The Long-Term Effects of Repeated Concussions in Contact Sports: A Review of Emerging Biomarkers and Prevention Strategies

Riaz Ahmed

ABSTRACT

This review examines the long-term effects of recurrent concussions in contact sports with an emphasis on emerging biomarkers and prevention strategies. Despite their prevalence in high-risk sports such as football, rugby, and hockey, concussions are associated with severe cognitive impairments, mood disorders, and neurodegenerative disorders, including chronic traumatic encephalopathy (CTE). Recent advances in the markers, both fluid-based markers (glial fibrillary acidic protein, neurofilament light, tau) and neuro-imaging techniques like tractography, have demonstrated that biomarkers are promising for detecting acute concussion effects and monitoring neurobiological recovery. Concussion prevention practices, such as the use of protective equipment, rule alterations, and neuromuscular training, have proven effective in reducing the incidence of concussion. However, there are still no solutions for the issues related to the validation of biomarkers and the clinical application of neuroimaging tools. Early detection, appropriate management, and a multidisciplinary approach to concussion prevention are emphasized in this review. Future work should focus on developing and validating biomarkers and personalized concussion management protocols for athletes in contact sports.

Keywords: Repeated concussions, Chronic traumatic encephalopathy, Fluid-based biomarkers, Neuroimaging, Prevention strategies

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Additional material is published online only. To view please visit the journal online.

Cite this as: Ahmed R. The Long-Term Effects of Repeated Concussions in Contact Sports: A Review of Emerging Biomarkers and Prevention Strategies. Premier Journal of Science 2025;9:100086

DOI: https://doi.org/10.70389/PJS.100086

Received: 9 May 2025

Revised: 5 June 2025

Accepted: 11 June 2025

Published: 25 June 2025

Ethical approval: N/a

Consent: N/a

Funding: No industry funding

Conflicts of interest: N/a

Author contribution: Riaz Ahmed – Conceptualization, Writing – original draft, review and editing

Guarantor: Riaz Ahmed

Provenance and peer-review: Commissioned and externally peer-reviewed

Data availability statement: N/a

Background and Introduction

Overview of Concussion Prevalence in Contact Sports

Concussions are a serious public health concern in areas where sports involve contact. The CDC report indicates that approximately 70% of the emergency department visits for sports and recreation-related injuries and concussions involve children aged 17 and younger.[1] Within this age group, boys face a greater risk of concussion-related visits compared to girls, with the incidence being approximately twice as high in boys. The CDC report suggests that youth tackle football has the highest concussion rate, with tackling accounting for 63% of cases, followed by soccer for girls and lacrosse for boys. In comparison, basketball for girls ranked eighth, with 51% of cases resulting from collisions with other athletes[1] (see Figure 1). Concussions are sport-specific, with boxing and American football as the most common, with 61% and 60% of respondents in a survey viewing them as prevalent in those sports.[2] Other contact sports, such as ice hockey and rugby, also have high concussion rates, with 38% and 35% of respondents reporting concussions as very common in such sports.[2]

Importance of Addressing Long-Term Effects

Recurrent concussions may have enduring health impacts, including cognitive impairments, mood disorders, among others, and neurodegenerative diseases such as chronic traumatic encephalopathy (CTE). These implications are especially dire for youth athletes since failure to manage concussions adequately can lead to impairments throughout a person's life. The study revealed that the rate of concussions differs between sports. Boxing (61%) and American football (60%) are believed to be the sports with the most commonly reported concussions according to public opinion in the United States, while tennis is considered to be the one with the least commonly reported concussions (8%)[2] (see Figure 2). In the range of youth sports, overall pooled incidence rates of sports-related concussions (SRC) are 1.41 (per 1000 airline exposures (AE) across 21 sports and 4.36 per 1000 player hours (PH) across seven sports.[3] Moreover, concussions are more likely to develop during matches rather than training, with greater rates of concussions in matches.[4] The effects of these injuries (particularly in youth athletes) accentuate the need to share the immediate and long-term effects of concussions.

Scope of the Review

This review determines the long-term consequences of successive concussions in contact sports, especially in developing biomarkers for diagnosis, monitoring, and prognosis. The fluid-based biomarkers, glial fibrillary acidic protein (GFAP), neurofilament light (NfL), tau, and imaging, are discussed to outline their use in diagnosing concussions and tracking the process of the associated brain injury.[3] Prevention measures, such as improved protective gear, modified game rules, and educational programs, are also examined to reduce the incidence of concussions. Concussions in youth sports have been shown to occur more commonly; research indicates prominent SRC prevalence in many sports. Rugby 7s, rugby league, and rugby union show the highest incidence rates of concussions per 1000 PH,[3] which has been found in a meta-analysis of 116 studies with over 3 million participants. Furthermore, the increased incidence and burden of a concussion in women's football compared to men's football calls for enhanced strategies. While these efforts have helped

Fig 1 | Concussion rates by contact sport[1]

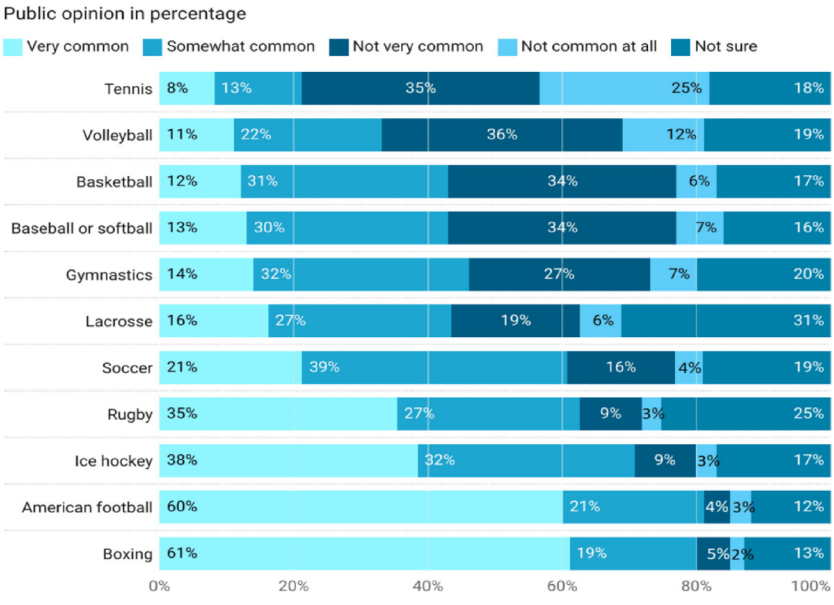

Fig 2 | Public opinion about sports in the US[2]

reduce concussion-related risks in contact sports, further research is needed to understand these risks better and identify ways to prevent them.

Research Objectives

- To investigate the chronic effects of repeated concussions in contact sports, including cognitive impairments, mood disorders, and the development of neurodegenerative diseases such as CTE.
- To assess the current state of research on fluid-based (GFAP, NfL, tau) and imaging biomarkers for SRC diagnosis, monitoring, and prognosis.
- To examine existing and novel approaches to prevent concussions in contact sports, including equipment innovations, rule modifications, and educational programs.
- To highlight limitations in current research and propose areas for future investigation to enhance understanding and management of concussion-related risks.

Understanding Concussions

Definition and Pathophysiology

A concussion is a mild type of traumatic brain injury (TBI) that arises from blows to the head or body, causing the brain to move violently within the skull. Mayo Clinic reports that symptoms of a concussion may include headache, dizziness, confusion, and even unconsciousness[5,6] (see Figure 3). The CDC defines a concussion as a mild TBI that causes disordered brain function, usually with temporary side effects.[7] Pathophysiology occurs through neuronal injury caused by mechanical forces leading to metabolic changes, ionic imbalance, and neurotransmitter release. An acute set of alterations can occur, which may subside or become permanent, especially in contact sports.[6] These alterations can impact cognitive functions, motor coordination, and emotional regulation, often resulting in difficulty concentrating and mood instability.

Mechanisms of Injury in Contact Sports

In contact sporting activities, concussions typically result from direct or indirect forces acting on the head. Brainstorm Florida notes that these injuries frequently result from rotational or linear acceleration of the brain against the skull.[8] According to Ha et al., in Taekwondo, where high-speed kicks or punches into an athlete's head are known to occur, head strikes, especially those on the side of the head, are the leading cause of concussions.[9] These impacts cause the rapid movement of the brain within the skull, leading to shearing forces that damage neuronal structures, disrupt normal brain function, and potentially result in a range of symptoms. For example, in soccer, Jo et al. found out that aerial challenges and contact with other players or the ground are the leading causes of concussions in collegiate players.[10]

DOI: https://doi.org/10.70389/PJS.100086 | Premier Journal of Science 2025;9:100086

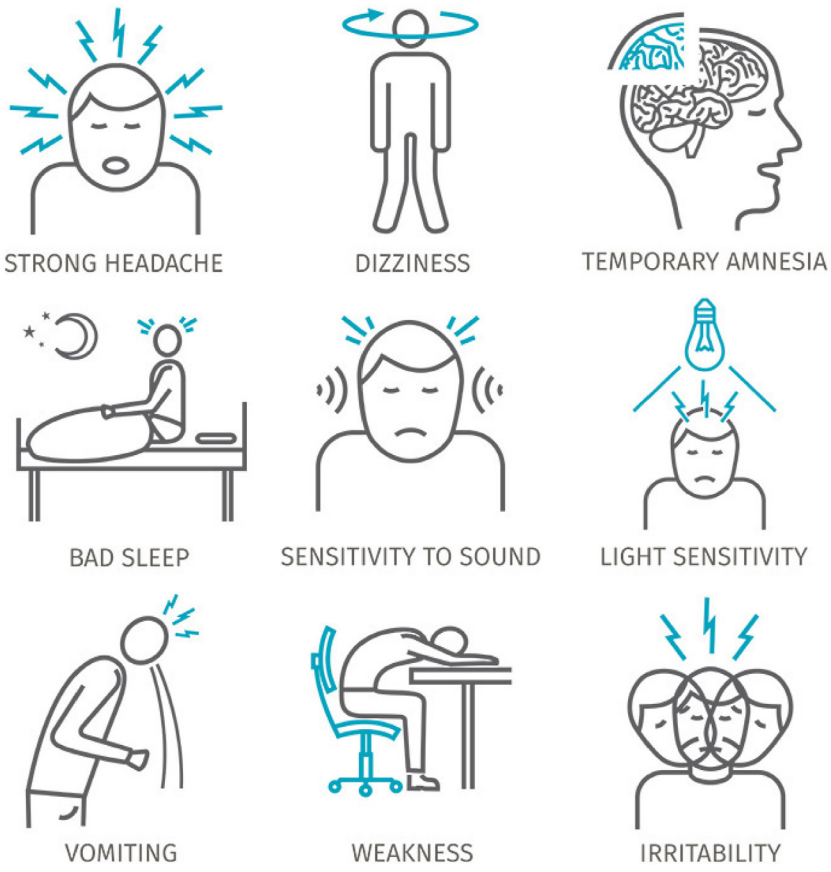

Fig 3 | Concussion symptoms[6]

Acute vs. Chronic Implications

Acute concussions induce immediate signs, which may include headache, nausea, and confusion lasting for a period of a few days or weeks. Nevertheless, subsequent concussions or improper healing of an initial one may cause chronic forms, including post-concussion syndrome or, as a result, neurodegenerative diseases of the brain, such as CTE. Moreover, the long-term consequences of SRC are becoming more appreciated, and exosomal biomarkers provide some insights into the biological mechanisms of chronic neurodegeneration.[11] There are especially concerning long-term effects of chronic concussion in athletes because the cumulative nature of the injuries increases the possibility of serious cognitive and emotional impacts in later life.

Long-Term Effects of Repeated Concussions in Contact Sports

Cognitive Deficits

Chronically repeated concussions in contact sports have been correlated, over the long term, with cognitive deficits such as memory impairments and difficulties with sustaining attention. Gallo et al. reported evidence indicating that athletes who suffered concussions in sports such as rugby, American football, and boxing had poorer cognitive function as they age, but the clinical significance is unclear.[12] Hallock et al. raised the point that, in turn, recurrent concussions also contribute to the increase of cognitive deficits, including memory loss and attention deficits, which underscores the need for a set of standardized guidelines for handling these long-term consequences.[13] These results emphasize the need to pursue cognitive rehabilitation among athletes who have concussions due to sports. Furthermore, the accumulation of repeated concussions can lead to a decline in executive functions.

Emotional and Behavioral Changes

Consistent concussions in contact sports have been associated with significant emotional and behavioral modification. According to one study, attention should be paid to such problems as mood-related issues, such as anxiety and depression, which affect almost 30% of athletes with SRC.[14] These mental implications can affect an athlete's mental health and well-being. In addition, Howlett and others emphasized the fact that TBIs, even as mild concussions, can result in emotional instability, irritability, and depression, and some athletes develop new-onset psychiatric diseases, for example, posttraumatic stress disorder.[15] Such findings reveal the need for improved psychological support and intervention for concussion victims who are athletes. Moreover, these emotional and behavioral changes can negatively impact an athlete's social interactions, personal relationships, and overall quality of life.

Neurodegenerative Conditions

The chronic sequelae of repeated head injury and SRC have become a significant issue concerning long-term neurodegenerative diseases in athletes, such as both CTE and Alzheimer's disease. Malcolm describes how repeated head impact in athletes, especially those in contact sports, might predispose them to such neurodegenerative conditions as CTE, but the evidence for this is not very easy and socially mediated by such variables as occupation and social environment[16,17] (see Figure 4). The Australian Institute of Sport identifies that CTE is associated with a history of repeated head injuries and a case study example showing neuropathological changes in retired athletes.[18] Another research study was conducted to make a complete sense of the risks of Alzheimer's disease, particularly with gender differences in susceptibility, where women are especially susceptible.[18] This evidence highlights the urgency of better management and further research into the relationships between head trauma and neurodegenerative diseases in athletes.

Impact on Quality of Life and Career Longevity

Athletes have been proven to have their long-term quality of life and career longevity adversely affected by SRC. By analyzing older exploit structures (starting about 240 years ago), Gouttebarge and Kerkhoffs have shown that individuals who have sustained several concussions as former elite athletes are more likely to experience mental symptoms. Retired professional American football players with three or more previous

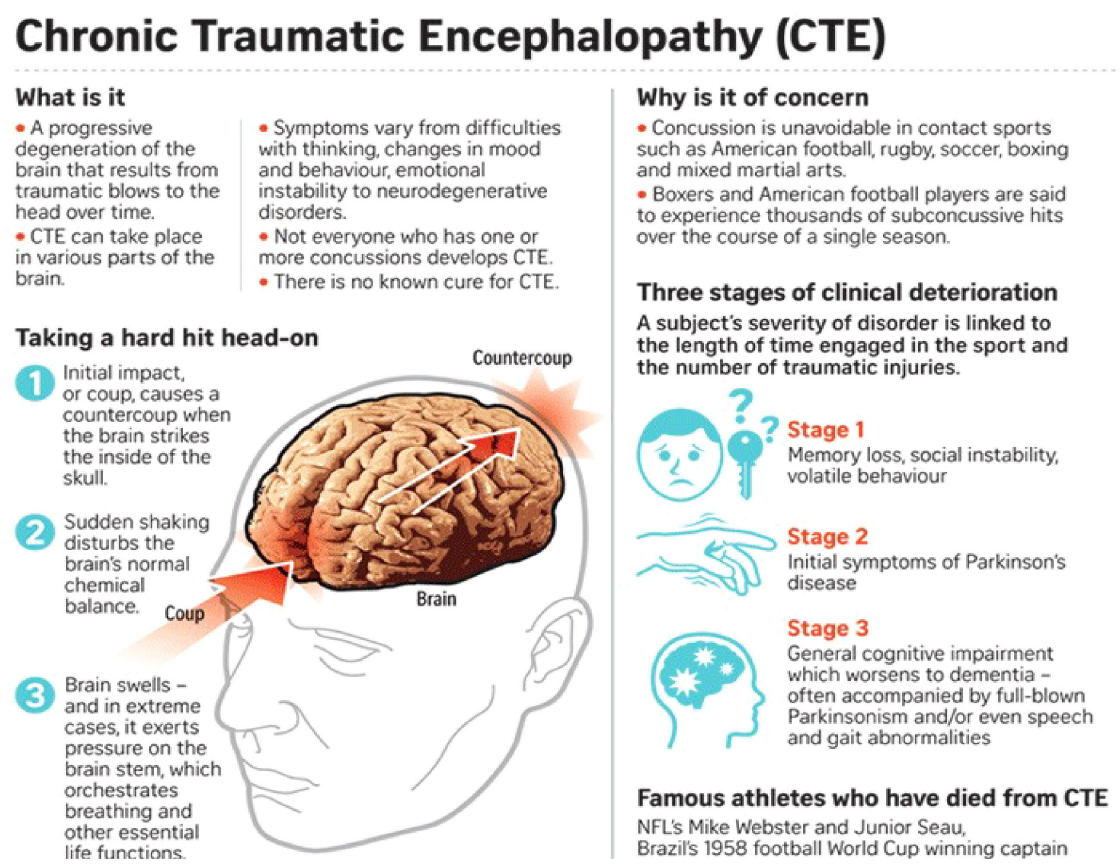

Fig 4 | CTE progression[17]

concussions were three times as likely to be diagnosed with depression as people without any prior history of concussions.[19] Furthermore, survivors of six or more concussions reported being up to five times more likely to develop mental health symptoms like anxiety and depression.[19] Nevertheless, another study recorded a significant fall in academic performance after SRC in young athletes. Out of 14 studies reviewed, one found a significant grade drop in some individuals, accompanied by substantial drops in GPA and examination scores after concussion.[20] Such results highlight the considerable implications of SRC in terms of both mental health and academic success and call for promising methods to manage these long-term effects on athletes' careers and quality of life.

Emerging Biomarkers in Concussion Research

Fluid-Based Biomarkers

Fluid-based biomarkers, including GFAP, NfL, and tau, are key to monitoring concussion recovery. These biomarkers can detect acute effects of concussion and track neurobiological recovery.[21] In particular, these blood biomarkers, such as GFAP with UCH-L1, have obtained FDA approval to help detect brain lesions in cases of mild TBI[22–24] (see Figure 5). Further, O'Brien et al. discovered that serum concentrations of GFAP and NfL can be informative concerning recovery trajectories, as higher levels may last for up to 4 weeks after a concussion in cases of loss of consciousness.[25] These biomarkers might be used to develop future return-to-play protocols, but their clinical utility is being researched. Additionally, the potential for these biomarkers to serve as early indicators of long-term neurodegenerative diseases, such as CTE.

Imaging Biomarkers

Neuroimaging is another important tool for evaluating brain injury following concussion because it helps to see structural and functional changes. Tabor et al. revealed that neuroimaging, including state-of-the-art modalities such as MRI and DTIs, has been beneficial in establishing brain structure alterations after SRC.[21] Similarly, Hossain et al. pointed out that neuroimaging and blood biomarkers may facilitate long-term outcomes by detecting residues of brain abnormalities post-clinical recovery.[22] However, the problem is that most neuroimaging techniques are expensive and varied, preventing their routine clinical use. Despite these challenges, ongoing advancements in neuroimaging technologies, such as functional MRI and machine learning algorithms for data analysis, may reduce costs and improve the sensitivity of detecting subtle brain changes.

Genetic and Molecular Markers

Genetic and molecular markers may provide information that will expose incidences of neurodegenerative

DOI: https://doi.org/10.70389/PJS.100086 | Premier Journal of Science 2025;9:100086

diseases like Alzheimer's and CTE after a concussion. Alanazi et al. reported a range of biomarker changes in retired rugby players who suffered multiple concussions, including tau and p-tau181, indicating an elevated risk for neurodegenerative diseases.[26] Although Tabor et al. noted that the effect of genetic testing on studying concussion prognosis is unclear, there has been increasing interest in what genetic predispositions may influence recovery trajectories and the onset of long-term conditions.[21] Genetic testing in the future may be able to identify athletes at a higher risk for severe impacts, but more research is needed to validate these markers.

Challenges in Biomarker Validation and Clinical Application

Several challenges in validation and standardization still prevent the clinical use of biomarkers for concussion. Hossain et al. highlighted the following about biomarkers, GFAP and NfL: they are promising, although the markers are limited in clinical use due to inconsistent results and disparities in concussion severity when measured.[22] Moreover, O'Brien et al. indicated that although biomarkers can provide information on recovery trajectories, their use in predicting long-term outcomes, such as cognitive decline, is inconclusive.[25] Furthermore, another study noted the underrepresentation of pediatric cohorts in biomarker research, making it difficult to apply findings obtained in adults to younger people.[27] These problems underscore the need for comprehensive, standardized studies to validate biomarkers and assess their effectiveness in clinical practice.

Prevention Strategies in Contact Sports

Protective Gear and Equipment

Protective equipment has been demonstrated to play a significant role in reducing SRC risks. Eliason et al. reported that a 26% reduction in incidence of concussions was associated with mouthguards in collision sports, with an IRR of 0.74.[28] Even headgear and helmets play a vital role in reducing head impulses. However, even though helmets reduce certain types of risks, they do not guarantee protection against concussions. Moreover, the effectiveness of protective gear, such

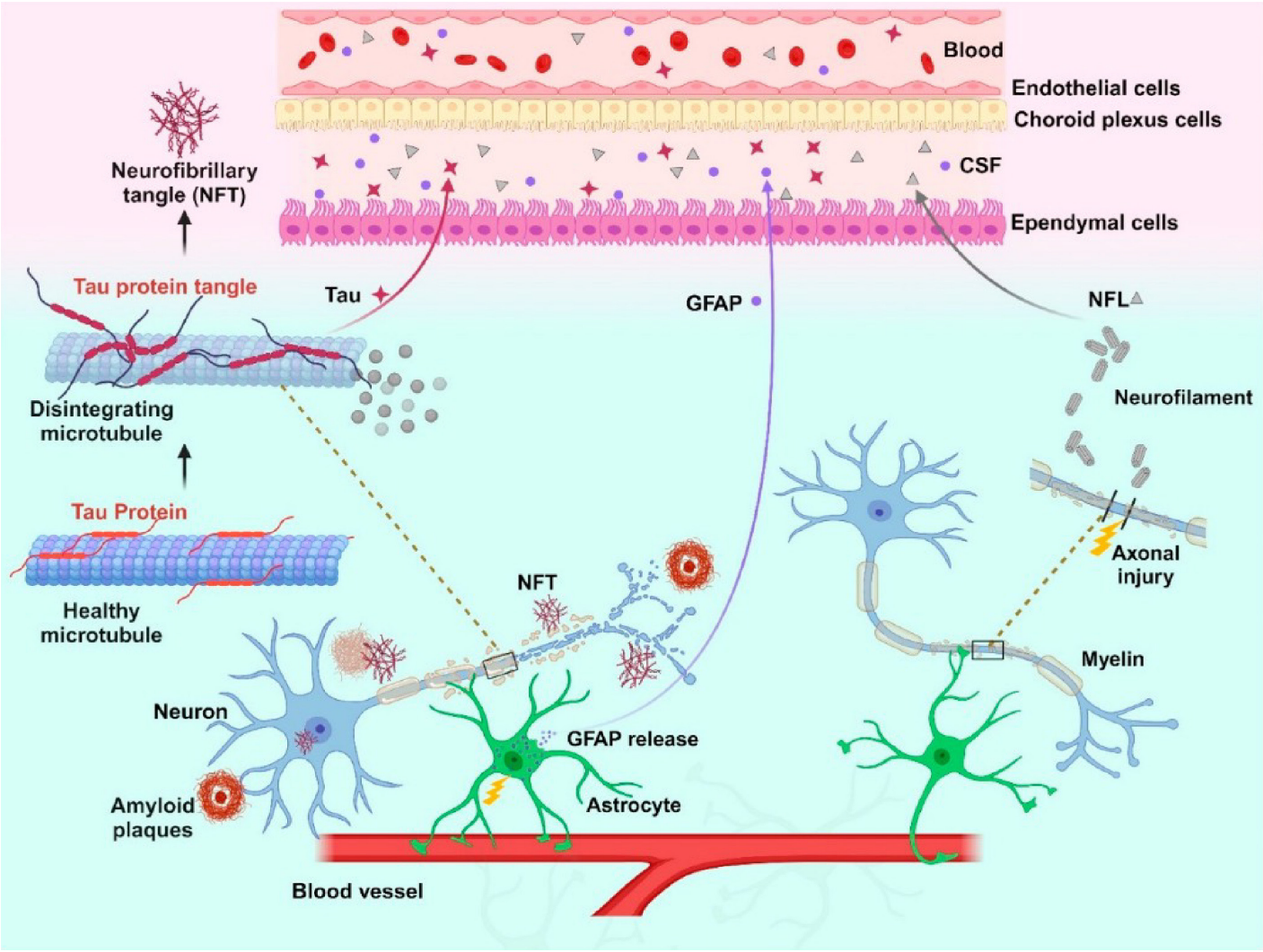

Fig 5 | Biomarker map in CSF and blood[24]

as helmets and mouthguards, may depend on proper fit, design, and usage. As pointed out by the CDC, the imposition of appropriately sized and well-maintained gear can promote athlete safety and minimize the risk of concussion-related injuries.[29]

Rule Modifications and Policy Changes

Sports rules and policy changes can go a long way in minimizing incidences of concussions. Based on a study, Eliason et al. demonstrated that a ban on body checking in youth ice hockey led to a 58% decrease (IRR 0.42) in concussion incidence compared to leagues that permitted body checking.[28] Similarly, American football policy changes, such as limiting contact in practices, resulted in a 64% reduction in practice-related concussions (IRR 0.36).[28] These results suggest that strategic rule changes, particularly in youth sports, may effectively prevent head injuries and enhance overall safety. Additionally, the implementation of stricter enforcement of rules regarding illegal hits, combined with ongoing education for athletes, coaches, and referees about the risks of concussion, could further contribute to reducing concussion-related injuries in contact sports.

Training and Neuromuscular Interventions

Contact sports need a training program to prevent concussions. Studies by Indharty et al. say that using neuromuscular warm-up programs in rugby has reduced the concussion rate by up to 60%.[30] These programs emphasize such improved techniques as right tackling, strengthening neck muscles, improving balance, etc (see Figure 6). Similarly, the physical training strategies, including strength and flexibility conditioning, are critical in avoiding injuries and reducing the level of impacts to the head. JAGPT also provides evidence that assumes that the use of jump training, yoga, and weightlifting could increase muscle strength and flexibility and the level of prevention of injuries in athletes.[31] Such preventive measures help guarantee safer involvement in contact sports games.

Current Debates and Research Gaps

Ethical and Sociocultural Challenges in Concussion Research

One of the most important controversies of concussion research concerns the ethical and sociocultural ramifications of concussion handling and the necessity of more holistic types of research practices. Research gaps in concussion were reported by McNamee et al., primarily concerning age, disability, gender, and race.[32] Ethical questions also arise from conflicting interests, claims of expertise, and inadequate inclusion of athletes in research and policy formulation. The existing guidelines highlight the medical aspects of concussions but do not address these gaps.[32] The lack of representation from diverse groups, including women and minority athletes, in concussion research can hinder

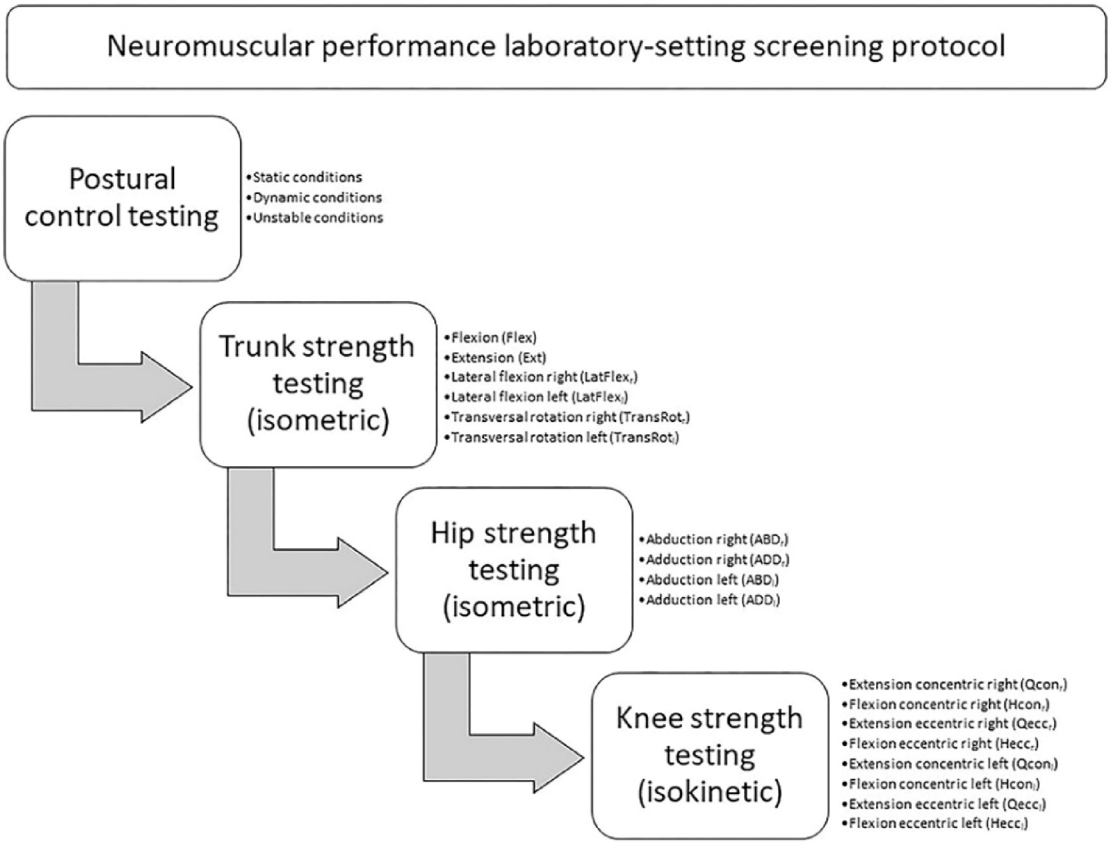

Fig 6 | Neuromuscular lab screening protocol

DOI: https://doi.org/10.70389/PJS.100086 | Premier Journal of Science 2025;9:100086

the development of universally applicable prevention and treatment strategies. Thus, the subsequent study must incorporate many different perspectives to provide better care for brain-injured athletes and to come up with more inclusive concussion policies.

Gaps in Recognition and Management of Concussion

One significant missing link in concussion management is the inability to recognize and diagnose concussions in a timely manner, as the symptoms can be subtle or delayed. Shelina and Hadley also pointed out that many athletes, including children, will not report symptoms of a concussion due to fear of the consequences (being left out of play) or not fully understanding the consequences.[33] Concussions may cause lingering problems such as depression, chronic headaches, and cognitive impairment if not treated properly. The Concussion Awareness Training Tool was created to solve such a problem by delivering educational materials, including the Parent/Coach Guide.[33] Workers need to do more to ensure that diagnoses are on time and that the right prescriptions are made for youth sports. Furthermore, there is a need for better education and training for coaches, parents, and athletes themselves, ensuring that concussion symptoms are recognized early and reported promptly.

Policy and Research Gaps in the Prevention of Concussion

An increasing body of evidence that associates concussion with long-term health problems has led to discussions regarding current prevention practices. The Senate Inquiry on concussions in contact sports indicates that some policy changes (such as restriction of contact during practices and enforcing safety measures) will go a long way in minimizing the concussion risks.[34] However, the challenges of enforcing and achieving compliance with these policies at different levels of sport still exist. Moreover, just like Gov.au points out, concussions are a problem not merely for elite sports but for all levels of sport and require larger gambits regarding athlete safety.[35] Further research is required so that a more comprehensive solution can be designed to address the clinical as well as societal implications of SRC.

Future Directions

In the future, studies and concussion management should adopt a multidisciplinary approach, incorporating elements from medicine, ethics, sociology, and policy. Diversity in expertise will help us better understand the complicated nature of SRC and its long-term implications.[35] This approach will provide a comprehensive element of prevention measures, better concussion management, and optimal care for athletes' overall well-being, aiming to eliminate disparities based on race, gender, and age.[32] Future research should prioritize the development of personalized concussion management strategies, incorporating genetic, environmental, and individual health factors. Furthermore, concussion history, genetics, and individual response to an injury may be used to have customized risk assessments, which can considerably improve the prevention and treatment of concussions.[21,25] Sports organizations need to implement clear concussion policies, education, and return-to-play policies to safeguard the focus on athlete safety and minimize long-term dangers.[34]

Conclusion

This research highlights the necessity of early diagnosis and prevention of SRC. Important results indicate that recognizing concussion symptoms appropriately and implementing effective preventive measures, such as protective tools, rule changes, and neuromuscular training, can lead to significant reductions in concussion incidence and duration. Moreover, the appearance of new biomarkers, such as fluid-based and neuroimaging markers, constitutes a promising tool for recovery tracking. As sports continue to increase in popularity and intensity, forward-thinking stakeholders in sports medicine, including coaches, medical providers, and sports bodies, must collaborate on developing and enforcing sophisticated concussion management protocols to protect athletes, ultimately making sports safer for all participants.

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