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TRAUMATIC BRAIN INJURIES IN SPORT – A REVIEW OF CURRENT KNOWLEDGE ON PREVENTION, DIAGNOSIS AND TREATMENT

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ABSTRACT

Sport-related traumatic brain injuries (SR TBI) represent a significant public health issue, the importance of which continues to grow alongside the global increase in recreational physical activity. Projections indicate that the incidence of traumatic brain injuries (TBI) will remain high through 2025, potentially reaching up to 70 million cases annually. TBI not only results in acute neurological symptoms, including the potentially fatal second impact syndrome, but can also lead to severe long-term consequences such as chronic traumatic encephalopathy (CTE). Understanding the pathophysiological mechanisms, epidemiology, and available diagnostic and therapeutic strategies is crucial for reducing risk and improving treatment outcomes of these injuries.

KEYWORDS

Traumatic Brain Injury, Second Impact Syndrome, Chronic Traumatic Encephalopathy, Prevention in Sport, Sport Injuries

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Introduction

TBI is a broad term, with concussion and diffuse axonal injury being the most common types encountered in sports. The National Institutes of Health (NIH) identifies hematomas, breakdown of the blood-brain barrier, and increased intracranial pressure as less common but significant forms of TBI.

It is essential to consider the epidemiology of long-term consequences of TBIs or microtrauma. In a large cross-sectional study published in *Lancet Neurology*, researchers referenced retrospective cohort analysis that compared mortality from neurodegenerative diseases in 7,676 former professional footballers with 23,028 individuals from the general population. It was demonstrated that mortality due to neurodegenerative diseases was approximately three times higher in former footballers compared to the control group. However, mortality from other common conditions (e.g. ischemic heart disease or lung cancer) was lower among former footballers (Maas et al., 2022).

Special attention will also be given to the controversial Second Impact Syndrome and the long-term consequences of head injuries and microtrauma — Chronic Traumatic Encephalopathy (CTE).

This article aims not only to elucidate the pathophysiology and clinical aspects of TBIs but also to provide a comprehensive review of current solutions aimed at minimizing the risk of acute neurological injuries.

TBI

A traumatic brain injury (TBI) is defined as a head injury resulting from external forces leading to brain tissue damage. Non-penetrating TBI is caused by external forces that induce displacement of brain structures within the skull. Penetrating brain injury (PBI) is defined as an injury involving rupture of the dura mater (Śmiłowska et al., 2015). Mechanical acceleration and deceleration forces cause deformation of brain tissues and axonal injuries. TBI leads to disturbances in cerebral blood flow and metabolism, resulting in reduced cerebral oxygen uptake, increased lactate production, and depletion of high-energy phosphate reserves (Veech et al., 2012).

Epidemiology

By 2025, projections indicate persistence or further escalation of global TBI incidence, remaining within approximately 50–70 million cases annually (Joannides et al., 2023). Brain injuries in sports, especially mild trauma (MTBI), account for approximately 20% of all athletic injuries (Shevelev et al., 2023). In the BIONIC population study, conducted in New Zealand since 2010 covered a 12-month period, researchers documented 1,369 TBI cases across all age categories within a population of 173,205 individuals. It demonstrated that approximately 21% of these injuries were associated with sports or recreational activities (Maas et al., 2022). In the TRACK-TBI study initiated in 2013, 218 (8.7%) out of 2,520 injuries occurred during sporting or recreational activities. It is important to note that these figures pertain to a selected cohort of patients whose injuries were sufficiently severe to seek hospital care. This data may not reflect the overall risk of sport-related TBI in the general population (Maas et al., 2022).

The number of sport-related TBIs has not decreased; analysis demonstrate a stable or increasing trend up to 2019, particularly among younger individuals and males (Theadom et al., 2020). According to data from the Centers for Disease Control and Prevention (CDC), approximately 70% of emergency department visits for sport- and recreation-related brain injuries involve children and adolescents under 20 years of age. Although boys more frequently present to emergency departments with such injuries, girls have a higher risk of sustaining concussions in sports with comparable rules, such as football or basketball (Sarmiento et al., 2019).

In the CENTER-TBI study initiated in 2014, sports and recreational activities were reported as the cause of TBI in 7% of 4,509 cases. Among these, the most frequent activities included horseback riding (19%), skiing and snowboarding (16%), cycling (11%), and football(11%) (Maas et al., 2022).

The incidence of concussions varies depending on the sport discipline. The highest rates are observed in American football, ice hockey, wrestling, and lacrosse, where physical contact is an inherent component of the game. In sports with identical rules for both genders, females exhibit higher concussion rates (Pierpoint & Collins, 2021).

SIS

Second Impact Syndrome (SIS) is a rare but potentially fatal neurological condition occurring in athletes who sustain a second head injury before fully recovering from a prior concussion. The concept dates back to the 1980s, with its definition and scope gradually modified over time, contributing to current ambiguities and controversies (Stovitz et al., 2017). Despite well recognised clinical symptoms and the potentially high risk of mortality, the absence of definitive diagnostic criteria for this condition prevents the establishment of an official ICD-10 definition (Hebert et al., 2016).

A 2016 review article search and identified 36 reported cases across 15 publications, of which 17 met the inclusion criteria (McLendon et al., 2016). Most sources report a high mortality rate for SIS, often described as “high” or “50–100%,” although these figures are primarily based on case reports, and the true mortality remains unknown (Stovitz et al., 2017).

The injury mechanism appears to involve axonal shearing, which triggers rapid neuronal depolarization, excessive neurotransmitter release, and ionic imbalances characterized by the efflux of potassium ions and influx of sodium and calcium ions into the cells. These alterations disrupt cerebral blood flow regulation, contributing to the development of edema. Consequently, the increased metabolic demand for glucose, coupled with the injury-induced reduction in resting cerebral blood flow, leads to an energy supply-demand mismatch (Harmon et al., 2019).

Diagnosis of TBI

In recent years, there has been increasing interest in blood biomarkers as non-invasive tools supporting the diagnosis of traumatic brain injury (TBI). Among them, particular attention has focused on GFAP (glial fibrillary acidic protein) and UCH-L1 (ubiquitin carboxy-terminal hydrolase L1), whose effectiveness was confirmed in a 2025 meta-analysis, demonstrating 100% sensitivity in ruling out intracranial lesions in adults with mild TBI (Lorton et al., 2024). The combination of GFAP and UCH-L1 was approved by the FDA in 2018 for TBI assessment in adults. Using these biomarkers can significantly reduce the number of CT scans performed, thereby limiting patient radiation exposure and easing healthcare system burdens (Śmiłowska et al., 2015). Additionally, GFAP, as an astrocyte-specific protein, shows correlation with neurostructural imaging, making it a reliable indicator of brain injury (Alosco et al., 2021). Another important marker, neurofilament light (NfL), has prognostic utility—its blood concentration rises within 1–2 weeks post-injury

and remains elevated for several months, correlating with the severity of axonal damage and long-term functional outcomes (Alosco et al., 2021), (Zafar et al., 2025), (Maas et al., 2010).

Neurocognitive and screening tests play a major role. They form the basis for identifying and managing TBI according to the Zurich consensus guidelines. Cognitive assessment should be part of return-to-play decisions but not the sole criterion. Baseline testing before the season is recommended. Neurocognitive tests include Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), Brain Injury Screening Questionnaire (BISQ), Automated Neuropsychological Assessment Metrics (ANAM), CogSport, Concussion Resolution Index (CRI), and Standardized Assessment of Concussion (SAC). Other available symptom scales include SCAT-PCSS, IMPACT-PCSS, Pittsburgh Steelers Post Concussion Scale, Concussion Symptom Inventory, and Head Injury Scale. None of these scales has proven clearly superior in detecting TBI. However, neurocognitive assessment (memory, attention, reaction time, processing speed)—particularly when comparing pre-injury and post-injury results—is highly useful for diagnosing and monitoring an athlete's condition (Sahler & Greenwald, 2012).

Treatment of TBI

After the acute phase, early and continuous rehabilitation is crucial, as it consolidates hospital treatment effects, shortens hospital stays, and reduces economic burdens. Unfortunately, disruptions in care continuity between acute treatment and rehabilitation are common, leading to poorer functional outcomes and lower patient satisfaction with care. Research data indicate insufficient access to rehabilitation – only 30% of patients with moderate or severe TBI received inpatient rehabilitation, and among those with mild TBI, even when symptoms persisted for months, outpatient rehabilitation was rarely provided. Additionally, many patients discharged from emergency departments received neither educational materials nor scheduled follow-up appointments, exacerbating difficulties in regaining full function (Maas et al., 2022).

In the treatment of post-traumatic headache (PTH), increasing attention is being given to pharmacotherapy targeting the calcitonin gene-related peptide (CGRP) system. Monoclonal antibodies such as erenumab (a CGRP receptor antagonist) and fremanezumab (a CGRP ligand neutraliser) have been used in migraine therapy and are currently under investigation for their efficacy in PTH. Preclinical studies have shown that administration of anti-CGRP antibodies within a few hours post-injury prevented allodynia in animal models. Nevertheless, results from clinical trials to date, particularly those involving fremanezumab, remain inconclusive and require further validation (Papenhoff & Dudda, 2023). Current data are promising, there is presently insufficient evidence to definitively recommend anti-CGRP therapy as a standard treatment for PTH. However, advancements in clinical and experimental research may soon alter these recommendations (Pellesi et al., 2024).

Long-Term Consequences of Brain Injury – CTE

Definition and Pathophysiology

First described in 1928, originally known as dementia pugilistica, it was mainly associated with boxers who exhibited characteristic neurological symptoms such as speech difficulties, gait disturbances, and limb tremors. Since 2005, the description of this disease has evolved to include a broader spectrum of psychiatric symptoms, mood disorders, depression, and cognitive impairments. Following the introduction of neuropathological diagnostic criteria for CTE in 2016 by the NINDS and NIBIB institutes, there has been a noticeable increase in research interest regarding this condition (McKee et al., 2023). Thanks to further revisions in 2021, it became possible to more precisely identify characteristic changes such as phosphorylated tau protein (p-tau) deposits located around blood vessels in the deep cortical sulci layers. Importantly, this form of deposition differs both structurally and molecularly from those observed in Alzheimer's disease or other tauopathies (Bieniek et al., 2021).

The difficulty in diagnosing CTE during life led to the development of the term "traumatic encephalopathy syndrome" (TES), which describes a set of clinical symptoms potentially associated with CTE, although it does not definitively confirm the presence of neuropathological changes. TES includes, among others, mood disorders, impulsivity, memory problems, and progressive cognitive decline (Katz et al., 2021).

Epidemiology

Collected data suggest that almost all documented CTE cases have been associated with prolonged exposure to repetitive head trauma – including both concussions and subclinical microtraumas without overt symptoms. In particular, a strong correlation has been observed between the number of years playing American football and the severity of neuropathological changes. Even after accounting for potential section biases, this relationship remains statistically significant, suggesting a clear causal link. Among sports with the highest risk of CTE are boxing, American football, soccer, rugby, hockey, and Australian football (McKee et al., 2023).

In a systematic review and meta-analysis from 2025 (Scandinavian Journal of Medicine & Science in Sports), eight studies (2015–2024) were included, encompassing 1,000 deceased athletes with a history of repetitive head trauma confirmed neuropathologically. The cumulative prevalence of CTE was found to be 53.7% (Qi et al., 2025).

It is estimated that 3–10% of dementia cases are associated with a prior traumatic brain injury (Byard et al., 2023).

Symptoms

CTE is characterized by difficulties in higher-level cognitive functions such as performing multiple tasks simultaneously (multitasking) and decision-making, along with short-term memory impairment, emotional instability, apathy, and depression. Clinical symptoms described in recent cases resemble depression in middle-aged men and show similarities to frontotemporal dementia during later stages of the disease (Gardner et al., 2014). There is also a well-established association between traumatic brain injury and dementia and/or motor disorders that occur later in life, such as Parkinson's disease and Alzheimer's disease (Byard et al., 2023). Symptoms also include various and non-specific motor function impairments (Mariani et al., 2020).

Diagnosis

CTE diagnosis is established through examination of tissue samples taken from the following brain structures: middle frontal gyrus, superior and middle temporal gyri, inferior parietal lobule, hippocampus, amygdala, basal ganglia, thalamus, midbrain including substantia nigra, pons with locus coeruleus, medulla oblongata, and cerebellar cortex, in accordance with previous consensus recommendations. The minimal diagnostic criterion for CTE is the identification of at least one pathognomonic lesion in the cerebral cortex. Such a pathognomonic lesion is characterised by p-tau protein aggregates within neurons, sometimes accompanied by tau-positive thorn-shaped astrocytes (TSA), located deep within cortical sulci, surrounding small blood vessels, and in deeper cortical layers, not limited solely to subpial regions or superficial layers. Cases are classified as mild CTE ("Low CTE") or advanced CTE ("High CTE"). This classification accounts for the heterogeneity of p-tau neuropathological patterns, enabling differentiation between focal changes and more widespread neurofibrillary pathology (Bieniek et al., 2021).

Increasingly, in the era of postmortem imaging, the skull is not routinely opened if no abnormalities are visible on CT examination. This may result in additional cases going unidentified, and the number of documented cases within the postmortem forensic population may decrease (Byard et al., 2023).

The DIAGNOSE CTE research project, whose baseline phase concluded in 2020 and testing phase was planned for 2021–2025, is a groundbreaking initiative aimed at developing methods for detecting and diagnosing chronic traumatic encephalopathy (CTE) in living individuals. Its goals include developing and validating fluid and imaging biomarkers, refining diagnostic criteria, and characterising the clinical presentation. The study enrolled 240 men aged 45–74 years, including former professional and collegiate American football players and individuals without head trauma exposure. All participants underwent comprehensive baseline assessments: neurological and neuropsychological evaluations, PET imaging for tau and amyloid, advanced MRI protocols, magnetic resonance spectroscopy (MRS), lumbar puncture for cerebrospinal fluid (CSF) biomarker analyses, as well as blood and saliva sampling.

Key diagnostic efforts focus on identifying in vivo biomarkers that could support probable CTE diagnosis. Fluid biomarkers investigated include CSF and plasma levels of p-tau (p-tau181, p-tau217, p-tau231), total tau, neurofilament light (NfL), glial fibrillary acidic protein (GFAP), soluble TREM2 receptor (sTREM2), and various cytokines (Alosco et al., 2021).

The project also evaluates the validity of updated NINDS consensus diagnostic criteria for traumatic encephalopathy syndrome (TES), proposed as the clinical equivalent of CTE. Diagnostic panels ensure reliable TES diagnoses based on standardised clinical, cognitive, and imaging data. Preliminary findings suggest that

cognitive impairments, particularly in executive functions and memory, may better predict CTE pathology than neuropsychiatric symptoms alone.

The ultimate aim of the DIAGNOSE CTE project is to build an evidence base enabling CTE diagnosis during life, which is crucial for early intervention, patient care, and the development of targeted therapies (Alosco et al., 2021).

No biomarker has yet been approved for routine clinical diagnosis of CTE (Alosco et al., 2021). However, growing hope lies in a panel of fluid biomarkers (NfL, p-tau, NSE) and inflammatory factors that characterise different subtypes and stages of the disease (Zafar et al., 2025). Elevated tau protein levels, especially when combined with UCH-L1, may indicate severe clinical symptoms and central nervous system damage extent. Using combinations of biomarkers such as GFAP, NfL, and tau could form the basis for developing integrated diagnostic models and monitoring post-traumatic disease progression, offering new opportunities for early therapeutic intervention (Lorton et al., 2024).

Neuroimaging does not yet replace post-mortem diagnosis but represents a promising tool in chronic traumatic encephalopathy (CTE) research. Particularly important is PET imaging using tau tracers (Tau-PET), which enables localisation of pathological p-tau protein within the cerebral cortex. This reveals a pattern distinct from Alzheimer's disease – in CTE, amyloid uptake is typically absent (amyloid-PET negative), while tau is predominantly located in the deep cortical sulci (Stern et al., 2019),(Alosco et al., 2021).

Structural imaging using magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI) consistently demonstrate atrophy and microstructural white matter damage, which is characteristic of CTE and allows differentiation from other neurodegenerative diseases (Koerte et al., 2015). On the other hand, positron emission tomography using fluorodeoxyglucose (FDG-PET) can support disease staging and visualise hypometabolism in characteristic brain regions (Josephs et al., 2010).

The future of CTE research in neuroimaging involves the need for long-term, multicentre research projects. Critical work will include the use of more specific tau PET tracers, high-resolution 3T and 7T MRI combined with advanced diffusion tensor imaging (DTI), as well as integrating FDG-PET with functional analysis. Another promising direction is combining neuroimaging data with fluid biomarker results (e.g. NfL, p-tau), enabling the creation of integrated diagnostic models. Standardising imaging protocols and conducting imaging-pathology correlation studies to verify CTE-specific patterns will also be essential (Maas et al., 2010), (Shenton et al., 2012).

Prevention of TBI

Effective prevention strategies include educating athletes, coaches, and medical staff, implementing head injury assessment protocols, and using appropriate protective equipment. In cases of suspected brain injury, it is crucial to immediately remove the athlete from play and conduct proper medical evaluation. The graduated return-to-activity protocol should be individually tailored, taking into account the athlete's symptoms and response to exertion**.**

Game Rules

Rule changes aimed at reducing risky behaviours can significantly decrease injury rates. For example, implementing a ban on bodychecking in youth ice hockey led to a 58% reduction in concussion incidence (Eliason et al., 2023). Data analysis from professional rugby league matches showed that approximately half of concussions occur during tackle attempts, most often affecting the player executing the tackle. Based on this information, World Rugby launched targeted initiatives to reduce tackle-related risks (Harmon et al., 2019).

Protective Equipment

Although no equipment guarantees complete protection against concussion, properly selected and fitted helmets and protective gear can reduce the risk of severe head injuries. Modern technologies, such as helmets equipped with impact sensors, are being tested to monitor impact forces and potential injury risk.

In recent years, innovative design solutions have emerged, such as rotational impact mitigation systems (e.g. MIPS, WAVECEL) and 3D structures adapting to individual head anatomy. Modern helmets are now tested not only for linear accelerations but also for rotational forces, significantly aligning protective design with on-field and operational realities (Goutnik et al., 2022).

Since 2024, NFL players have been allowed to wear Guardian Caps – soft helmet covers designed to reduce impact forces. Although the league claims they have reduced concussions by 52%, independent studies confirming their effectiveness are lacking (Donahue et al., 2023).

Mouthguards can absorb impact forces, stabilise the jaw, increase neck muscle activity, and alter temporomandibular joint positioning, thereby reducing force transmission to the brain. A review of 39 studies confirmed a significant reduction in concussion incidence among athletes wearing mouthguards, particularly in hockey, where a risk reduction of approximately 28% was observed (Knapik et al., 2019).

The Q-Collar is a neck-worn device designed to reduce concussion risk by gently compressing the jugular vein. This compression increases blood volume within the skull, theoretically creating a "cushion" that protects the brain during impacts. This mechanism is intended to limit brain movement within the skull during sudden acceleration and deceleration.

Animal model studies have shown that jugular vein compression may reduce white matter damage after head trauma. For example, experiments on rats demonstrated reduced such damage with this method, although the Q-Collar device itself was not directly tested.

Human study results remain inconclusive. One study conducted on young American football players suggested that using the Q-Collar was associated with smaller changes in brain white matter over a season. However, it is important to note that this study was funded by the device manufacturer, raising concerns about bias. Additionally, results were inconsistent, actual concussions were not analysed, and the clinical significance of the detected white matter changes remains uncertain.

The device has been approved for sports use by the FDA, which determined that potential benefits outweigh potential risks. This decision does not confirm Q-Collar's effectiveness but allows its legal marketing for specific applications.

Despite promising theoretical foundations, the Q-Collar still raises many research questions. Key issues include whether increased jugular vein pressure truly reduces concussion risk, whether long-term use is safe, and whether observed white matter changes translate into real brain protection (Delgadillo et al., 2025).

Supportive Training

Neuromuscular training (NMT) holds a particularly important role. NMT programmes include balance, stabilisation, and plyometric exercises performed at least three times per week for a minimum of 20 minutes. These exercises integrate elements of postural control, muscle strengthening, dynamic stabilisation, and sport-specific movements with feedback from a coach. Studies have shown that in rugby players, NMT implementation was associated with a 59% reduction in concussion incidence and a significant decrease in orthopaedic injuries. These programmes are also recommended in other sports disciplines, although further research is needed across different age groups and sports (Williams et al., 2021).

Research indicates that neuromuscular programmes in rugby can reduce concussion rates by up to 60% (Eliason et al., 2023).

The FIFA 11+ programme is a comprehensive injury prevention initiative developed by FIFA, primarily targeting football players aged 14 and above. Its goal is to reduce injury incidence through training protocols tailored to the physiological and biomechanical development of children and adolescents. The programme is based on a standardised warm-up routine that enhances functional strength, balance, and neuromuscular control. It consists of 15 exercises divided into three parts and has strong foundations in biomechanical research. Studies show that FIFA 11+ can reduce the number of severe lower limb injuries by approximately 37%.

FUNBALL is a programme targeting youth aged 13–19 years, promoting safe behaviours and a positive attitude towards physical activity. This programme combines elements of traditional injury prevention exercises (stabilisation, balance, coordination) with tasks engaging working memory, attention, executive functions, and reaction speed. Training is conducted in the form of dual-task activities that simulate the complexity of on-field situations. Studies have shown that programme participants improved their performance in all assessed cognitive domains, including executive functions, visual memory, and motor control, whereas the control group even demonstrated declines in some test outcomes (Meha et al., 2025).

In recent years, there has been growing interest in early, controlled aerobic exercise as a safe and effective strategy to support recovery from concussion in adolescents. Contrary to traditional recommendations of strict rest until symptom resolution, randomised clinical trials have shown that individually tailored aerobic training performed below the symptom-exacerbation threshold accelerates recovery. The Buffalo protocol, which involves daily moderate-intensity exercise (e.g. treadmill or stationary cycling) introduced at least 48 hours post-injury, proved more effective than a placebo stretching-based intervention. Programme participants regained full function on average 4 days faster than those in the control group and were less likely to experience prolonged recovery (>30 days). These findings confirm that early, targeted physical activity may serve as a safe and effective alternative to passive symptom waiting, reducing the risk of persistent symptoms and negative educational and social consequences (Leddy et al., 2019).

Education

Raising awareness about the symptoms and consequences of brain injuries among athletes, coaches, and parents is crucial. Educational programmes such as CDC's HEADS UP promote recognition of concussion symptoms and encourage appropriate responses.

"Suspect and Protect: No Match is Worth the Risk" is a global FIFA educational campaign conducted in collaboration with the World Health Organization (WHO), aiming to increase awareness of concussions in football. The initiative emphasises that concussion is a serious brain injury that can affect any player and promotes knowledge of symptoms and proper management when injury is suspected. The campaign targets players, coaches, team doctors, parents, and entire football communities at all levels – from professional leagues to amateur football.

The campaign is based on three main recommendations: BE AWARE (awareness of injury and its symptoms), SUSPECT (assessing the player after head or torso impact), and PROTECT (immediate removal from play and medical consultation). Educational materials will be available in multiple languages and disseminated by FIFA's 211 member associations at national and local levels.

The campaign highlights that concussion symptoms can appear up to 72 hours post-injury and may evolve over time; thus, rapid action and adherence to medical return-to-play guidelines are essential. These efforts aim to improve player safety and build a culture of health protection in sport.

It is also important to reduce pressure on athletes and shift away from the previously dominant "no pain, no gain" mentality. Such attitudes may contribute to premature return to play, training beyond capacity, or disregarding symptoms.

Nutrition

In light of recent experimental findings, prophylactic administration of branched-chain amino acids (BCAAs) may represent an effective neuroprotective strategy in the context of sports-related head injuries. A mouse model study demonstrated that BCAA administration prior to TBI (particularly using a pre- and post-injury scheme) significantly improved motor and cognitive functions, reduced astrocyte activation marker expression (GFAP), and normalised microglial responses. These effects were linked to leucine's role as a nitrogen donor in glutamate and glutamine synthesis and its involvement in regulating the glutamatergic pathway, whose excessive activation is a key component of the neurotoxic cascade following injury. Importantly, BCAAs may act not only as supplements supporting recovery but, when administered preventively, may limit primary injury severity by modulating metabolic and inflammatory responses. Considering the safety of oral BCAA intake at recommended ratios (2:1:1 leucine:isoleucine:valine), their potential warrants further clinical research and consideration as a preventive element against brain injuries in contact sport athletes (Dickerman et al., 2022).

Some studies also mention the provision of DHA. Currently, clinical trials are being conducted on the role of supplementation with, among others, probiotics, lactate, and amino acids in protecting the nervous system against the effects of brain injuries (Walrand et al., 2021).

Other Methods

In head injury prevention in sports, increasing importance is being attributed to brain temperature control, particularly in the context of mild traumatic brain injuries (MTBI). The use of selective cranial-cerebral hypothermia (SCCH) – involving cooling of the scalp and cortical surface – has demonstrated neuroprotective effects, limiting the consequences of exercise-induced hyperthermia, which promotes brain edema, increased intracranial pressure, and enhanced inflammatory responses. Studies using microwave radiometry (MWR) have shown that SCCH reduces cortical temperature by 2–4°C without affecting core body temperature or hemodynamic parameters. Preventive application of SCCH before physical activity not only reduces the risk of secondary injury but also improves aerobic performance and delays the onset of central fatigue. Brain thermography observations after sparring indicate that SCCH effectively eliminates focal hyperthermia in areas most susceptible to injury. Thus, SCCH and MWR technologies may represent valuable additions to current head injury prevention strategies, especially in contact sports (Shevelev et al., 2023).

Discussion

This analysis has highlighted the complexity and multidimensional nature of sport-related traumatic brain injuries (SR TBI), emphasizing both the diversity of pathophysiological mechanisms and the clinical variability of different injury types.

An important achievement of this work is the compilation of current TBI diagnostic strategies, with particular emphasis on the potential role of biomarkers such as GFAP, UCH-L1, and NfL. Available study results indicate high sensitivity and specificity of these markers in identifying brain injuries, which could significantly reduce the number of imaging studies performed and improve early diagnostics. However, further research should focus on validating these biomarkers in a wide population of athletes, considering various disciplines and injury severities.

Second Impact Syndrome (SIS) remains an important yet still insufficiently studied issue. Despite the high risk associated with this phenomenon, the lack of clear diagnostic criteria and the limited number of case reports hinder the formulation of consistent clinical guidelines. Further epidemiological studies and the development of education in the sports community about the risk of SIS are needed to minimise its occurrence.

In the case of chronic traumatic encephalopathy (CTE), the paper highlights the importance of the DIAGNOSE CTE project, which is a promising initiative aimed at developing diagnostic tools for this disease during life. However, further validation studies on biomarkers and imaging methods such as tau-PET and DTI are still needed to unambiguously identify neuropathological changes characteristic of CTE. These studies are necessary to create reliable diagnostic standards and develop effective therapeutic strategies.

An important contribution of this work is also the analysis of preventive strategies. The implementation of comprehensive educational and training programmes such as FIFA 11+, FUNBALL, or the Buffalo protocol has shown clear effectiveness in reducing neurological injuries in sports. However, further research is needed on the effectiveness of these programmes in different age groups and sports disciplines, as well as the long-term effects of their implementation.

In terms of protective equipment, despite promising innovations (MIPS, WAVECEL, Guardian Caps, Q-Collar), further independent clinical studies are necessary to assess their real effectiveness in reducing the number and severity of brain injuries. Supplementation, including the use of branched-chain amino acids (BCAAs) and DHA, also requires further clinical studies to confirm their neuroprotective potential and effectiveness in TBI prevention.

Summary

Brain injuries in sport remain a serious health challenge, with an upward trend both in terms of case numbers and their health consequences. This paper presents a broad analysis of the current state of knowledge on SR TBI and indicates areas requiring intensified research. Key directions for future work should include further biomarker validation, development of precise diagnostic criteria, assessment of the effectiveness of innovative preventive and protective methods, and extensive education of athletes, coaches, and medical staff. Joint efforts of sports, medical, and scientific communities can significantly contribute to reducing the negative effects of sport-related brain injuries.

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