutely modulate prefrontal activation and task performance. Third, fNIRS demonstrates potential not only for understanding performance optimization but also for detecting early neurophysiological changes linked to repetitive head impacts, even in asymptomatic individuals. These converging findings illustrate the multidimensional applications of fNIRS across athletic populations and settings, paving the way for more ecologically valid, field-based assessments of brain function in sports contexts.

4. LIMITATIONS

This review has certain limitations. The literature search was limited solely to the Web of Science database, and only studies published in English between 2017 and 2024 were included. Consequently, relevant studies available in other databases or published in different languages were not considered in this review.

5. CONCLUSION AND RECOMMENDATION

fNIRS has emerged as a bridge between sports sciences and neuroscience, enabling a deeper understanding of athletes' cognitive processes. The high temporal resolution offered by this technology has garnered significant attention from sports scientists. An evaluation of findings from 35 scientific studies reviewed in this research highlights the broad applicability of fNIRS in enhancing cognitive performance in athletes, observing neurological adaptations, and understanding the effects of exercise on the brain.

fNIRS has become a valuable tool in sports science due to its ability to analyze brain activity during and after exercise. The findings from 35 reviewed scientific studies reveal that fNIRS offers significant applications in training, rehabilitation, and performance enhancement processes. One of its key advantages is its portability and suitability for use in field conditions, distinguishing it from other neuroimaging techniques such as EEG and fMRI. This capability allows for real-time analysis of athletes' brain activity during training and competition, providing unique insights into cognitive and neural processes in dynamic environments.

Research conducted with fNIRS technology provides extensive data on its applications across various sports disciplines. From combat sports to strategic sports, findings offer valuable insights into the effects of different types of sports on brain activity. fNIRS plays a crucial role in understanding the impact of exercise type and intensity on the brain, serving as a critical tool for exploring both the acute and chronic neurological effects of exercise. Additionally, fNIRS has proven to be highly valuable for monitoring the effects of neurological injuries. It enables detailed analysis of the neurological impacts of head traumas, contributing to the development of preventive strategies to protect athletes. Understanding conditions such as sports-related concussions is vital for safeguarding the long-term health of athletes and advancing protective measures in sports.

In conclusion, fNIRS has proven to be an effective technology for understanding cognitive and neurophysiological processes in sports sciences. This technology has raised significant awareness regarding enhancing athlete performance, grounding training practices on scientific principles, and protecting individuals' neurological health. By providing a robust scientific framework for understanding and optimizing cognitive and physical processes, fNIRS opens new horizons for improving athletic performance. In the future, the integration of fNIRS into sports sciences is expected to increase further. Additionally, its combined use with other neuroimaging techniques is anticipated to broaden its contributions, offering even greater insights and applications in sports science.

6. ETHICS STATEMENT

Since this study did not involve human participants or personal data, ethics committee approval was not required. Additionally, this systematic review was not registered in PROSPERO.

7. AUTHOR CONTRIBUTIONS

MSÇ took the lead in the conception, design, and execution of this review study. ÖG provided guidance during the research process and contributed to the critical evaluation and refinement of the manuscript. Both authors reviewed and approved the final version of the paper.

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