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Protecting Athletes' Brains from Repetitive Head Impacts: An Evidence-Based Perspective

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Abstract

Background. Repetitive head impacts (RHI) are increasingly recognized as a significant source of cumulative brain injury in contact and collision sports. Despite often being subclinical, repeated concussive and subconcussive events are associated with microstructural brain damage, neuroinflammation, and long-term neurodegenerative processes, including chronic traumatic encephalopathy (CTE).

Material and methods. This narrative literature review synthesized 52 studies from PubMed database. Inclusion criteria comprised studies published between 2011-2026, emphasizing systematic reviews and clinical trials.

Aim. Summary of current evidence on the pathophysiology of RHI, evaluation of the role of biomarkers and neuroimaging, and discussion of evidence-based prevention strategies in athletes.

Results. RHI induce cumulative neuronal and glial damage through biomechanical forces, particularly rotational acceleration, leading to axonal injury and white matter disruption detectable with advanced imaging techniques. Among biomarkers, neurofilament light chain shows the most consistent association with axonal damage, while tau-related markers remain

less reliable for clinical use. Preventive strategies, including exposure reduction, rule modifications, and technique optimization, demonstrate effectiveness but vary in strength and consistency of evidence.

Conclusions. RHI represent a complex and multifactorial clinical problem with significant long-term neurological implications. Although emerging diagnostic tools offer promising insights, their routine clinical utility is still constrained by methodological limitations and lack of standardization. A multidimensional prevention approach and further large-scale, longitudinal research integrating biomechanical, imaging, and biomarker data are essential to improve risk assessment and reduce the burden of RHI-related brain injury.

Keywords. Repetitive Head Impacts, RHI, Head Trauma, Chronic Traumatic Encephalopathy, CTE, Subconcussion, Neuroimaging, Biomarkers, Neurofilament Light Chain, NfL, Axonal Injury, Sports, Athletes.

Introduction

Repetitive head impacts (RHI) represent a growing concern in a wide range of sports, including football (soccer), rugby, American football and boxing. This area of medicine has also attracted attention in non-sports contexts, including military blast exposures, accidental injuries, domestic violence victims, patients with epilepsy, and individuals with repetitive head-banging behaviors, especially in psychiatric populations [1-3].

Due to their subclinical nature, RHI are challenging to quantify at a population level, and exact prevalence estimates are not available. Nevertheless, research using neuroimaging, biomarkers and sensor-based monitoring suggests that exposure is common in high-risk environments [1,4]. For example, American football players have been recorded sustaining over 6000 head impacts during a single season [5].

The terminology surrounding head impacts remains inconsistent. Concussion encompasses a range of conditions within the spectrum of mild traumatic brain injuries (mTBIs) and is defined as a brain trauma caused by biomechanical forces transmitted to the brain following a direct or indirect impact to the head, neck, or body [6]. Subconcussion is defined as cranial impact that does not produce any clinical symptoms yet may still produce subtle physiological or structural brain changes [7]. The biomechanical threshold for clinically significant effects varies and depends on individual susceptibility and impact characteristics. Subconcussive head impacts appear to have the most harmful effects when they accumulate, and repeated exposure is associated with long-term neurological conditions such as chronic traumatic encephalopathy (CTE) [8]. CTE is a progressive neurodegenerative tauopathy associated with

repetitive head trauma, characterized by the accumulation of phosphorylated tau (p-tau) within sulci and perivascular regions of the brain [9].

In recent years, CTE and RHI have received increasing scientific and clinical attention due to the growing number of known effects. Headaches, short-term memory loss, inattention, difficulties with concentration and language, depression, impulsivity, executive function disorders, stress, dementia, and suicidal thoughts are among cognitive, behavioral, and mood-related symptoms associated with RHI and are thought to be linked to CTE pathology [10]. To better understand the mechanisms underlying the development of these conditions, researchers began to examine objective markers capable of detecting brain injuries associated with repetitive brain impacts. Given the subclinical nature of RHI, traditional clinical assessment may fail to identify early or cumulative brain changes, and CTE can currently only be definitively diagnosed postmortem. Therefore, biofluid biomarkers have emerged as a promising tool for evaluating neuronal injury and monitoring brain health in exposed individuals. Proteins such as neurofilament light chain (NfL), tau and glial fibrillary acidic protein (GFAP) have been shown to reflect axonal damage and astroglial activation, even in the absence of overt clinical symptoms. These biomarkers may provide valuable insights into the underlying pathophysiology of RHIs and hold potential for improving early detection, risk stratification and prevention strategies [11,12].

Epidemiology

Repeated exposure to head impacts remains a significant clinical and research challenge, largely due to the frequently subclinical nature of these injuries at the moment of occurrence. This issue is particularly relevant in sports characterized by a high degree of physical contact. For instance, RHI may arise during heading in football (soccer), body checks and fights in ice hockey, as well as tackles and blocking actions in American football. Additionally, direct blows to the head are inherent to boxing and other combat sports. Recent advances in sensor-based technologies have enabled more precise quantification of head impact exposure, facilitating the identification and analysis of impact frequency and magnitude [8, 12].

A prime example is football (soccer), which ranks among the most popular sports in the world, with over 270 million active players worldwide. According to studies related to the 2014 FIFA World Cup, the head was the second most injured part of the body. Soccer players are primarily at risk of head injuries resulting from accidental impacts, such as collisions with opponents and heading the ball. Studies indicate that the average soccer player makes 6–12

headers per match, which, over a 20-year career (not counting daily heading during training), amounts to over 2,000 head impacts [13-15].

Boxing and other combat sports have long been associated with repetitive head injuries. The term chronic traumatic encephalopathy was formally introduced in 1949, however, earlier clinical descriptions date back to 1928, when the neurological sequelae observed in boxers were colloquially referred to as "punch-drunk" [10, 16-18]. Evidence from a large-scale systematic review encompassing more than 733 000 boxers indicates a substantial injury burden, with an average injury incidence of 223.9 per 1000 athletes, rising to as high as 400 per 1000 in professional competitions. Notably, concussions account for approximately 12.9% of all reported injuries. Collectively, these findings underscore the heightened susceptibility of boxers and other athletes participating in combat sports to RHIs [19].

Research on ice hockey provides a useful model for studying sex-related differences in head injury epidemiology. While male athletes experience higher overall injury rates, female players have been shown to sustain a higher proportion of concussions. In collegiate populations, concussion incidence has been reported to be higher in women (0.82 per 1000 athlete exposures) than in men (0.72 per 1000), despite lower exposure to high-impact collisions. These findings suggest that biological and biomechanical factors may contribute to increased susceptibility to brain injury in female athletes [20-21].

Risk Factors

Repetitive head impacts in athletes are influenced by multiple factors, which can be broadly categorized into several groups.

Exposure-related factors are the most widely described risk modifiers. The greater the accumulation of impacts and the total duration of exposure, the greater the risk of structural and functional changes in the brain. Both concussive and subconcussive impacts contribute to the development of long-term neurological consequences [23-25].

Sport-related factors are strictly bound to exposure. Contact sports, such as American football, football (soccer), and ice hockey, subject athletes to greater forces and higher frequency of impacts than non-contact sports [1,2,5,8]. Additionally, within these sports, players in different positions may be exposed to RHI to varying degrees. For example, in American football, linemen and linebackers experience a greater number of impacts, although these are typically low-force, whereas quarterbacks sustain fewer impacts but of greater magnitude [26-28]. Data indicate that athletes who are constantly exposed to RHI without recovery time may

potentially experience amplified cumulative neurological damage; this is particularly relevant for younger athletes [5,28].

Individual factors include age at first exposure, sex, and genetics. Early exposure to head impacts has been linked to increased vulnerability to cognitive and neurobehavioral deficits [29]. Evidence regarding sex differences is limited, but some studies suggest that women may be at greater risk [20-21]. Genetic predispositions, including variants such as APOE $\epsilon 4$, may also increase the risk, although they remain insufficiently studied [30,31].

Overall, the risks associated with RHI are closely linked to the frequency and magnitude of impacts, as well as individual modifiers. Recognizing these factors is key to raising athletes' awareness and promoting prevention.

Mechanisms of Injury

Repetitive head impacts involve concussive and subconcussive forces of an accelerative nature—both linear and rotational—that can lead to cumulative brain damage despite the absence of clear clinical symptoms following a single event [8,10,32]. Understanding the pathomechanisms of injuries resulting from RHI is crucial for developing preventive strategies to protect athletes.

The injury mechanism is primarily based on the action of direct and inertial forces (e.g., whiplash), which generate accelerations and shear stress. Particular importance is attributed to the rotational component, which induces extensive shear stresses in brain tissue, contributing to diffuse damage, while linear accelerations are associated, among other things, with increased intracranial pressure. Biomechanical parameters such as the number and duration of impacts and their force are also significant [8,10,33].

At the axonal level, these impacts lead to disruptions in the integrity of nerve fibers, manifesting as axonal swelling and a reduced structural cohesion. This results in disturbances in nerve impulse transmission and changes in the neuronal cytoskeleton, which may lead to the progression of chronic damage. In neuroimaging studies, these changes correlate with a decrease in fractional anisotropy (FA) and an increase in mean diffusivity (MD), indicating the disintegration of white matter microstructure [8,10,32].

At the neuronal level, structural changes are observed, including a reduction in fiber integrity, neuroinflammation, and, in the long term, neuronal loss. These changes can be either acute or chronic and are associated with a dose-response effect. Importantly, even a single season of exposure to impacts can lead to measurable changes in the white matter [8,34].

At the glial level, repetitive head impacts induce sustained activation of microglia, leading to increased phagocytic activity and aberrant synaptic remodeling. This glial response contributes to chronic neuroinflammation and may further cause progression of neurodegenerative processes [35].

At the whole-brain level, the mechanisms of injury primarily involve diffuse white matter damage resulting from shear forces that disrupt connections between brain regions and compromise the integrity of the blood-brain barrier. However, these changes do not always translate into detectable functional deficits, suggesting the existence of some level of neuronal compensation. Nevertheless, serious consequences of repetitive head impacts are observed, such as cognitive impairments, memory disorders, depression, suicidal tendencies, apathy, and poor impulse control, with some studies potentially linking RHI with ALS [2, 8-11, 24].

In summary, the mechanisms of injury in repetitive head impacts are predominantly biomechanical and microstructural, involving linear and rotational forces that generate shear stress, leading to axonal damage characterized by swelling and loss of integrity. These processes are accompanied by white matter changes, detectable as diffusion abnormalities on MRI, as well as secondary processes such as neuroinflammation and, potentially, neurodegeneration. A key feature is the cumulative nature of the injury, resulting in progressive disruption of neuronal structures, even in the absence of acute clinical symptoms.

Biomarkers of Brain Injury

Biofluid biomarkers have emerged as a promising approach for assessing the biological consequences of repetitive head impacts. A broad spectrum of molecular markers measurable in blood, cerebrospinal fluid, saliva, and urine has been investigated, reflecting subtle neurobiological alterations associated with such exposures. These biomarkers encompass proteins related to neuronal and glial injury, including S100 calcium-binding protein B (S100B), ubiquitin C-terminal hydrolase L1 (UCH-L1), glial fibrillary acidic protein (GFAP), neurofilament light (NfL), and tau, as well as more complex panels involving microRNAs, inflammatory mediators, and hormonal markers. Together, these findings highlight the multifactorial biological response to repetitive head impacts, involving axonal injury, astroglial activation, and neuroinflammatory processes [3, 11].

Among the available biomarkers, neurofilament light (NfL) has demonstrated the most consistent evidence as a sensitive indicator of axonal injury. Studies in contact sports such as football (soccer), American football, and boxing show increases in NfL concentrations following both acute (e.g., single training sessions) and cumulative exposure across a season,

suggesting its potential utility as a marker of cumulative neuronal damage. Similar trends have been observed in both blood and cerebrospinal fluid, reinforcing its robustness across biological matrices. In contrast, other markers such as neuron-specific enolase (NSE) have shown some promise but with less consistent evidence [11, 34, 36].

Tau protein presents as particularly important biomarker due to its central role in the pathophysiology of CTE caused by RHIs. The pathological accumulation of hyperphosphorylated tau (p-tau), especially in perivascular regions within cortical sulci, is considered a hallmark of CTE and reflects progressive neurodegeneration. Circulating forms of tau, including total tau (t-tau) and phosphorylated tau, have been investigated as potential indicators of brain injury burden. Elevated plasma tau levels, particularly t-tau, may reflect cumulative exposure to repetitive head impacts and have been associated with higher lifetime exposure to RHI. However, the relationship between tau concentrations and current clinical status remains unclear, as studies have not demonstrated consistent correlations with cognitive performance or symptom severity. Moreover, findings regarding tau responses to acute or seasonal exposure are inconsistent, with some studies showing no significant changes or lack of association with impact frequency or magnitude. Although phosphorylated tau may offer greater specificity for neurodegenerative processes, its clinical applicability remains limited due to insufficient sensitivity and specificity for in vivo diagnosis [3,12,34].

Other commonly studied biomarkers, such as S100B and GFAP, reflect astroglial activation and blood–brain barrier disruption, but their interpretation is complicated by limited specificity. For example, S100B levels may increase in response to intense physical exercise independent of head impacts, highlighting the challenge of separating brain-specific injury signals from systemic physiological responses. Similarly, inflammatory biomarkers, including cytokines and chemokines, are gaining attention as potential indicators of neuroinflammation, which may play a key role in both acute and chronic responses to repetitive head trauma [11, 34, 37].

A key aspect of biomarker research in RHIs is temporal variability. Acute studies reflect transient biochemical responses, whereas semi-acute and chronic studies assess cumulative or long-term neurobiological changes. Thus, biomarker elevations may indicate either short-term physiological disturbances or longer-term adaptive or injury-related processes [11].

Overall, while biofluid biomarkers offer a promising avenue for detecting and monitoring the effects of repetitive head impacts, current evidence remains inconclusive. NfL appears to be the most reliable marker of axonal injury, whereas tau holds particular relevance for long-term neurodegenerative processes, but lacks sufficient diagnostic precision. The field

continues to face challenges related to specificity, standardization, and confounding influences.

Neuroimaging in Subconcussive Injury

Neuroimaging in the study of effects of repetitive head impacts continues to evolve, particularly in the context of detecting subtle, subclinical changes that are not detectable using standard imaging methods. Classic techniques, such as CT and conventional MRI, primarily serve to detect severe structural damage, whereas modern methods significantly expand the possibilities. As a result, neuroimaging has diagnostic, prognostic and monitoring potential, making it an essential tool in patient care and the development of preventive strategies.

Conventional imaging methods, including computed tomography (CT) and standard magnetic resonance imaging (MRI), have limited sensitivity in detecting brain alterations associated with RHI. CT serves as a tool for identifying acute, macroscopic abnormalities such as hemorrhage or skull fractures, but it is insensitive to subtle tissue damage. In fact, a large proportion of CT and MRI examinations in subconcussive brain injuries are mostly non-diagnostic. There are reports indicating that up to 95% of scans show no changes in individuals exposed to mild traumatic brain injuries. T1- and T2-weighted MRI sequences provide high-resolution image and are useful for detecting chronic or advanced structural changes. However, in early stages of RHI, these techniques are mostly normal. This highlights their limited ability to diagnose subconcussive brain injury [6, 34, 38].

In contrast, advanced MRI techniques offer increased sensitivity to mild brain trauma. Diffusion MRI (dMRI) is one of the most widely used tools for investigating microstructural integrity. It is based on the measurement of water molecule diffusion, which reflects tissue organization, including axonal density and fiber orientation. The most commonly applied method is diffusion tensor imaging (DTI). It provides quantitative parameters such as fractional anisotropy (FA), mean diffusivity (MD), axial diffusivity (AD), and radial diffusivity (RD). Among these, FA is the most consistently reported metric, with many studies demonstrating decreased FA in individuals exposed to repetitive head impacts. These changes are often connected with increases in MD, RD, and AD, suggesting disruptions of white matter microstructure. Abnormalities are frequently observed in long white matter tracts, particularly in the corpus callosum, pointing to diffuse axonal injury as a key mechanism [34, 38-41].

Diffusion kurtosis imaging (DKI) represents an extension of DTI, allowing for a more detailed characterization of tissue complexity. It provides additional parameters such as mean

kurtosis (MK), axial kurtosis (AK), and radial kurtosis (RK). Some studies suggest that DKI may be more sensitive and specific than DTI, with more consistent findings, including increases in kurtosis metrics following exposure to RHI. However, findings across studies of DTI and DKI remain heterogeneous, which may reflect both injury and recovery processes [38, 39].

Susceptibility-based imaging techniques, particularly susceptibility-weighted imaging (SWI), provide insight into microvascular changes. SWI detects subtle signal alterations that may reflect microbleeds or vascular injury following repetitive head impacts. Although these findings suggest the presence of subclinical vascular pathology, their relationship to long-term outcomes and neurodegeneration remains unclear [40, 41].

Functional MRI (fMRI) enables assessment of brain activity through blood oxygenation level-dependent (BOLD) signals and can be performed both at rest and during cognitive tasks. Resting-state fMRI (rs-fMRI) allows evaluation of functional connectivity between brain regions, while task-based fMRI (tb-fMRI) assesses activation patterns during specific cognitive processes. In individuals exposed to RHIs, alterations in functional connectivity have been observed, however, in some populations, particularly pediatric groups, increased connectivity has been reported, which may reflect compensatory mechanisms. Long-term studies indicate that such changes may persist over time, even in the absence of clear clinical differences. Despite its sensitivity, fMRI is limited by variability in methodology and challenges in interpretation [6, 38].

Perfusion imaging techniques, including arterial spin labeling (ASL), are based on non-invasive measurement of cerebral blood flow. While some studies using perfusion-weighted imaging have not demonstrated significant differences between exposed individuals and controls, ASL has revealed regional perfusion alterations in individuals with a history of RHI, particularly in those with cognitive or mood symptoms. These changes have been associated with poorer performance on neuropsychological testing, suggesting a potential link between hemodynamic alterations and functional outcomes [41, 42].

Magnetic resonance spectroscopy (MRS) provides metabolic information and demonstrates long-term neurochemical differences following RHI, however, the specific patterns of metabolite changes are not consistently described, and findings remain relatively general [41, 43]. Structural MRI-based morphometry also remains a potentially useful technique. While cortical thickness and volume measures often do not show significant differences, more detailed analyses reveal selective alterations in subcortical structures. For example, reduced thalamic volume has been associated with longer exposure to contact sports, while variations

in hippocampal and striatal volumes may depend on concussion history. These findings suggest region-specific vulnerability rather than global brain atrophy [44].

Other imaging methods provide additional information about the long-term consequences of subconcussive injury. Positron emission tomography (PET) studies suggest increased accumulation of pathological proteins, including amyloid- β and neurofibrillary tangles, in individuals exposed to RHIs, supporting a possible link with neurodegenerative processes. Magnetoencephalography (MEG), often used with fMRI, is another possibly useful technique. Due to its non-invasive character, it may offer opportunities for future research, however, current knowledge on how to apply it to subconcussive head injuries is limited [41, 45].

Despite significant progress, the application of neuroimaging in RHI faces numerous limitations. These include, above all, the heterogeneity of the study populations, variations in the time elapsed since injury, a lack of standardization in methods for assessing RHI exposure, and small sample sizes. As a result, although neuroimaging is already proving indispensable and providing researchers with valuable information, its role requires further validation in large, prospective studies.

Evidence-Based Prevention Strategies

Prevention of repetitive head impacts (RHIs) in contact sports requires a multidimensional approach that targets both exposure reduction and injury mitigation. Current strategies are based on contact limitations, game and rule changes, safer technique coaching, protective equipment, educational interventions and medical staff interventions. Collectively, such approaches aim not only to reduce the incidence of acute injuries but also to minimize the cumulative burden of subconcussive impacts.

Contact Limitations

Reducing exposure to head impacts is presented as a key mechanism for preventing RHIs in contact sports, particularly in football (soccer), ice hockey, and American football. In soccer, heading is considered the most significant issue. The biomechanics of heading are described as a complex process in which reducing head acceleration can be achieved by increasing neck muscle activation and improving the stability of the entire kinematic chain. It is emphasized that exposure to repetitive impacts, even at low intensity, has a cumulative effect in the context of microtrauma. Restrictions have been implemented in youth populations, including a total ban or significant limitation on heading, which is due to the greater vulnerability of the developing brain, weaker neck musculature, and lower body mass [2, 46].

Research on ice hockey has shown that banning body checking in children's and youth groups is associated with an approximately 58% reduction in the risk of concussion. This finding indicates that systematically limiting physical contact in younger age groups is one of the most effective strategies for preventing head injuries [47].

In American football, the importance of managing exposure based on a player's position is also emphasized, as, for example, linemen and special team players are subjected to a higher number of repetitive head impacts. This highlights the need for more precise, individualized contact limits based on a player's risk profile [28].

Game and rule changes

Changes to the rules of the game and the enforcement of safety protocols are consistently identified as key factors in reducing head injuries in contact sports. In soccer, it has been shown that penalizing dangerous behaviors, such as elbow-to-head contact, introduced in 2006, led to an approximately 29% reduction in the frequency of head injuries [46].

In American football, the importance of rule adjustments regarding kickoffs has been emphasized, where the introduction of the rule to start play from the 25-yard line after a fair catch significantly reduces the risk of high-speed collisions [28].

In ice hockey, rule-based reductions in body-checking exposure among youth populations have been associated with up to a 60% decrease in the concussion rate [47].

Additionally, players should be removed from the game even after a mild head injury for further clinical evaluation, which is a potential element of regulation [9].

In contact sports, the complete elimination of dangerous contact between players is not possible, however, controlling it through regulations and sanctions is essential for risk mitigation [10, 46].

Safer Technique Coaching

Safer technique coaching is crucial for reducing RHIs across contact and collision sports. In football (soccer), proper heading technique requires coordinated whole-body kinematics, where force transfer begins in the lower limbs and is transmitted through an aligned trunk-neck-head system, rather than being isolated in the head. This highlights the importance of neck musculature training. Smaller body mass and weaker cervical musculature, especially in youth players, increase head accelerations during heading. In contrast, improved biomechanical execution, including appropriate body positioning and increased effective body mass at the moment of contact, lowers the level of risk. Anticipatory neck muscle activation

before ball contact can also reduce the magnitude of accelerations transmitted to the brain, while unanticipated or unexpected head impacts with poor neck activation and trunk stabilization are identified as high-risk situations. Visual and oculomotor training interventions are also suggested to improve anticipatory capacity and sensorimotor response, thereby potentially reducing head impact severity [2, 46].

A study in rugby indicates that proper warm-ups and neuromotor training can reduce the incidence of concussions by 32–60%, further supporting the importance of training interventions [47].

Finally, the analyzed studies highlight the importance of educating coaches and players in the context of implementing training changes, as risk awareness contributes to increased safety and reduced exposure to head injuries [9, 46].

Protective Equipment

Protective gear has become an integral part of contact sports, with helmets being the most complex and largest piece of equipment. The primary function of helmets in sports such as American football and ice hockey is reducing linear and rotational accelerations of the head by absorbing impact energy through deformation of cushioning materials, which prolongs the duration of the impact impulse and lowers its peak magnitude. Importantly, the historical development of helmet safety standards has largely focused on preventing skull fractures and severe traumatic brain injuries rather than concussions, which contributes to misconceptions regarding their perceived inefficacy in concussion prevention [33].

Analyses suggest that inter-model differences exist and may be clinically relevant. Modern helmet designs demonstrate improved attenuation of both linear and rotational accelerations compared with older models, largely due to thicker and more compliant padding materials. Increased padding capacity is considered biomechanically relevant in the context of RHIs, as it may better absorb both low- and high-energy collisions that occur repeatedly in contact sports. Despite these improvements, helmets do not completely eliminate head trauma risk because rotational kinematics remain a key driver of brain injury that is difficult to manage through structural design alone. Overall, helmets remain effective for preventing severe head injury but provide only partial mitigation of concussion risk and RHI exposure [33].

Protective headgear used in sports such as rugby and football (soccer) provides substantially less reduction in head acceleration. Reduced effectiveness is primarily attributed to structural constraints, including thinner protective materials and lower cushioning volume, which limit energy absorption capacity during impacts. As a result, headgear may offer only limited

biomechanical protection against repetitive head impacts, particularly those of low to moderate energy that are common in these sports [33].

Mouthguards were designed to protect oral structures rather than the brain. Although theoretical mechanisms have been proposed, such as mandibular stabilization and reduced force transmission to the skull base, the evidence supporting a protective effect against brain trauma is limited. Nevertheless, studies in ice hockey potentially link mouthguards with 28% lower concussion rate. Overall, mouthguards are not currently considered effective tools for reducing outcomes of RHIs, despite their established role in preventing dental injuries [33, 47].

A growing number of protective gear incorporate sensor-based technologies. Sensors integrated into helmets or other equipment enable the measurement of head kinematics during sports participation and provide the necessary data for research. While these technologies do not protect mechanically or reduce impact forces, they play an important indirect role in prevention by giving information useful in identification of high-risk situations. It is emphasized that a data-driven approach could, in the future, enable the establishment of safe exposure thresholds and more precise management of training load [33, 47, 48].

Educational interventions

The authors point out that effective prevention requires a cultural shift in how contact sports are taught and practiced. A key element of this change is a proper understanding of the importance of training in safe techniques, alongside penalizing risky behaviors and dangerous contact. Another important component is creating a safe environment in which athletes are encouraged to report symptoms of injury to referees, coaches, and medical staff [9, 46]. Multidisciplinary analyses of strategies for preventing sport-related concussions indicate that educational and behavioral interventions alone do not demonstrate strong, consistent effects in reducing the incidence of concussions. At the same time, their significant role is emphasized as supporting components for the implementation of other prevention strategies, including rule changes and limiting exposure to contact. These interventions primarily influence the behavior of players and staff, particularly their willingness to report symptoms and adherence to safe play guidelines [47].

Raising awareness of the symptoms and consequences of brain injuries and promoting fair play leads to improved behavior, including a greater willingness to report injuries and adhere to safety rules. Simultaneously, it is noted that despite growing awareness in youth sports, there remains a tendency to downplay the risk of head injuries, which limits the effectiveness

of educational efforts. However, due to the limited number of research studies on this topic and inconsistent evidence, this area offers possibilities for future researchers to explore [46].

The role of the medical staff

From a medical standpoint, detecting head impact exposure as quickly as possible is crucial to minimizing the effects of such an incident. Medical staff, particularly team doctors, can play a key role in this by quickly removing injured players from the field and monitoring them further.

Studies emphasize that players who have suffered a head injury should be removed from the field for follow-up medical evaluation, even in cases of mild head impact. Additionally, monitoring a player after a head injury is crucial, as improper management can lead to a worsening of the clinical condition. Re-exposure to injury shortly after a concussion may increase the risk of further damage and delay the recovery process [9, 10]. In the context of returning to play after a brain injury, neuropsychological tests can help determine the appropriate amount of time that must elapse. It is pointed out that a safe return to play may require at least one month of recovery, which aims to ensure a more complete recovery and reduce the risk of further injuries [10].

Establishing a baseline neurocognitive profile for an athlete is recommended as an effective reference point for tracking changes in cognitive function over time. Real-time monitoring of head impact exposure is likewise useful for supporting clinical decisions regarding limiting an athlete's participation in training or competition. It is underlined that effective prevention requires collaboration among healthcare professionals, coaches, and sports organizations, as well as the implementation of strategies based on exposure-related information [9, 46, 48, 49].

Challenges and Limitations

A key limitation is that the effects of RHIs can develop gradually and remain subclinical for a long time, which makes early identification challenging and limits the effectiveness of prevention strategies based solely on clinical symptoms [8].

Another major limitation is the lack of clearly defined, safe exposure thresholds for RHI, which makes it impossible to precisely define contact limits in both training and matches. This results from the heterogeneity of biomechanical exposure, which depends on many variables, such as technique, situational context, ball properties, and the nature of contact, making it difficult to standardize protective guidelines [2, 50, 51].

Another significant problem is that exposure to RHI is multidimensional and cannot be reduced solely to individual indicators, such as the number of headers, because unintentional contacts and varied match and training situations also contribute significantly to the total load. Consequently, strategies that limit only heading may be insufficient to fully reduce the risk, as they do not address all sources of injury [50].

Other significant limitation is that even modern helmets, despite improvements in their ability to reduce accelerations, do not eliminate the risk of concussion, as it is heavily dependent on the rotational component, which cannot be fully controlled by design. Similarly, headgear in sports without full head protection exhibits only limited biomechanical effectiveness [33].

Finally, a significant limitation is the lack of new research and inconsistent evidence regarding the effectiveness of many educational interventions, which, although potentially important for behavioral change, do not always translate into a measurable reduction in exposure to RHI [47, 49].

Future Directions

The importance and necessity of protecting players from head injuries have been repeatedly emphasized for many years, yet there is still significant scope for improvement in this area. One of the key areas of development in RHI prevention is the further optimization of exposure control through precise management of impact dose based on objective biomechanical measurements. In this context, monitoring systems are becoming increasingly important, as they enable the identification of high-risk situations and can form the basis for future adaptive training and match regulations. The development of sensor-based technologies, particularly ones that measure head acceleration more precisely than helmet sensors, is cited as a significant step toward better quantifying RHI exposure, although their role currently remains primarily research-oriented [33, 47, 48].

A significant future challenge is to identify safe exposure thresholds, as there are currently no standardized values for the number of head impacts or acceleration levels that can be considered safe in the short or long term. Consequently, future regulatory strategies should include not only intentional contacts (e.g., headers) but also unintentional collisions and situational context, as exposure to RHI is dependent on various factors [50, 51].

Another crucial area for development involves systemic modifications to the training structure, which is the principal source of exposure to RHIs. Consideration should be given to limiting full-contact training sessions and eliminating the most high-impact forms of activity that generate the greatest accumulation of head accelerations [5, 47, 48].

The next direction for development is the integration of neuromotor programs and neck muscle control training in order to reduce the risk of injury, as increased strength and neuromuscular coordination can reduce head accelerations. In parallel, strategies for optimizing movement technique are being developed, including Behavioral Skill Training (BST), which may reduce the biomechanical load on the brain during contact [46, 47].

Regarding protective equipment, future research should focus on improving helmet design by further enhancing the attenuation of both linear and rotational accelerations, although even modern helmets do not eliminate the risk of RHI [33].

Making changes to the rules is also critical for future interventions, particularly regarding sanctioning dangerous behavior and reducing high-risk contact situations, such as elbow strikes and head-to-head collisions. Researchers also suggest that the complete elimination of certain elements of the game, such as kickoffs in American football, could reduce exposure to head impacts, particularly in youth populations. At the same time, it is emphasized that the complete elimination of contact is not possible; therefore, future regulations should focus on controlling it rather than eliminating it [28, 46].

Another important focus for the future is the development of educational and behavioral interventions, which should simultaneously promote fair play, increase knowledge about the actual risk of RHI, correct misconceptions, and modify emotional components of attitudes, such as excessive fear of injury. The effectiveness of future prevention strategies will likely depend on integrating regulatory interventions with educational ones, as regulatory changes alone may not lead to behavioral change without a parallel shift in risk perception [46, 49].

When it comes to neuroimaging, future research should prioritize the development and application of advanced, multimodal neuroimaging approaches, particularly in understudied populations such as pediatric cohorts, to increase sensitivity for detecting subtle brain changes associated with RHIs. Efforts should also focus on improving the diagnostic and prognostic utility of neuroimaging through the development of standardized methodologies, longitudinal study designs, and integration with complementary data modalities. In this context, data-driven techniques, including machine learning, are expected to play a key role [38, 39, 52].

Finally, a better understanding of the dose–response mechanisms between RHI and neurological changes, including subtle, subclinical effects that may not be detectable in standard clinical assessments, remains an essential direction for future research. Only the integration of biomechanical, neuroimaging, and behavioral data will enable the design of precise, evidence-based preventive interventions at the sport and system levels [50].

Conclusions

Repetitive head impacts (RHI) represent a clinically significant and widely recognized source of cumulative brain injury among both athletes and non-athletes. Despite its often-subclinical nature, literature suggests that cumulative exposure to forces causing concussion and to those of lower intensity can lead to progressive microstructural brain damage, neuroinflammation, and long-term neurodegenerative changes, including those associated with chronic traumatic encephalopathy (CTE). Importantly, these effects appear to follow a strict relationship, in which both frequency and force of impacts, as well as individual vulnerability factors, influence the overall risk.

Advances in neuroimaging and biological fluid biomarkers have substantially improved the ability to detect subtle brain changes associated with RHI. Techniques such as diffusion MRI and functional imaging provide insights into white matter integrity and functional connectivity, while biomarkers, particularly light neurofilaments, offer a promising approach to quantifying neuronal damage. However, their current clinical utility remains limited by variability in results, a lack of standardization, and insufficient specificity.

Prevention remains the foundation of management for injuries caused by RHI. Scientific evidence supports a multidimensional strategy that combines exposure reduction, modification of game rules, optimization of training techniques, and close medical supervision. Nevertheless, significant challenges remain, including the lack of clearly defined safe exposure thresholds and heterogeneity in measurement methods.

Future research should focus on large-scale, longitudinal, and multimodal studies that integrate biomechanical data, neuroimaging, and biomarkers to better characterize the pathophysiology and clinical course of RHI. Establishing standardized assessment protocols and exposure metrics will be essential for improving comparability across studies. Ultimately, a more precise understanding of dose-response relationships and individual vulnerability will be critical for developing targeted, evidence-based preventive strategies aimed at reducing the long-term neurological burden associated with RHI.

Disclosure

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