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Analyzing sports-related concussions and traumatic brain injuries and their effects on adolescents and athletes

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Abstract
In this paper, the current literature focused on concussions and traumatic brain injuries is comprehensively examined and reviewed, with a particular emphasis on the impact of these injuries on adolescents and athletes. Symptoms, including cognitive impairment, headaches, and nausea, frequently associated with concussions and traumatic brain injuries are reviewed while underlying biomechanical and neurological mechanisms that contribute to these injuries are also examined with additional focus on the possible effects of multiple subconcussive impacts on brain structure and function. The concussion and traumatic brain injury diagnosis process is discussed, including an examination of the emerging literature surrounding traumatic brain injuries diagnosed with the use of miRNA biomarkers in saliva samples. Additionally, the frequency and prevalence of concussions in youth and athletic populations is investigated, highlighting both sport-specific risks and gender-based differences. Various prevention strategies are discussed including sport-specific rule changes, education-based interventions, shock-absorption and impact reduction helmet technology, and the use of baseline testing for diagnoses. Special attention is given to the emerging field of head and neck strengthening as a potential method for reducing concussion risk. The possible future development of a pre-activity sports drink designed to prime the brain of an athlete prior to a competition or practice is proposed. Critical gaps in the existing research literature are identified and areas for future study are identified, particularly in regard to the development of personalized prevention programs and improved understanding of underlying processes.

Keywords
Concussion, Traumatic brain injury, Sports-related injury, Adolescents, High school athletes, College athletes, Professional athletes, Head and neck strengthening, Baseline testing

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1. Introduction

Sports related concussions (SRCs) and traumatic brain injuries (TBIs) are highly prevalent injuries in the United States. SRCs can occur in various sports including football, soccer, hockey, basketball, wrestling, baseball, and lacrosse, due to collisions, falls, or other high-impact incidents. Concussions can also occur in non-sport instances, caused by car wrecks, falls, or other events in which an individual suffers head trauma. It was estimated that in 2013 there were approximately 2.8 million TBI-related emergency department (ED) visits, hospitalizations, and deaths in the United States. This statistic includes ~ 2.5 million TBI-related ED visits, ~ 282,000 TBI-related hospitalizations, and ~ 56,000 TBI-related deaths (1). The issue of concussions is particularly prevalent among adolescents and athletes. Sports were second only to motor vehicle crashes as the leading cause of TBI among individuals aged 15 to 24 (2). Additionally, ~ 7 out of 10 ED visits for sports-related or recreation-related TBIs and concussions were among children ages 17 and under (3). Taylor et al. (2017) found that concussions represented 8.9% of all high school sport-related injuries (1).

2. Discussion

2.1 Definition of a concussion

Despite the widespread nature of these injuries, the definitions of a concussion and of a TBI remain elusive, partly due to the variability associated with these injuries. Biomechanical examinations of concussions revealed different effects on brain regions depending on the force of the injury-causing impact, site of impact, bony architecture of the skull, and individual toleration to head impacts. Human toleration to head impacts can also vary, depending on excess energy status, history of previous concussions, and genetics (4). In addition, concussions are not associated with observable changes in brain structure. Concussions may result in neuropathological changes, but any acute clinical symptoms largely reflect a functional disturbance, not a structural injury (5). Giving a broad definition, the Mayo Clinic describes concussions as mild traumatic brain injuries that affect brain function. The clinic adds that most concussions are caused by an impact to the head or body that is associated with a change in brain function while also noting that the vast majority of concussions do not cause the injured individual to lose consciousness (6). The American Association of Neurological Surgeons (AANS) provides further insight, claiming that concussions are brain injuries that result in temporary loss of normal brain function, specifying that, medically, a concussion is defined as a clinical syndrome characterized by immediate and transient alteration in brain function, including alteration of mental status or level of consciousness, that results from mechanical force or trauma (7). The AANS also provides the definition of a concussion used by the National Collegiate Athletic Association (NCAA). The NCAA, the leading governing body in college athletics, defines a concussion as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces (7). When looked at collectively, these varied definitions focus on two key points: first, head trauma, and second, a change in brain function caused by the aforementioned trauma. These two aspects of concussions are related through multiple pathways. Concussions often arise when the brain rapidly moves back and forth, or when the brain makes contact with the side of the skull (8). These sudden movements can stretch and damage brain tissue, tear blood vessels, pull nerve fibers, and bruise the brain, triggering a chain of reactions which negatively impacts brain function (7). Despite the possible damage to brain tissue, blood vessels, and nerve fibers that can occur due to concussions, these injuries are typically associated with grossly *normal* neural images, including those from magnetic resonance imaging (MRI) and computed tomography (CT) scans (5). The lack of neuroimaging identification for concussions occurs due to the fact that these injuries are metabolic and microscopic in nature (7). It is also important to note that concussion-related symptoms and problems can occur without a single, strong head impact. Repetitive subconcussive blows to the head may lead to cognitive deterioration of brain function (5). Hack et al. (2024) conducted an examination of repetitive subconcussive head impacts (RSHIs) in sports and possible changes to brain structure and function as a result of these impacts. (9). A subconcussive head impact was characterized by a cranial impact that did not result in overt symptoms, such as dizziness, headaches, or short term memory loss. The authors concluded that RSHIs may cause structural white matter alterations, such as axonal swelling, axonal integrity reduction, and neuroinflammation (9). The authors claimed that these alterations displayed signs of neurophysiological brain injury, such as damage to the axons' structure, the myelin sheath surrounding them, compromised axonal integrity, and signs of chronic axonal injury. Additionally, the authors identified a dose-response relationship between white matter abnormalities and the sustained cumulative number of RSHIs, implying that the cumulative number of impacts, rather than a single impact event, was the cause of structural damage (9). Mainwaring et al. (2018) conducted a systematic review of the research literature surrounding sports related subconcussive head impacts (10). The authors concluded that evidence, predominantly from studies focusing on male athletes in contact and collision sports, identified that repetitive hits to the head were associated with microstructural and functional changes in the brain (10). The conclusions of Hack et al. (2024) and Mainwaring et al. (2018) collectively indicate that subconcussive impacts do alter brain structure; however, no clear conclusions can be made concerning altered brain function. Further research is necessary to identify the possible impacts of the altered brain structure caused by RHSIs.

2.2 Symptoms and recovery

Common concussion and TBI symptoms include headache, dizziness, nausea, confusion, and other changes in cognitive functions such as diminished concentration, attention, and memory (5). As mentioned, concussions can vary on an individual-to-individual basis. Because of this variability, concussion symptoms can also vary and are specific to each injured individual (5). When managing concussions and TBIs, there are no blanket solutions or treatments. For athletes and other patients suffering from concussion, gradual return to learning and physical activity is individual and depends on a patient's specific symptoms; therefore, the recovery process should always be supervised by a healthcare professional (6). The most vulnerable period following the initial concussion is the 7 to 10 day period in the immediate aftermath of the injury (5). In this period immediately following a concussion, an individual's brain needs time to heal in order to prevent future complications. Because of this recovery timeline, individuals with concussions should never return to sports or other physical activity sooner than 1 week after sustaining the injury in order to avoid successive TBIs or SRCs (11). Research has also shown that concussions can have compounding effects. Individuals who suffer a concussion are at 3 to 6 times greater risk for sustaining a second concussion (5). Concussion symptoms may also worsen after a series of injuries. Covassin et al. (2010) found that concussed high school athletes with a history of 3 or more concussions presented more symptoms and a significantly lower memory performance at 2 days post-injury, compared to concussed athletes without a history of concussion (5). Concussion recovery can also vary from case to case. Approximately 80% of concussions resolve over 7 to 14 days, with an average recovery time of 10 days (11).

2.3 Concussions in sports

For athletes, sports can create environments in which head trauma, concussions, and TBIs are more likely to occur. Head impacts increase the risk for TBIs and other serious brain injuries. The risk for these head impacts is highest in contact sports, such as tackle football (6). Kerr et al. (2019) conducted an overview of concussions in high school sports. An overall rate of 4.17 concussions per 10,000 athlete exposures was found, with an athlete exposure (AE) being defined as an athlete taking part in either a game or practice in which there was the possibility of sustained injury (12). Of the 20 sports examined, football had the highest concussion rate with 10.40 concussions per 10,000 AEs (12). From 2013 to 2018, competition-related concussion rates increased from 33.19 concussions per 10,000 AEs to 39.07 concussions per 10,000 AEs while practice-related concussion rates decreased from 5.47 concussions per 10,000 AEs to 4.44 concussions per 10,000 AEs (12). When observing sports concussion data, it must be noted that the collection of these figures typically relies on athletes or organizations to self-report the prevalence of these injuries. Tadmor et al. (2023) conducted an online survey of 422 Men's and Women's Super League rugby players. In the survey, 20% of respondents stated that they did not report concussion-related symptoms to medical staff during the 2020 and 2021 seasons. Further, 17% of players responded to not reporting a suspected concussion 1–2 times and 2% responded to not reporting a suspected concussion 3–5 times. Two of the most common reasons for the lack of reporting were that the individual "didn't want to be ruled out of a match" (35% of respondents) or "didn't want to let down the team" (24% of respondents) (13). These results reveal the tendencies of professional athletes, and athletes in general, to under-report concussion symptoms while also highlighting athletes' hopes to stay in a game, possibly amplified by the social pressures that surround teams and other sports organizations. When comparing National Football League (NFL) data to electronic health records (EHR) regarding SRCs, the NFL data showed significantly lower reporting than the EHR did (14). This under-reported data reveals the tendency for leagues like the NFL to downplay the significance and prevalence of concussions. Together, the tendency for both league administrators and individual athletes to under-report either the severity of concussions or the cases themselves can create challenges for researchers. Further studies are needed to examine the social pressures that athletes face in the context of their sport and to illuminate the scale at which sports leagues like the NFL under-report these injuries. It is also recommended that future researchers observing professional sports leagues directly work with players to monitor symptoms and mental performance throughout a season or other prolonged period of time, in order to avoid the possibility of under-reporting.

2.3.1 *Adolescent SRCs*

Contact sports, including football, basketball, and soccer, are associated with 45% of all ED visits for sports-related and recreation-related TBIs and concussions among children ages 17 and under (6). Holmes et al (2020) conducted a survey focused on reviewing cognitive challenges faced by 130 individuals ranging in age from 14-24, who suffered an SRC in the past year. The survey found that more college students (84.5%) reported “difficulty concentrating” than high school students (68.6%). On the other hand, younger students were less tolerant in performing academic tasks after a concussion than older students. These results suggest that academic performance and cognitive performance can be negatively impacted regardless of age (15). Interestingly, key differences emerged, with college students having a higher perceived difficulty concentrating while younger students were less tolerant to academic work than older students when completing tasks post-injury. To that end, young athletes with a concussion exhibited increased impulsive response as well as impairment in psychomotor speed and visual spatial skills in the immediate aftermath of the injury (15). Additionally, high school athletes often demonstrated longer recovery times with respect to neurocognitive performance than concussed collegiate athletes (5). Further research is needed on the level at which brain development plays a role in concussion recovery and symptoms. This data also raises questions concerning brain development and the brain growth timeline. Specifically, further research is recommended utilizing quantitative measures to observe these differences over a large, diverse sample of adolescents.

2.4 Gender differences in the effects of concussions

Because of the biological differences in the brains of males and females, male and female individuals can experience concussions in different ways. Some differences that may play a role in diverse injury outcomes are the differences in neck musculature between boys and girls, with stronger necks possibly limiting the impact of significant head contact. Hormones and cerebral blood flow may also play a role in these sex differences (16). Covassin et al. (2010) found that female athletes demonstrated slower simple and complex reaction times after a concussion compared to baseline scores and 1.7 times more impairments on reaction time measures compared to male athletes (5). On the other hand, in a survey among sex-comparable sports, concussion rates were higher in girl’s sports with the same rules as the comparable boy’s sports (3.35 concussions per 10,000 AEs for girls vs 1.51 concussion per 10 000 AEs for boys). Another study found a similar result, concluding that girls have a higher chance of experiencing sports-related concussion than boys in sports that use the same rules, such as soccer and basketball (6). When compared to males, females also reported larger proportions of recurrent concussions (12). Further research is needed to examine the difference in social pressures that male and female athletes feel around reporting concussions, whether first injuries or repeated injuries. Further research is also recommended to better understand the differences in male and female neck musculature and how those differences may affect concussion outcomes. When comparing concussion return-to-learn timelines (number of days for athlete to return to school with no accommodations) with gender as an independent variable, a greater portion of boys returned to learning 3 weeks post injury (93.5% of boys vs 89.4% of girls); however, no significant difference was observed at 1 week or 2 weeks after the injury (17). This data may imply that girls face a greater number of persistent concussions; or more long-term effects from a single event concussion; however, no conclusive statement can be made. Further research is needed to confirm any differences in female and male return-to-learn timelines.

2.5 Concussion and TBI assessment and diagnosis

The prevention of concussions is challenging due to the nature of the injury and the lack of biological markers that can be used to identify the injury. While biomarkers used in the diagnosis of concussions and TBIs continue to be evasive, current research is emerging surrounding the possibility of diagnosing mTBIs using saliva RNA. Based on the fact that the noncoding RNA (ncRNA) content of salivary vesicles may change in order to regulate neuroinflammation and synaptic repair following mTBI, researchers hypothesized that differences in saliva RNA can be examined to help determine if an individual has suffered a mTBI (18). Hicks et al. (2020) sought to assess the ability of salivary ncRNA to serve as a diagnostic adjunct to current clinical tools. They concluded that a set of noncoding RNA (ncRNA) biomarkers in saliva existed that could differentiate individuals with mTBI from peers without mTBI. The authors also concluded that present saliva ncRNA biomarkers maintained similar diagnostic accuracy to a limited neurocognitive battery and provided added value when combined with an algorithm relying solely on symptom scores (18). Analysis of four specific microRNAs (miR-34a-5p, miR-192-5p, miR-27a-5p, and miR-4510) used in a predictive model for mTBI found that these miRNAs were associated with genes involved in several key brain processes. These included the synaptic vesicle cycle, SNARE-mediated vesicular transport, and GABAergic synapses (18). These findings suggested that changes in saliva-based miRNA expression were indicative of underlying biological processes in the brain after concussion. This changed saliva profile in the aftermath of an injury supports the potential of using salivary RNA profiles as non-invasive biomarkers for diagnosing and monitoring mTBI (18). Di Pietro et al. (2021) investigated the role of salivary small noncoding RNAs (sncRNAs) in the diagnosis of SRC specifically through the Study of Concussion in Rugby Union through

MicroRNAs (SCRUM) (19). Using the Kyoto Encyclopedia of Genes and Genomes (KEGG) pathway, the authors evaluated the plausibility of the identified microRNA biomarkers as being indicative of a concussive event. The researchers were able to determine, after a large prospective observational study, unique signatures in the saliva of male athletes diagnosed with concussion (19). Additionally, the authors identified 32 different small nuclear RNAs (sncRNAs) across three time points that were differentially expressed in rugby players with a clinical diagnosis of concussion compared with those cleared of concussion after examination. Overall, the authors identified a panel of 14 different biomarkers that accurately predicted clinical diagnosis of concussion in professional rugby players when prospectively tested on independent data (19). These advancements in the field of saliva RNA testing exhibit promise for the future of concussion biomarkers. Further research is needed to continue examining saliva RNA and to begin implementing saliva RNA testing for athletes in order to provide additional information throughout the injury diagnosis process. In addition to the emerging field of concussion identification through RNA biomarkers, high school, college, and professional sports organizations utilize various other strategies to limit concussion and improve concussion diagnosis. Common strategies are practice guidelines, physical preparations, and baseline mental testing for athletes at the beginning of the season and at any point after a suspected concussion. These baseline tests can also aid in establishing recovery timelines. The Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) is a baseline test used to compare pre-trauma mental ability with post-trauma ability. The ImPACT test utilizes 6 neuropsychological tests, with each test targeting a different aspect of cognitive functioning (20). These aspects include attention, memory, processing speed, and reaction time. With these 6 neuropsychological tests, four separate composite scores (verbal memory, visual memory, visuomotor speed, and reaction time) are generated. Schatz et al. (2006) found that individuals who took the ImPACT test multiple times did not improve their score, indicating that the test composite was not hindered by a practice effect (20). In addition, the research demonstrated that the ImPACT test was both a specific and sensitive instrument for the assessment of the neurocognitive and neurobehavioral sequelae of concussion (20). It was concluded that individuals who perform significantly worse on the ImPACT test in the aftermath of a head injury had a concussion with high probability, with 85% of cases being correctly classified as either concussed patients or control patients. (20). The ImPACT test provides additional avenues for future research, specifically in regard to how certain metrics are affected depending on the individual, the strength of a head impact, neck musculature, or other significant variables. Further research is needed to examine these differences across age groups, across genders, and across other populations. This test also has limitations because of the necessity for a baseline prior to the injury, for a diagnosis to be made. In addition, neuropsychological tests often exclude the possibility of an athlete suspected of being concussed, returning to the game while the game is still in progress. Salivary testing that returns biomarker levels within minutes, may allow the player to return to the game in the event of a negative result. Such expedited results may also significantly decrease the phenomenon of under-reporting.

2.6 Concussion and TBI prevention

Alongside the baseline testing measures, many sports leagues utilize rules and regulations surrounding practice limitations for teams. Bretzin et al. (2022), studied Michigan High School Athletic Association (MHSAA) implemented rules aimed at reducing the number of collisions that occurred in football practices for member teams from 2015-2020 (21). In the 2016-17 season, teams were limited to 2 collision practices per week after the first regular season game. In the following years, more restrictions were added. In the 2019–2020 season, the limitations were the most restrictive, with teams limited to 6 hours per week of collision practice in the 2 weeks before a contest and limited to only 30 minutes of collision practice after the first regular season game (21). During the 5-year period, 7,755 football SRCs were diagnosed, with an overall incidence rate of 8.03 SRCs per 10,000 AEs. In addition, the competition SRC rate (30.13 SRCs/10,000 AEs) was higher than the practice SRC rate (3.51 SRCs/10,000 AEs). These results implied that athletes may put themselves at higher risk or may expose themselves to greater levels of contact during games. Further research is needed to examine this discrepancy between the rates of practice SRCs and competition SRCs and to evaluate methods to limit the increased exposure that competitions create. The researchers following the concussion trends found that progressive limitations to collision practices were protective against SRCs, as the rate of SRC over a season was lower in the 3 most recent seasons relative to 2015–2016 (21). With fewer contact practices, fewer concussions occurred. In addition, estimated competition SRC rates decreased across the study period, suggesting that risk mitigation occurred in competition when collision limitations in practice were imposed. This may provide evidence that implies the small-scale brain damage that occurs in collisions during practice may be contributory to competition concussions (21). Further research is needed on the effects of practice collisions on the vulnerability of an athlete's brain to concussion during competition. This research avenue relates to the prior discussion surrounding RSHIs, and further research is also needed to examine these events in conjunction.

While practice limitations and baseline testing are two methods of concussion reduction and diagnosis, additional prevention strategies exist, including through sports equipment worn by athletes during practices and competition. One commonly examined tool that aims to limit SRCs and TBIs is the football helmet. The technology used in football helmets has dramatically evolved since helmets were originally introduced and made part of game play. Currently, helmets can consist of various shock absorbing technologies with differing mechanisms for energy absorption and force attenuation, with modern technologies including viscoelastic foams, buckling beams and structures, gas chambers, and 3D printed lattices (22). Football helmets are designed to negate impacts of low and high velocities; however, current testing standards and rankings for helmets emphasize the ability of a helmet to limit the magnitude of impacts associated with diagnosed concussions or more serious injuries (22). Cecchi et al. (2023) examined the effectiveness of a football helmet featuring liquid shock absorbers when protecting against concussive and subconcussive head impacts (22). The researchers hoped to maintain protection against high velocity head impacts while also mitigating the possible effects of low velocity impacts, which can be characterized as subconcussive impacts. The liquid helmet model yielded an average 33.0% and 32.0% reduction of force over the existing helmet models at each impact condition in the subconcussive and concussive tests, respectively. The researchers also concluded that brain strains in the aftermath of impacts were lower when utilizing the liquid helmet model (22). These results are promising and suggest that liquid shock absorbers within helmets may help combat the high rate of brain trauma in football. Further research on liquid shock absorption technology and overall helmet technology is needed to improve athlete safety and to continue mitigating TBI risk for football players. Alongside liquid shock absorption technology, other impact-reducing technologies are being developed, including collapsible fluid-filled fabric shock absorbers. These fluid-filled absorbers work in a similar manner to liquid shock absorption and may provide an additional avenue for impact mitigation in helmets (23). Further research is necessary to examine the effectiveness of new helmet technology and to observe the implementation of this technology in both non-professional athletics at the high school, college and recreational level, and in professional sports leagues such as the NFL and the NHL.

Another proposed method of concussion prevention is individual physical preparation conditioning with the hope of preventing these injuries, with methods including neck training. These methods are difficult to test in humans because of the nature of concussions and the difficulties associated with the establishment of an experimental group. Garnett et al. (2021), a performed a literature review on 11 articles, focused on physical conditioning strategies for the prevention of concussion in sport (24). In the first article, Mansell et al. (2005) conducted an 8-week isotonic resistance training program on head-neck segment dynamic stabilization for soccer players. After the trial, improvements in neck strength and girth were seen; however, the researchers concluded that, despite improvements in neck isometric strength and increases in neck girth, the resistance training protocol did not increase head-neck segment dynamic stabilization during force application in soccer players, implying that concussion cases would not be limited (25). Schmidt et al. (2014) found that the likelihood of sustaining higher magnitude head impacts was reduced in players with greater cervical stiffness and in those who experienced a smaller amount of angular displacement after head impacts. Cervical stiffness refers to stiffness in the muscles responsible for head and neck movements, posture, and stability. On the other hand, the results did not support the idea that stronger and larger neck muscles reduced the severity of head impacts (26). Lisman et al. (2012) conducted an 8-week isoinertial cervical resistance training program. Results yielded modest increases in isometric strength in cervical extension (7%) and left lateral flexion (10%); however, the 8-week program did not increase dynamic stabilization of the head and neck during a football tackle, implying that concussion incidence would not be reduced (27). Mihalik et al. (2011) measured isometric strength using a hand-held dynamometer, an instrument typically used to measure force, tension, and power. The analysis identified significant differences in cervical muscle strength between the participants. On the other hand, no differences were recorded in peak linear or peak rotational acceleration for the anterior neck flexors, anterolateral neck flexors, cervical rotators, posterolateral neck extensors, or upper trapezius. It was concluded that cervical muscle strength was a factor in modifying head impact severity (28). Collins et al. (2014) developed and validated a cost-effective tool to measure neck strength. Using this new tool, a high correlation between the hand-held dynamometer and tension scale measurements was found. A smaller mean neck circumference, smaller mean neck to head circumference ratio, and weaker mean overall neck strength were significantly associated with concussion. The authors also reported that for every 1 lb increase in neck strength, the likelihood of concussion decreased by 5% (29). These findings find significance in the prevention of concussion by increasing neck strength, while other articles found no significant results; however, if the research of Collins et al. (2014) were to be replicated and found to be well-grounded, neck training would become a strong avenue for concussion prevention. Hislop et al. (2017), prescribed a series of progressive warm-up exercises for rugby players. The warm-up protocol included isometric neck exercises, whole-body resistance training, plyometric training, and landing and cutting running movements. These exercises were to be completed in the initial 15 minutes of training and before every match. It was found that the players in the intervention group reported substantially reduced incidence of upper limb injury and concussion. In addition, teams that completed the intervention program 3 times per week reported substantial reductions (72%) in overall match injury incidence and concussion incidence compared with the control (30). These results indicate the importance of warm-ups and physical preparation prior to sports or other physical activities; however, they do not necessarily imply that physical preparation contributes to concussion prevention. Attwood et al. (2018) introduced a movement control program to examine possible reduction in injury risk for rugby union players during 7 progressive phases, all of which followed a 6-week model. While no clear effect was identified for the intervention program using intention-to-treat analysis for overall injury burden, overall injury incidence or severe injury incidence, concussion incidence (1.2 injuries/1000 player match-hours vs 3.4 injuries/1000 player match-hours) was 60% lower in the intervention group compared with the control group, a group that undertook a non-targeted routine (31). These results may indicate that the targeted movement program played a role in concussion reduction incidences. Eckner et al. (2014) examined the influence of neck size, neck strength, rate of force development, and muscle activation on head kinematics following loading in multiple planes. They found that superior neck strength and anticipatory muscle activation were individually associated with a decreased kinematic response to impulsive forces applied to a subject's head. While these results do not directly indicate a reduced concussion incidence; by decreasing kinematic response to impulsive forces, concussions may indirectly be mitigated (32). Caccese et al. (2018) examined the factors that contribute to head acceleration during soccer heading. Studying anthropometric measurements, isometric strength, and electromyography of muscles of the neck and upper torso, it was concluded that greater head and neck size predicted lower peak linear and rotational accelerations (33). Finally, Eckersley et al. (2019) used validated neck model simulations to examine the effects of cervical muscle strength on head kinematics. The authors found that no consistent effect on the injury metrics for SRCs was evident by changing neck muscle force in models (34).

3. Conclusion

3.1 Recommendations for further study

As highlighted, the literature surrounding concussions is expansive; however, continued exploration is necessary to gain a better understanding of these injuries and their impact on adolescents, athletes, and the broader population. Further study is first needed in regard to the observation of concussion related symptoms. By finding the specific processes that induce headaches, nausea, and sensitivity to light and by exploring the reasons why some individuals experience these symptoms on a greater level than others, a deeper understanding of concussions symptoms and diagnosis may be gained. In regard to SRCs, further study is needed to examine the effect of neck strengthening and other physical preparation strategies. Additionally, further work is needed with the ImPACT test to evaluate possible correlation between variables and test performance on an individual-by-individual basis.

3.2 Perspectives

In the aftermath of a TBI, the expression of certain ncRNAs increases. These ncRNAs are often involved in regulatory responses, and their upregulation can be associated with protective, compensatory mechanisms, including increased production of corresponding coding RNAs (cRNAs) and proteins (18). Injured brains increase ncRNA and protein expression to compensate or repair brain structures in the aftermath of an injury-inducing impact (35). Therefore, a tantalizing possibility exists that if these ncRNAs' were to be deliberately increased *prior* to a concussion (i.e. prior to practice and games), the brain could be 'primed' such that subsequent detrimental neurocognitive, ischemic, neuro inflammatory, hyper-angiogenic and impaired neurotransmissive responses could be significantly blunted. Yang et al. (2023) demonstrated that ncRNA plays a crucial role in regulatory signaling after an injury, reducing brain edema by inhibiting NF-κB/IL-6 pathways after TBI (35). In the aftermath of head trauma, specific ncRNAs interact with mRNAs and regulatory proteins which modulate transcription and translation to activate and control protective cellular responses (36). Therefore, agonists of these genes, pathways, and enzymes may be able to be used to prepare the brain prior to a game or practice so that immediate relief is available in the case of a concussion-causing impact. By activating genes or pathways with agonists prior to an injury, the brain's defenses may be better prepared, enabling quicker and more robust protective responses. Such agonists may even be envisaged to be formulated as constituents in a pre-activity sports drink. For example, adenosine is a V-ATPase agonist, which could aid in the pre-activation of V-ATPase, which; in turn; plays a crucial role in the brain's response and recovery, contributing to the healing process in the brain after TBI. Battistone et al. (2017) found that extracellular adenosine stimulates V-ATPase (37). Research has also shown that adenosine is anti-inflammatory, which could aid in the prevention of TBI (38). When adenosine receptors are activated, glutamate release and neuronal excitability are reduced. Exogenous adenosine administered after ischemia has been shown to improve hippocampal neuron survival, neuroprotection, and functional recovery in rodents (39). Further research is necessary to identify other possible effects in humans and the effectiveness of adenosine administered prior to an injury in the mitigation of said injury; however, adenosine provides an attractive option as a key ingredient of the priming, pre-activity drink. The drink could possibly also contain theanine which could act as a nutraceutical gamma-aminobutyric acid (GABA) modulator. The GABA modulator is responsible for maintaining excitatory–inhibitory balance, reducing neuronal hyperexcitability, and modulating stress responses. In the aftermath of a TBI, a pre-administered GABA agonist could suppress overexcitation and potentially protect neurons from acute damage. The neuroprotective effect of theanine is mediated by GABA receptors (40). Unfortunately, many anxiolytic drugs similar to theanine can act as sedatives, hence further research must be conducted to examine the possibilities of their inclusion in the drink and to correctly manage potential dosages and timings. Thrombospondin-1 (THBS1) agonists present in specific soy products and mushrooms may also provide advantages and could be included in the pre-activity sport drink. After brain trauma, uncontrolled angiogenesis, the process by which new blood vessels form from existing ones, can exacerbate neuroinflammation and edema. Since THBS1 acts to limit angiogenesis, supporting THBS1 function could help prevent vascular leakage and secondary injury after head trauma. Galvez et al. (2012), determined that lunasin, which is found in soy, led to epigenetic upregulation of THBS1 expression (41). Certain types of mushrooms can also act as angiogenesis inhibitors, which could possibly mimic the effects of THBS1 expression (42). Further research is necessary to identify correct dosages, timings, and efficacy; however, both soy and mushrooms in their roles as angiogenesis inhibitors could play a key role in the pre-activity sports drink. Yet another possible ingredient in the pre-activity sports drink could be lithium. In the aftermath of a TBI, SNARE complex formation, which is essential for synaptic vesicle docking and fusion, is reduced (43). This disruption in the SNARE complex can lead to impaired neurotransmission, impacting communication between neurons and affecting brain function. Lithium has been shown to modestly improve cognitive performance after TBI and can promote recovery in the injured brain. Treatment with lithium increased the abundance of synaptic proteins that facilitate neurotransmission. Lithium also increased SNARE protein and SNARE complex abundance after TBI (43). Further research is needed to identify the efficacy of lithium for pre-activating the brain prior to trauma and limiting the negative effect that TBI can have on the SNARE complex. The inclusion of lithium therefore presents a compelling case for inclusion in the priming sports drink. On the whole, the possibility of a pre-activity sports drink containing adenosine, lithium, theanine, mushroom extract, and certain soy products should be investigated further in controlled trials. This pre-activity drink could become mandatory for all contact sport athletes before a game or practice. The suggestion of a pre-activity drink is made all the more convincing considering the wins of the otherwise mediocre Florida Gators (including winning the Orange-Bowl in 1967) subsequent to the development and introduction of Gatorade™ by the team's Coaches and researchers. This is currently an unexplored topic in the literature and offers a research worthy avenue in the science of TBI and concussion prevention.

3.3 Summary

Contact sport related concussions and traumatic brain injuries plague adolescent players. Current concussion protocols require onerous baseline testing followed by computerized testing (lasting >20 minutes) after the suspected concussion, in part because standard neuroimaging techniques such as CT and MRI are unable to detect differences post concussion. Results of such testing can take more time than the remaining length of the game or practice, with the result that players sit out the rest of the game or practice; and maybe the season. This leads to under-reporting, with consequent exacerbation of symptoms and injury. Compounding this scenario are the as-yet unknown additive or synergistic effects of multiple subconcussion injuries, their inability to be measured by conventional testing and the conundrum of why similar impact forces affect different athletes differently. Tailored training protocols including focused neck strengthening and physical preparation strategies, limiting contact events during practices and the use of advanced helmet technology have reduced effective impact intensity. In addition, emerging diagnostic tools such as identification of biomarkers in saliva specific for concussions, consisting of non-coding mRNA, have the potential to significantly decrease the time to definitive diagnosis, even without baseline testing. Lastly, a pre-training and/or pre-game sports drink is proposed, containing agonists of gene expression, signaling pathways, and enzymes and/or proteins that elicit a protective cellular response, which is anticipated to prepare and 'prime' the brain prior to a game or practice so that immediate cellular and organ relief is available in the case of a concussion-causing impact.

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