Adolescent Concussion in High School Athletes: Neurodevelopmental Risks, Diagnostic Biomarkers, and Gaps in Clinical Management

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Abstract

High school athletes are a population that face a significantly elevated risk of concussion. Despite this, research and resources remain heavily skewed toward collegiate and professional athletes. Adolescence is marked by ongoing development in the brain, especially in regions such as the prefrontal cortex, which increases the vulnerability to traumatic brain injuries. The following research synthesizes peer-reviewed literature on both cognitive and developmental consequences of concussions in U.S. high school athletes. It focuses on disparities in care access (notably in rural and underfunded schools), gender differences in symptoms and recovery, and the cumulative effect of subconcussive impacts with potential long term effects. Emerging research in the utility of exosomal biomarkers for longitudinal monitoring of mild traumatic brain injuries (mTBI) and post-concussion syndrome symptoms is also largely limited to adult populations, with adolescent-specific usage still in development. By combining findings from studies focused on adolescents and adults, the paper highlights important gaps in adolescent specific concussion management. This paper concludes with evidence-based recommendations to improve prevention, assessment, monitoring and recovery protocols that are specifically tailored for high school settings.

Introduction

Concussions, a type of mild traumatic brain injury (mTBI), are a growing public health concern, particularly among high school athletes in the United States. According to the CDC, approximately 14.3% of high school students reported sustaining one or more sports-related concussions in the past year, representing nearly 2.3 million adolescents nationwide (Sarmiento et al., 2023). Despite this, there is currently no FDA-approved pharmacological treatment targeting the underlying physiology. Discussion is typically based on symptoms and targets treatment rather than prevention, and usually emphasizes rest and gradual return to activity. During this time, students may face cognitive, emotional, and academic challenges that are less discussed (Giza & Hovda, 2014; Robinson et al., 2022).

Concussions involve mechanical forces that disrupt brain function, triggering a neurometabolic cascade including inflammation and altered neural communication, especially in white matter regions responsible for brain connectivity (Giza & Hovda, 2014). While often labeled “mild,” these injuries can result in serious consequences, especially when repeated or undertreated.

Adolescents are uniquely vulnerable to concussion due to brain development. The prefrontal cortex, which controls executive functions such as decision-making and impulse control, continues maturing into the mid-20s, generally lasting longer for males. Trauma during this developmental window may increase the risk of lasting cognitive or emotional problems.

Although collegiate and professional athletes often benefit from real time diagnostic tools, such as helmet or mouthguard based impact sensors, these technologies are rarely available at the high school level. Most current tools rely heavily on subjective symptom reporting, which can be especially unreliable in adolescent populations. Emerging innovations, including blood-based biomarkers and AI-assisted analysis, may eventually offer more objective, scalable alternatives. Even more accessible tools, like baseline testing or structured return-to-play protocols, remain underutilized in many schools (Meehan et al., 2012; Tamura et al., 2020). In addition, underdiagnosis and poor management can lead to prolonged recovery, repeated injuries, and long term symptoms (van Ierssel et al., 2021).

These gaps in care are especially significant in underfunded schools, where access to certified athletic trainers is limited. A 2019 report found that 31% of U.S. public high schools lacked any certified athletic trainer (Huggins et al., 2019). Additional gender gaps exist, as research suggests that female athletes face greater risk of prolonged recovery and more severe postconcussive symptoms than males (Koerte et al., 2021; McGroarty et al., 2020).

This literature review examines current research on high school sports-related concussions, with a focus on developmental vulnerability, gender based differences, and the availability of diagnostic and management tools. By synthesizing findings from neuroscience, public health, and clinical care, the aim is to identify critical gaps and propose potential improvements in concussion management for adolescents.

Methods

This paper utilizes a narrative review methodology. Approximately 60 peer-reviewed articles published between 2010 and 2025 were selected for analysis. Searches were conducted via databases such as PubMed, Google Scholar, and ScienceDirect, using key terms including “adolescent concussions”, “high school traumatic brain injury”, “post-concussion syndrome teenagers”, “subconcussive impacts”, “gender differences regarding concussion”, and “exosomal biomarkers and TBI”.

Articles were selected based on the following criteria: (1) relevance to high school or adolescent populations, (2) focus on sports related head trauma, (3) discussion of cognitive, neurological, or developmental outcomes, and (4) availability in English-published academic journals. Preference was given to recent studies with empirical data.

Discussion

Concussions present unique risks for adolescent athletes because of their effects on a brain that is still structurally developing. Rather than relying solely on adult-based models of injury and recovery, it is essential to consider how age-specific biological and psychological factors may shape the trajectory of symptoms in adolescents. The following section synthesizes current research on how concussions impact brain development, cognitive function, as well as emotional health in adolescents, with emphasis on emerging diagnostic tools and disparities and care.

1. mTBI Vulnerability and Developmental Differences In Adolescents

The adolescent brain is in a critical and vulnerable state of development, making it particularly susceptible to both acute and long term effects of concussions. Unlike the adult brain, which is largely stable structurally and functionally, the adolescent brain undergoes major changes well into the mid 20s (Johnson et al., 2010). These include maturation of the frontal cortex, a region responsible for executive functions such as impulse control, planning, attention, and working memory (Friedman & Robbins, 2021), and continuing changes in the limbic system, particularly the amygdala and hippocampus, which support emotional regulation and memory encoding (Arain et al., 2013). These changes may heighten emotional reactivity and sensitivity to stress.

Concussive trauma during this stage can disrupt important developments such as synaptic pruning, which is the elimination of weaker or unused neural connections to optimize brain efficiency, as well as myelination, the formation of a fatty cover around axons that accelerates neural signal conduction. Although myelination is a process that begins during infancy, it continues in several brain regions, including the prefrontal cortex, during adolescence (Buyanova & Arsalidou, 2021). Incomplete myelination makes “white matter” more vulnerable to diffuse axonal injury (DAI), a common mechanism of concussions in which neural fibers are stretched or torn, impairing communication between brain regions.

Adolescents recovering from mTBI often show prolonged emotional symptoms, including depression, anxiety, and mood swings, which are likely exacerbated by hormonal changes and developing emotional regulation (Morse & Garner, 2018). While specific pathways are still being researched, estrogen and progesterone have been implicated in modulating inflammation and recovery post injury, potentially contributing to symptom differences between individuals (Huang & Woolley, 2012). Prolonged symptoms can significantly disrupt adolescent life; students with post-concussion syndrome (PCS), defined as symptoms lasting more than a month after injury, may experience difficulties with concentration, fatigue, and sleep, which can interfere with academic performance, social connection, and even self esteem (Robinson et al., 2022). Teenagers dealing with PCS often miss school, fall behind academically, and may withdraw from their friends, creating a vicious cycle that can worsen both mental health and recovery. Physically, adolescents also tend to report vestibular dysfunction and balance disturbances, likely due to underdeveloped sensorimotor systems. Symptoms such as dizziness and headache can persist longer in teens than adults. Unfortunately, these issues are often underestimated by coaches and even clinical experts, in part due to a lack of awareness and social pressures on student athletes to “tough it out” or quickly return to play (Holmes et al., 2020). This pressure can increase the risk of Second Impact Syndrome (SIS), a condition described as rapid and often fatal brain swelling following a second head injury before full recovery from an initial concussion. While historically cited in case reports, SIS is extremely rare and its classification as a distinct clinical condition remains debated (Bey & Ostick, 2009; McCrory et al., 2012). While SIS and PCS are distinct—PCS involves long lasting symptoms whereas SIS is acute and potentially catastrophic—the risk of SIS is greatly magnified in environments where recovery is rushed and symptoms are not taken seriously. Stress, particularly the kind that is associated with pressure to return to school or athletics, may worsen symptom expression and delay healing process, but is not a directly known cause of SIS.

Compounding these issues, adolescents with a history of concussion are at significantly greater risk of re-injury, with studies showing a 4 fold increase compared to peers with no prior history (van Ierssel et al., 2021). Despite these known vulnerabilities, most concussion protocols used in high school sports are based on adult recovery trajectory. They fail to account for age specific brain development, which is more fragile. High school athletes would benefit from individualized recovery strategies that recognize their ongoing brain development and the broader impacts injury can have on learning and both cognitive and emotional health.

2. Gender Differences In Concussion Outcomes

Research suggests that sex and gender may meaningfully influence both the likelihood of sustaining a concussion and the experience of recovery. Female athletes in particular tend to report higher rates of concussion and a broader spectrum of symptoms than males. A meta analysis of sports related concussion studies found that female high school athletes were significantly more likely to report concussions across multiple sports, including soccer and basketball, with a 76% and 99% higher incidence, respectively (Cheng et al., 2019).

These disparities likely come from a combination of biological and social factors. As mentioned, hormonal fluctuations, particularly regarding estrogen and progesterone, are believed to affect the body’s response to injury. These hormones may affect inflammation and alter recovery by impacting neuroplasticity—the brain’s ability to reorganize itself following trauma (Huang & Woolley, 2012; Wunderle et al., 2014). Although more research is needed in this area, sex-related physiological differences may help explain why female athletes often experience longer symptom duration and require greater academic support during recovery. In one study, female adolescents took an average of 75.6 days to recover, compared to 49.7 days for males—a 52% longer duration. This disparity may reflect hormonal changes, biomechanical differences, or variations in symptom reporting, and highlights the need for more individualized care models (Kostyun & Hafeez, 2015). Biomechanical differences also play a role, as female athletes generally have less neck strength and smaller cervical spine muscle mass relative to body size, which reduces their ability to stabilize the head upon impact. This decreased stability can lead to greater rotational acceleration of the brain, a force closely linked with concussion mechanisms. A 2005 study found that females experienced 50% greater angular head acceleration and 39% more displacement than males when exposed to an external force, despite activating their neck muscles earlier and using a higher percentage of their available muscle capacity. The increased movement was largely attributed to weaker isometric strength (49% lower), smaller neck girth (30% less), and lower head mass (43% less); factors that together resulted in 29% less head neck stiffness (Tierney et al., 2005). Sports involving high rates of falls or collisions, such as soccer, cheerleading, or basketball, may amplify this vulnerability.

There are also consistent differences in symptom expression. Female athletes tend to report more emotional and cognitive symptoms, such as anxiety, sadness, and sleep disruption. In contrast, males more often report physical symptoms like headaches or sensitivity to light (Koerte et al., 2020). Whether these differences reflect genuine biological differences or are influenced by social norms, such as stigma around emotional expression or fear of being benched, is still debated. However, it's likely that both biology and social context shape the patterns of symptom expression and recovery. Recognizing these differences is crucial for tailoring post concussion care, ensuring that both male and female athletes receive accurate diagnoses and appropriate support based on their unique symptom profiles.

Despite clear differences, no formal concussion guidelines currently differentiate protocols by sex despite evidence of differences in recovery. This can lead to mismanagement. Female athletes may be cleared prematurely, or avoid reporting lingering symptoms if they do not align with the expected profile. Addressing this gap requires a nuanced and individualized approach to care. Incorporating gender specific diagnostic tools, educating providers on hormonal influences, and building flexibility into recovery frameworks will help ensure that concussion care serves all athletes equally.

Beyond the physical and cognitive effects, concussions can disrupt critical aspects of adolescent identity formation. Many student-athletes strongly associate their self worth and social belonging with sport participation. Injury related withdrawal from team activities, in addition to academic or emotional difficulties, can challenge their sense of purpose and peer integration. This disruption may contribute to anxiety, depression, or disengagement from school, particularly in athletes with limited coping support.

3. Subconcussive Impacts and Cumulative Risks

While most concussion research focuses on diagnosed injuries, growing evidence highlights the risks posed by subconcussive impacts, which are repetitive, weaker blows to the head that do not cause immediate symptoms but may result in long term brain changes. These impacts are common in contact sports such as football, soccer, lacrosse, and basketball, where frequent jostling, collisions, or heading the ball expose players to repeated minor trauma. For example, high school football players experience an average of 652 head impacts during a 14-week season, with linemen reporting up to 868 hits, often without formal diagnosis or intervention (Broglio et al., 2011).

Unlike a single concussive event, subconcussive trauma often goes unrecognized due to its subtlety, as it lacks visible signs or clinical documentation. However, advanced imaging technology has revealed that these seemingly minor impacts may have measurable effects on the brain. Diffusion tensor imaging (DTI), which maps the diffusion of water along axonal pathways, can detect microstructural changes in white matter. DTI is especially sensitive to diffuse axonal injury (DAI), a sign of both concussive and subconcussive trauma, caused by microscopic tearing or stretching of neural fibers (Gajawelli et al., 2013). In adolescent athletes, DTI has shown reduced fractional anisotropy, an indicator of white matter health, even in the absence of diagnosed concussion (Koerte et al., 2023).

Functional MRI (fMRI), which measures real time changes in brain activity using blood oxygen levels, has also revealed abnormalities in adolescents exposed to repeated head impacts. Studies show disrupted connections between the prefrontal cortex and limbic system, which are areas responsible for attention, impulse control, and emotional regulation (Healey et al., 2022). These disruptions may reflect unseen problems in large-scale brain networks that are necessary for proper academic, social, and behavioral functioning.

The implications are significant. Adolescents may be especially vulnerable to cumulative neurological disruption, as their brains are still undergoing myelination and cortical reorganization, during which gray matter (composed primarily of neuronal cell bodies, dendrites, and synapses) undergoes cortical thinning and synaptic pruning to optimize cognitive processing. Gray matter plays a central role in processing functions such as memory, emotion, decisionmaking, and sensory perception. It is especially concentrated in regions like the cerebral cortex, hippocampus, and amygdala. Disruption to these areas during development may have lasting effects. For instance, one longitudinal study found that concussed adolescents demonstrated prolonged deficits in attention and executive function, including slower reaction times and task switching abilities, persisting up to two months following injury (Howell et al., 2013). These impairments occurred even in the absence of physical symptoms, highlighting the potential for subtle but sustained cognitive effects. This concern extends beyond diagnosed concussions; exposure to subconcussive trauma has also been linked to impaired memory consolidation and emotional regulation, suggesting that even repeated minor head impacts may interfere with the brain's ability to recover and reorganize effectively.

Detection remains a major challenge. Tools like helmet based accelerometers can record real time head impact data, but are rarely available in secondary school settings due to cost and limited infrastructure. Without observable symptoms, many student athletes continue play while absorbing multiple subconcussive blows. This invisible accumulation of trauma undermines the effectiveness of current concussion protocols, which are often based on symptoms and not designed to account for physiological changes that develop silently.

To address this gap, a proactive approach is necessary; future policies and changes should include education on subconcussive risk, increased funding for head impact monitoring, and support for development of experimental diagnostic tools, such as fluid based biomarkers and portable EEG systems. In adolescent athletes, prevention must be treated equally as important as treatment, if not more so.

Conceptual Framework: Understanding Recovery and Cognitive Impact

To better understand the neurological and functional consequences of concussion in adolescents, the following framework combines established recovery phases with the memory domains most commonly affected by mild traumatic brain injury (mTBI). This approach offers educators and caregivers a more comprehensive perspective on how concussions affect physical recovery as well as long term cognitive development and academic success.

Table 1: Concussion Recovery Phases in Adolescents

Recovery Phase	Timeframe	Description
Immediate Phase	0–24 Hours	Acute symptoms (e.g., headache, confusion, light sensitivity) driven by neurometabolic disruption and impaired cerebral blood flow.
Acute Phase	1–14 days	Persistent cognitive and emotional symptoms. “Relative rest” recommended with light cognitive and physical activity introduced gradually.
Subacute Phase	15 days–3 months	Emerging or intensifying deficits in attention, memory, and executive function, often overlapping with academic challenges.
Chronic Phase / PCS	3+ months	Persistent symptoms like sleep disturbances, mood changes, and cognitive impairments requiring further support.

Domains of Memory Affected by Concussions

Memory disruption is a core feature of concussion related cognitive impairment, particularly in adolescents whose cortical and subcortical structures, responsible for higher level cognitive functions and basic processes, are still developing. These deficits can affect school performance, task execution, and social functioning. See table 2 below regarding types of memory affected by brain trauma.

Table 2: Memory Domains Affected by Concussion

Memory Domain	Description	Anatomical Basis
Episodic Memory	Difficulty recalling specific events or contexts, such as a classroom incident or game moment. Symptoms like delayed recall can persist weeks post-injury.	Hippocampus and medial temporal lobes
Semantic Memory	Challenges with general knowledge and factual recall, potentially impairing performance in school subjects like vocabulary or history.	Lateral temporal lobe
Working Memory	Impaired ability to hold and manipulate information, such as remembering instructions or solving mental math under pressure, often long-lasting after mTBI.	Prefrontal cortex
Prospective Memory	Reduced capability to remember future tasks like submitting assignments or attending practice sessions which is rarely tested but essential for daily life.	Prefrontal cortex, especially right dorsolateral/medial prefrontal cortex regions

Understanding the patterns allows educators to implement accommodations that align with the trajectory of the student's cognitive recovery, reducing frustrations and promoting wellbeing.

4. Disparities in Management Resources

While concussion protocols and recovery guidelines have evolved significantly at the collegiate and professional levels, these advancements are not consistently implemented across high school sports. In particular, high school athletes in rural, underfunded, or underserved districts face a significantly higher risk of undiagnosed or mismanaged head injuries due to systemic disparities in healthcare infrastructure (Yue et al., 2023).

One of the most pressing gaps is the lack of access to certified athletic trainers (ATCs), who are often the first responders to sports injuries. A 2019 survey conducted by the National Athletic Trainers' Association found that ~31% of public high schools in the United States have no access to a full time athletic trainer, and this number is disproportionately higher in low income, rural areas. In fact, schools without any athletic trainer had an average of 52.9% of students eligible for free or reduced price lunch, compared to 45.8% in schools with a part time athletic trainer and 41.1% in those with full time coverage (Barter et al., 2023). Without trained personnel to identify, assess, and monitor concussions, many injuries go unnoticed or are evaluated by untrained coaches, teachers, or even peers.

Geographic differences also play a significant role. Athletes in urban or suburban districts may have access to neurologists, neuropsychologists, and concussion clinics, whereas others in rural or underfunded areas often rely on primary care providers or community clinics with limited experience in managing traumatic brain injury (Mohammed et al., 2024). In cases where transportation and social disparities are barriers, follow up care may be delayed or entirely missed.

Students without timely evaluation may return to play too soon, increasing their risk for additional injuries or developing long term symptoms that interfere with academic performance and emotional wellbeing (Rao et al., 2017); a survey found that 43.5% of athletes returned to their sport too soon post concussion, and 44.7% of student athletes in the same study returned to school too early. Premature return to action is linked to a significantly increased risk of a second concussion or musculoskeletal injury, as one study reported a 34% increased risk. Inconsistent application of baseline testing, limited access to imaging tools, and lack of clear guidance further widens the disparity in outcomes between school systems that are rich or poor in resources.

In addition, this disparity intersects with race, language access, and school culture. Students in predominantly minority districts may be less likely to receive formalized care or concussion education, adding to existing health inequities (Mohammed et al., 2024). The absence of culturally competent educational materials and underrepresentation in concussion research also limits the effectiveness of outreach in these communities.

Addressing these disparities will require more than isolated policy shifts. Sustainable change depends on more investments in medical infrastructure, funding for ATCs in public schools, and the development of mobile concussion support services for rural areas.

5. Exosomal Biomarkers and Emerging Diagnostic Tools

Despite growing awareness of the complexity of concussions, diagnosis still relies heavily on subjective symptom reporting and clinical judgment, both of which are prone to bias and vulnerability. In adolescent populations, these limitations are intensified by factors such as social pressure, fear of being removed from play, and limited self-awareness. As a result, researchers have turned to objective, biologically based diagnostic tools—particularly fluid-based biomarkers—to support and refine concussion evaluation.

Among the most promising developments in this area is the use of exosomal biomarkers. While exosomes have shown promise in adult TBI research, most current studies involving adolescents rely on plasma-based biomarkers due to easier access and validated protocols. Exosomes are small, lipid-bound vesicles (between 30–150 nm) that are secreted by neurons and other cells into bodily fluids such as blood, saliva, and cerebrospinal fluid. These vesicles carry proteins, microRNAs (miRNAs), and other molecular signals that reflect the physiological state of their originating cell (Mavroudis et al., 2023). Because exosomes are stable and resistant to enzymatic breakdown, researchers can use cell-specific surface markers to selectively isolate those released by neurons or glial cells. These vesicles offer a highly specific and durable window into brain health following injury.

Recent studies have identified several neuronal and glial cell derived exosomal proteins as potential biomarkers for mild traumatic brain injury (mTBI), including Neurofilament light chain (NfL), tau protein, Glial fibrillary acidic protein (GFAP), S100B, and Ubiquitin C-terminal hydrolase L1 (UCH-L1). See table 3 below.

Table 3: Key Exosomal Biomarkers for Mild Traumatic Brain Injury

Biomarker	Origin	Function	Diagnostic Value	Notes
Neurofilament light chain (NfL)	Neurons (myelinated axons)	Structural protein	Indicates damage to axons, and remains elevated for weeks	Correlates with axonal injury severity and recovery time; useful for long-term tracking but less effective for acute diagnosis.
Tau protein (t-tau)	Neurons (Microtubules)	Stabilizes neuron structure	Linked to cognitive deficits, memory, and attention	Associated with cognitive deficits after injury, but findings are inconsistent, and its diagnostic utility remains under investigation.
Glial fibrillary acidic protein (GFAP)	Astrocytes	Involved in repair and inflammation	Suggests blood-brain barrier (BBB) disruption and inflammation	Reliable marker of astrocyte activation and blood-brain barrier disruption; elevated in moderate to severe injuries.
S100B	Astrocytes	Calcium binding protein	Helps rule out the need for CT	Useful for ruling out serious brain injury, but lacks specificity

			scans	as levels may also rise from non-neurological trauma such as bone fractures.
Ubiquitin C-terminal hydrolase L1 (UCH-L1)	Neurons	Protein degradation enzyme	Used in acute screening along with GFAP	May show sex-specific patterns post-injury, but this is an emerging area and not yet part of standard diagnostic practice.

Compared to subjective tools such as symptom checklists or sideline evaluations, exosomal biomarker analysis offers a noninvasive, longitudinal approach to monitoring injury progression and recovery. Tracking biomarker levels over time may help detect delayed recovery or evolving damage that might otherwise go unnoticed. When combined with cognitive testing, neuroimaging, or machine learning–based risk models, exosomal biomarkers may significantly enhance both the sensitivity and specificity of concussion diagnosis (Papa, 2016).

In addition to biomarker research, several emerging diagnostic technologies are being considered:

- Oculomotor screening (e.g. King-Devick Test) to assess saccadic (rapid or jerky) eye movements for signs of neurological disruption,
- Quantified vestibular testing to measure balance and spatial orientation control, and
- Portable EEG systems which detect real time changes in brain activity on the sidelines.

While these tools hold promise for improving concussion assessment, particularly in settings without access to full medical teams, most remain in early validation stages and are not yet widely implemented at the high school level (Brown et al., 2023). In parallel, integrating artificial intelligence (AI) into concussion diagnostics represents a promising long-term strategy for improving access, particularly in settings with limited medical resources. Machine learning models trained on exosomal biomarkers, head impact telemetry, or cognitive performance could assist in identifying athletes at risk of prolonged recovery or undetected injury. While advanced tools like portable EEGs or biomarker analyzers may initially remain concentrated in well-funded programs, future implementation could prioritize low cost platforms capable of integrating simple sensor data and automated decision support. By reducing reliance on physically present specialists, such technologies could help close care gaps if paired with equitable policy frameworks and development pipelines that look to include underserved schools from the start.

6. Current Protocols

Over the past two decades, concussion management has become more structured, especially in collegiate and professional athletics. Tools such as the SCAT5, ImPACT, and Graduated Return-to-Play (GRTP) protocols have contributed to more standardized approaches to diagnosis and recovery. However, implementation in high school settings remains inconsistent, and many of these tools carry limitations, particularly when applied to adolescents.

The Sport Concussion Assessment Tool – 5th Edition (SCAT5) is a widely used sideline screening tool that combines symptom checklists, balance assessments, and cognitive tasks. While it provides a standardized evaluation process, it is not recommended for athletes under age 13 and depends heavily on self-reported symptoms, which can be underreported, especially by teens eager to play. A recent study of over 2,800 high school athletes found that SCAT5 scores varied significantly by age, sex, and medical history, with female athletes reporting more mood related symptoms at baseline, and males showing higher rates of ADHD and previous hospitalizations for head injury (Shaffer et al., 2024). Even in high school populations, SCAT5 shows limited test-retest reliability and lacks developmental sensitivity, which raises concerns about its utility for tracking recovery in adolescents.

ImPACT (Immediate Post-Concussion Assessment and Cognitive Testing) is a computerized neurocognitive test used to assess memory, processing speed, and reaction time. Ideally, it's administered pre-season to establish a baseline, then repeated after injury. However, baseline testing is rarely consistent in high schools, especially in underfunded programs. Even when used, validity issues are widespread. A study of nearly 9,000 high school athletes found that over 54% produced at least one questionable or invalid baseline score, with only a small fraction flagged by the test's own validity checks (Tsushima et al., 2023). This suggests that many athletes may not fully engage with the test or understand its importance, limiting its diagnostic value.

Performance-based tools such as the King-Devick Test (assessing oculomotor speed) and the Balance Error Scoring System (BESS) are also used in some schools to screen for vestibular and motor control deficits. However, access to these tools is often limited to programs with athletic trainers or sports medicine support. Even when available, these tests have limitations, as they are short term, task-based evaluations that offer little insight into long term cognitive or emotional recovery. For instance, while BESS is useful for detecting large balance deficits, its reliability can vary, and it may miss subtler impairments (Bell et al., 2011). These tools are best used as part of a larger system that includes follow-up care, something that is often lacking in under-resourced settings.

Most of these tools are embedded within protocols such as Graduated Return-to-Play (GRTP) and Return-to-Learn (RTL) frameworks, which offer step by step guidelines for reintroducing physical and academic activities after injury (Tamura et al., 2020). These models represent an improvement over outdated "rest only" strategies, but they depend on consistent monitoring and trained oversight, which many high schools lack. Another central concern is that current protocols are not tailored to the developmental needs of adolescents. As mentioned, the adolescent brain is still undergoing synaptic pruning, myelination, and maturation of executive function. As a result, teens may experience longer recoveries, more variability in symptoms, and greater difficulty accurately self reporting. Social pressures, stigma, and limited self awareness further undermine the effectiveness of symptom-based tools in this population.

7. Limitations in Current Research and Future Directions

Despite growing research on concussion over the past two decades, key limitations continue to limit understanding of the topic, especially regarding adolescents.

First, much of the concussion literature remains focused on adults, drawing data from collegiate or professional athletes. While these studies offer insight into brain injury mechanisms, they often do not translate directly to adolescents, whose brains are still undergoing major developmental changes. This gap is particularly notable in exosome-based biomarker research, where adolescent-specific data remains sparse compared to plasma-based studies. Studies on youth are often underfunded, based on small sample sizes, or grouped broadly with younger children, masking age specific patterns.

Second, many tools still rely heavily on subjective symptom reporting. Assessments like SCAT5 and ImPACT depend on athlete self reporting, which is often biased or incomplete. Adolescents may underreport symptoms due to social pressure, fear of removal from play, or limited understanding of what they're experiencing. This underreporting makes it difficult to assess true recovery timelines and long term impacts.

Third, there is a shortage of longitudinal research. Most studies are cross sectional or short term, limiting our ability to track the effects of concussion or subconcussive trauma on cognitive development, academic performance, and emotional regulation. Without long term follow-up, it remains difficult to predict which adolescents are most vulnerable to lasting deficits. To address this limitation, future efforts should prioritize the development of widespread longitudinal databases that follow adolescent athletes over several seasons or years. Programs like the TRACK TBI of UCSF and CARE Consortium have provided foundational data on adult and collegiate populations and could potentially be adapted to high school athletes to monitor long-term cognitive, behavioral, and academic outcomes. Integrating school-based academic records, cognitive tests, and injury history into a national youth concussion registry would enable researchers to better assess developmental trajectories and delayed symptoms. However, the creation of a youth concussion registry would need to address challenges around data privacy (e.g., FERPA, HIPAA), secure data sharing infrastructure, and sustainable funding.

Fourth, population representation is severely lacking. Many studies fail to include or separate data by race, socioeconomic status, or geographic location. A 2020 survey found that 21.9% of youth with brain injuries did not receive timely medical care, highlighting disparities in access to follow-up (Gordon, 2020). Additionally, a 2024 review found that 84.4% of concussion studies failed to report race or ethnicity as a variable (Jo et al., 2024). Most large concussion datasets come from suburban or private school programs with better infrastructure, which tends to skew findings and underrepresent the experiences of marginalized groups.

Fifth, methodological inconsistencies limit comparability. Definitions of concussion, diagnostic criteria, and outcome measures vary widely across studies. This lack of standardization makes it difficult to synthesize findings and weakens the evidence base for clinical recommendations.

Lastly, funding and publication bias likely shape the field. Commercially viable tools like baseline testing platforms receive disproportionate attention, while cheaper, community-based interventions may be overlooked or underreported in the academic literature.

Conclusion

Concussions in adolescent athletes remain a serious concern due to the mismatch between the complexity of the injury and the underdeveloped systems in place to manage it. Adolescents face a unique set of risk factors: their brains are still maturing, access to trained medical personnel is often limited, and recovery is complicated by academic demands, identity development, and varied symptom expression.

Current tools such as SCAT5, ImPACT, and Graduated Return-to-Play (GRTP) protocols offer good foundation but rely heavily on self-reported symptoms and were primarily designed for adults. These tools remain poorly adapted to the developmental profile of adolescents. In addition, disparities in access to athletic trainers, baseline testing, and follow-up care disproportionately affect rural or low income communities, leaving many student athletes vulnerable to underdiagnosis or premature return to activity.

Emerging innovations are beginning to shift concussion care in a more objective and personalized direction. Biomarker research, particularly involving exosomal vesicles and fluid based proteins such as GFAP, NfL, and tau, offers the potential for earlier and more precise diagnosis, even in the absence of visible symptoms. These tools have the potential to enhance live clinical decisionmaking, especially in sideline or school-based settings. However, their clinical validation in youth populations remains limited, and access is uneven.

To bridge the gap between scientific advances and real-world care, future efforts must prioritize three core areas. First, diagnostic models should integrate biological markers with neurocognitive and behavioral assessments tailored to adolescent development. Second, infrastructure must be strengthened so that all schools, regardless of geography or funding, have access to certified athletic trainers, consistent baseline testing, and education for students, families, and coaches. Third, research must be more inclusive and longitudinal, tracking outcomes over time across diverse populations to better understand risks and strategies.

Emerging technologies—particularly those that incorporate AI in an equitable, evidence-based manner—may also help translate advanced science into practical tools for a broader range of school settings. When designed with scalability and fairness in mind, these innovations can support specialists and improve care in areas where resources are limited.

Finally, policy level interventions are essential. These may include requiring full-time athletic trainers in public high schools, mandating baseline testing for contact sports, and investing in telehealth solutions to bring concussion expertise to underserved areas. Expanding education and outreach will also be critical to supporting safe recovery.

Clarifying the role of plasma and exosomal biomarkers in youth populations will also be critical to bridging the current translational gap between biomarker discovery and practical use in schools. Only by advancing diagnostic accuracy, ensuring fair access to care, and expanding inclusive research can we build a concussion care system that truly meets the needs of adolescent athletes.

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