Traumatic Brain Injury in Sports: Long-Term Neurological Effects, Pathophysiology, and Prevention

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Abstract

Traumatic brain injury (TBI) in sports has become a growing public health concern due to its long-term impact on cognitive, emotional, and neurological functioning. Although often viewed as short-term injuries, concussions and subconcussive impacts can lead to serious and sometimes irreversible consequences. Athletes in high-contact sports such as football, boxing, and hockey are especially vulnerable to repeated head trauma, which can lead to chronic symptoms like memory loss, depression, impaired decision-making, and neurodegenerative diseases such as chronic traumatic encephalopathy. The brain damage associated with TBI often includes diffuse axonal injury, persistent inflammation, and pathological tau protein accumulation. Many of these effects may not manifest until years after the initial injuries, making early detection and treatment difficult. While protective equipment, education, and concussion protocols have improved, significant gaps remain in prevention and long-term care. This review explores the current understanding of sports-related TBI and its persistent effects on brain health. Despite progress, the long-term consequences of sports-related TBI remain a serious and insufficiently addressed health concern, demanding further research, improved diagnostic tools, and stronger preventative strategies to protect athletes at all levels of play.

Introduction

In recent years, traumatic brain injury (TBI) and chronic traumatic encephalopathy (CTE) in contact sports participants have received intense media, medical, and scientific attention. (Ling et al., 2015). A traumatic brain injury (TBI) refers to a brain injury that is caused by an outside force. TBI can be caused by a forceful bump, blow, or jolt to the head or body (National Institute of Health(NIH), 2018). TBIs are unique because they disrupt complex brain functions in ways that are often invisible. Even mild TBIs can lead to lasting issues like memory loss, mood changes, and difficulty concentrating, despite normal brain scans (McInnes et al., 2017). These injuries are often underestimated because symptoms can be delayed, subtle, or mistaken for other problems. In athletes and military personnel, repeated head injuries are common and frequently go unreported, further masking the true impact (Daneshvar et al., 2011). As a result, the long-term consequences of TBIs—especially repeated mild ones—are often overlooked until serious damage has occurred. The long-term impact of TBI includes neurodegenerative diseases like CTE, as well as impairments in decision making and executive function. In football and boxing, players may experience thousands of subconcussive hits, or head injuries that do not result in a clinically diagnosed concussion or result in any immediate symptoms, throughout a single season (McKee et al., 2009). Subconcussive impacts may warrant similar attention in clinical care and research as impacts resulting in a concussion because they may contribute to cumulative brain damage over time (Davenport et al., 2016). There is still much to learn about the mechanisms underlying long-term TBI consequences and how to best mitigate these effects (Ling et al., 2015). The purpose of this review is to examine the long-term of sports-related TBI, including cognitive decline, mood disorders, and neurodegenerative diseases.

Types of TBI

There are three main types of TBI: Mild TBI or concussion, Moderate TBI, and Severe TBI.

-Mild TBI

Most TBIs that occur yearly are mild, and these injuries are typically considered as non-life-threatening (CDC, 2024a). Symptoms of mild TBI include headache, confusion, dizziness, ringing in the ears, memory impairment, blurred vision, and behavioral changes such as irritability, mood swings, impulsivity, and difficulty with concentration (Commissioner, 2025).

-Moderate and Severe TBI

A severe bump, blow, or jolt to the head causes a moderate or severe TBI. In the United States, severe TBIs are linked to thousands of deaths each year (although most of these are due to the etiology of the severe TBI, such as gunshot wounds, car accidents, or falls) (CDC, 2024b). For those who survive, a moderate or severe TBI may lead to long-term or lifelong health problems that may affect all aspects of a person's life (CDC, 2024b). Immediate treatment for a severe TBI focuses on preventing death. (CDC, 2024b). Moderate and severe TBIs can produce symptoms such as repeated vomiting or nausea, slurred speech, weakness in the arms or legs, problems with thinking and learning, and even potentially cause death (Commissioner, 2025). Overall, the severity of a TBI significantly influences its symptoms and long-term effects, with even mild cases potentially leading to behavioral issues like irritability, mood swings, and impulsivity, as well as cognitive difficulties such as memory problems and trouble concentrating.

Pathophysiology of Long-Term Brain Damage

The physical forces involved in traumatic brain injuries can cause widespread structural and cellular damage in the brain, setting the stage for both immediate and long-term neurological consequences. Rapid acceleration and deceleration forces on the brain, either linear or rotational, are the primary mechanisms in which concussion and subconcussion occur (Ling et al., 2015). Examples of rotational acceleration are blows to the head by hook punches in boxing, and examples of linear acceleration could be straight head blows and head contact in other sports such as American Football. When subjected to rapid acceleration, deceleration, and rotational forces, the brain and all its components, including neurons, glial cells, and blood vessels, are stretched, which may disrupt their normal functions (Ling et al., 2015). Axons that span long distances from the cell bodies are particularly susceptible to stretching, which may lead to diffuse axonal injury. Diffuse axonal injury refers to a form of traumatic brain injury caused by shear and tensile forces within the brain. It is characterized by severe deficits, including coma and decerebrate posturing–an involuntary extension of all limbs–is a sign of significant brain damage.(Ling et al., 2015). Chronic neuroinflammation is a key factor in the long-term consequences of TBI. Microglial activation, a hallmark of persistent inflammation, releases pro-inflammatory cytokines that contribute to neuronal damage and cognitive decline (McKee et al., 2015).

One explanation of the progressive loss of cognitive function in CTE may be neurofibrillary tangles, or intracellular tangled proteins, which decreases brain function overall. This mechanism is similar to what is observed in Alzheimer's disease and other forms of dementia (McKee et al., 2015). Repeated TBIs have been strongly linked to the hyperphosphorylation of

tau protein, which in its insoluble form can build up inside neurons and make their function decrease or cause neuron death (Donison et al., 2025). Tau buildup is a defining feature of CTE, a progressive neurodegenerative disease associated with repeated head trauma. (Mez et al., 2017). Neuroimaging studies of retired athletes with a history of multiple concussions have shown cortical thinning and brain atrophy in key regions, including a number of areas associated with memory and mood, such as the hippocampus (memory), prefrontal cortex (executive function), and amygdala (emotions such as fear and aversion) (Koerte et al., 2012). These structural changes correlate with long-term cognitive decline, such as memory deficits and executive function (Blennow et al., 2012). Understanding how to prevent tau buildup is crucial, especially as athletes and others face risks from repeated head impacts.

Cognitive Consequences of Sports-Related TBI

A systematic review concluded that individuals with a history of multiple concussions are at an increased risk for cognitive impairments, particularly in areas such as memory and attention (*A Systematic Review of Potential Long-Term Effects of Sport-Related Concussion | British Journal of Sports Medicine*, n.d.). The authors emphasized the need for further research to fully understand the prevalence of CTE and other neurological conditions related to repetitive neurotrauma in sports (*A Systematic Review of Potential Long-Term Effects of Sport-Related Concussion | British Journal of Sports Medicine*, n.d.). The review concluded that repeated concussions are associated with long-term deficits in memory and attention, supported by objective neuropsychological testing and imaging evidence.

The potential link between repetitive concussions and neurodegenerative disease has been a subject of ongoing research. While some studies suggest an association between multiple concussions and conditions like CTE, the exact relationship has not been fully elucidated due to diagnostic limitations and limited longitudinal data (McAllister & McCrea, 2017). The review indicates that further research is needed to determine the extent to which concussions and repetitive head impacts contribute to the development of neurodegenerative diseases (McAllister & McCrea, 2017).

Psychological and Behavioral Effects

Depression and anxiety are among the most frequently reported psychological consequences of sports-related TBI (*Traumatic Brain Injury-Traumatic Brain Injury - Symptoms & Causes*, n.d.). According to the Mayo Clinic, individuals with TBIs often experience mood swings, irritability, and heightened emotional responses (*Traumatic Brain Injury-Traumatic Brain Injury - Symptoms & Causes*, n.d.). Research also suggests that post-concussion syndrome can exacerbate these symptoms, leading to prolonged periods of emotional distress (*Traumatic Brain Injury-Traumatic Brain Injury - Symptoms & Causes*, n.d.). Behavioral changes, including increased aggression and impulsivity, have also been linked to repeated sports TBIs. A study of former football players found that those with a history of concussions were more likely to exhibit aggressive tendencies and poor impulse control (*One-Third of Former Football Players Believe They Have Degenerative Brain Disease CTE, New Report Finds*, n.d.). Many of these athletes reported difficulties with decision making and emotional regulation (*One-Third of Former Football Players Believe They Have Degenerative Brain Disease CTE, New Report Finds*, n.d.).

The case of former NFL star Aaron Hernandez provides a striking example of how TBIs can contribute to extreme behavioral changes. A postmortem examination revealed that Hernandez had severe CTE, which may have played a role in his violent behavior and erratic decision-making before his death (*Psychologist Looks at Where NFL Star Aaron Hernandez's Demise May Have Started*, n.d.). This case highlights the devastating impact of repeated head injuries on personality and mental stability. (*Psychologist Looks at Where NFL Star Aaron Hernandez's Demise May Have Started*, n.d.). One of the most alarming consequences of sports-related TBIs is the increased risk of suicidal thoughts and behaviors. Studies indicate that athletes with a history of multiple concussions are more likely to experience suicidal thoughts compared to those with no history of concussions (*Psychological Aspects of Sports Concussion*, n.d.). The connection between CTE and suicide has been widely discussed, particularly in cases involving former professional athletes who exhibited severe depression and cognitive decline before taking their lives (*Psychological Aspects of Sports Concussion*, n.d.).

CTE

First identified in former boxers as "punch-drunk syndrome," chronic traumatic encephalopathy (CTE) has since been recognized in athletes who have experienced repeated concussions or subconcussive blows to the head. CTE is a progressive neurodegenerative disease linked to repeated head injuries, particularly in contact sports such as football, boxing, and hockey. CTE is irreversible and progressive, marked by the accumulation of abnormal tau protein in the brain (Smith et al., 2019). CTE differs from other neurodegenerative diseases in its unique pattern of tau protein accumulation in the brain (Smith et al., 2019), which is detected by brain tissue analysis. Postmortem studies have revealed that individuals with CTE exhibit perivascular tau deposition: a marker of degeneration of brain tissue, particularly in the depths of cortical sulci, which is not typically observed in other tauopathies such as Alzheimer's disease (Smith et al., 2019). Currently, CTE can only be diagnosed postmortem, which presents significant challenges for early detection and intervention. Researchers are working on developing biomarkers and imaging techniques to identify CTE in living individuals, but none exist yet. The limitation complicates efforts to track the progression of the disease and implement preventative measures for at-risk athletes (Smith et al., 2019).

However, there is a clinical diagnosis associated with CTE, meaning a diagnosis while the patient is still alive, based on the symptoms associated with this particular neurodegeneration. Individuals with CTE often experience progressive cognitive impairment, including memory loss, executive dysfunction, and difficulties with concentration. These symptoms may emerge years or even decades after an athlete's exposure to repetitive head injuries. In addition to cognitive deficits, behavioral changes such as impulsivity, aggression, and emotional instability are common (Smith et al., 2019).

Prevention and Management

Utilizing appropriate protective gear is fundamental in reducing the risk of head injuries. Properly fitted helmets can lower the chance of TBIs during sports and recreational activities, although they may not entirely prevent concussions. Additional equipment like mouthguards and padded headgear can offer supplementary protection (CDC, 2024c). Education plays a pivotal role; informing athletes, coaches, and parents about the signs and symptoms of concussions

promotes early recognition and appropriate response. Implementing and strictly enforcing rules that minimize dangerous plays, such as targeting or high tackles, can reduce head injuries. Teaching proper heading techniques in soccer can reduce head impact exposure. Incorporating neck-strengthening exercises into training regimens may help stabilize the head during impacts, potentially reducing the severity of injuries (*Concussion Prevention Strategies*, n.d.)

Additionally, reducing the frequency and intensity of contact drills during practice can lower cumulative exposure to head impacts over the season (*Concussion Prevention Strategies*, n.d.). When a concussion is suspected, immediate action is essential. Athletes should be removed from play and evaluated by a healthcare professional; the principle “when in doubt, sit them out” underscores the importance of caution. Standardized assessment tools help diagnose concussions and assess their severity. Management should be tailored to the individual’s symptoms, initially incorporating physical and cognitive rest, followed by a gradual return to activity. Athletes should only resume playing once fully cleared by a health professional (Sahler & Greenwald, 2012).

Discussion

The long-term effects of sports-related TBIs remain a growing concern in medical, athletic, and scientific communities. The evidence reviewed highlights the significant cognitive, psychological, and neurodegenerative consequences associated with repeated head impacts, particularly in contact sports such as football, boxing, and hockey. CTE, a progressive neurodegenerative disease linked to repeated TBIs, underscores the need for increased awareness and preventative measures. Studies indicate that structural and functional brain changes occur in athletes with a history of multiple concussions, leading to impairments in memory, executive function, and emotional regulation. Furthermore, behavioral changes such as aggression, impulsivity, and increased risk of depression and suicidal ideation emphasize the serious nature of these injuries.

Despite advancements in prevention and care, including improved protective gear, rule modifications, and education, eliminating the risks of TBI remains a major challenge. Continued research is necessary to evaluate emerging protective measures and refine existing protocols. Further studies should focus on early detection methods, such as neuroimaging and biomarkers, to identify TBI-related changes before significant symptoms develop. Additionally, long-term studies on former athletes could provide deeper insights into the progression of neurodegenerative diseases linked to sports-related TBIs. Increased collaboration between medical professionals, sports organizations, and researchers is essential in developing evidence-based strategies to protect athletes while preserving the integrity of sports. Ultimately, balancing player safety with the competitive nature of sports requires ongoing innovation, education, and a commitment to athlete well-being. Ultimately, protecting brain health in sports requires not just innovation, but a cultural shift that prioritizes long-term well-being over short-term performance.

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