

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

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Adolescent athletes face distinct risks from sports-related concussion due to ongoing neurodevelopment, variable symptom expression, and inconsistent access to medical support. This narrative review evaluates current evidence on adolescent-specific vulnerability, sex and gender differences, diagnostic limitations, emerging biomarkers, and disparities in school-based concussion management. Across studies, adolescents show more variable and sometimes prolonged recovery than adults, influenced by continued maturation of the prefrontal cortex, limbic regions, and white matter pathways. Evidence also suggests sex-based differences in symptom burden and biomechanical risk, though findings remain mixed and influenced by social factors. Existing tools, such as SCAT5/SCAT6, Child SCAT6, ImPACT, and return-to-play/return-to-learn frameworks, provide basic structure but rely heavily on subjective reporting and lack developmental sensitivity. Emerging plasma and exosomal biomarkers, including GFAP, NfL, and tau, offer potential for more objective diagnosis but require further validation in youth and consideration of cost and feasibility in school settings. Persistent disparities in athletic trainer access and follow-up care further complicate recovery for students in underserved districts. Collectively, current evidence highlights the need for developmentally informed assessment practices, equitable access to trained personnel, and more inclusive longitudinal research to improve concussion management for high school athletes.

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 nationwide¹. Despite this, there is currently no FDA-approved pharmacological treatment targeting the underlying physiology. Clinical management typically relies on symptom-based 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^{2,3}.

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 connectivity². 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^{4,5}. In addition, underdiagnosis and poor management can lead to prolonged recovery, repeated injuries, and long term symptoms⁶.

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 trainer⁷. Additional sex-based differences have been reported, with female athletes frequently experiencing greater symptom severity or prolonged recovery. Proposed explanations include hormonal influences, neck biomechanical differences, and higher rates of symptom reporting, although evidence remains mixed across studies^{8,9}.

Prior reviews seem to have examined biomarkers, clinical management tools, or developmental risk factors individually.

However, few integrate these domains to address how neurodevelopment, sex-based differences, diagnostic limitations, and disparities in school-based resources collectively shape concussion outcomes in adolescents. This narrative review aims to integrate evidence on adolescent neurodevelopment, sex-related symptom patterns, diagnostic tools, and structural disparities to clarify current gaps and inform more adolescent-specific concussion management.

Methods

This review uses a narrative literature review approach to summarize existing research on concussions among U.S. high school athletes. Relevant publications were identified through keyword-based searches in PubMed, Google Scholar, and ScienceDirect, focusing on work published between 2010 and 2025. Searches included terms related to adolescent concussion, high school traumatic brain injury, post-concussion symptoms, subconcussive impacts, sex-based differences, and emerging biomarker research.

Sources were selected for their relevance to adolescent populations and for the insight they provided into neurodevelopmental risk, diagnostic approaches, biomarkers, or disparities in concussion management. Both empirical studies and review articles were included when they offered useful conceptual or methodological perspectives. Articles unrelated to sports injuries, non-peer-reviewed sources, and papers not written in English were excluded. Most exclusions resulted from a lack of adolescent-specific data, insufficient methodological detail, or a focus on non-sport or adult populations.

In line with narrative review practices, the selection process emphasized conceptual relevance rather than formal screening procedures or standardized quality assessments. Studies using validated assessment tools or adolescent-specific samples were given greater attention, but no systematic coding or scoring framework was applied. The final body of literature consulted consisted of 48 peer-reviewed publications that collectively inform the themes discussed in this review.

Discussion

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 20s¹⁰. These include maturation of the frontal cortex, a region responsible for executive functions such as impulse control, planning, attention, and working memory¹¹, and continuing

changes in the limbic system, particularly the amygdala and hippocampus, which support emotional regulation and memory encoding¹². These changes may heighten emotional reactivity and sensitivity to stress. However, developmental trajectories may vary widely among adolescents, and many studies rely on cross-sectional designs, making it challenging to draw firm conclusions about the specific timelines and vulnerability windows associated with mTBI.

Concussive trauma during this stage can disrupt important developments such as synaptic pruning, 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 adolescence¹³. 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. Much of the evidence for DAI in adolescent mTBI relies on diffusion imaging markers rather than direct histopathological confirmation, and reported effects may vary across different imaging modalities, emphasizing uncertainty in the field.

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 regulation¹⁴. 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 individuals¹⁵. However, findings on the influence of sex hormones remain mixed, with some studies reporting no significant associations between hormone levels and symptom duration, suggesting that multiple biological factors likely contribute. 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 esteem¹⁶. 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. Reported prevalence of PCS varies widely due to inconsistent diagnostic criteria and reliance on self-reported symptoms, further complicating the characterization of long-term outcomes in adolescents.

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. Unfortu-

nately, 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 play¹⁷. This pressure may lead to an increase in 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^{18,19}. Given the limited number of documented cases and the reliance on retrospective reports, the true incidence of SIS in adolescents remains unclear, and more research is needed to establish its mechanisms and risk factors.

Compounding these issues, adolescents with a history of concussion are at significantly greater risk of re-injury, with studies showing a fourfold increase compared to peers with no prior history⁶. However, estimates of re-injury risk differ substantially across studies, many of which rely on self-reported history or school-based injury logs, both of which may undercount total exposure. 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. Evidence suggests that adolescent athletes may benefit from more developmentally tailored recovery strategies, although such approaches have not yet been uniformly validated in youth populations. Recognizing these developmental considerations may help guide more appropriate monitoring frameworks that support both cognitive and emotional recovery. These neurodevelopmental vulnerabilities also interact with themes discussed in later sections, including sex-based symptom patterns, recurrent subconcussive exposure, and disparities in access to athletic healthcare.

Sex-based Differences In Concussion Outcomes

Research suggests that sex 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, respectively²⁰. However, incidence estimates vary across studies due to differences in reporting practices, sport exposure, and diagnostic thresholds, with some research showing smaller or nonsignificant disparities.

These differences likely stem from a combination of biological and social factors. As mentioned, hormonal fluctuations, particularly involving estrogen and progesterone, are believed to affect the body’s inflammatory response and neural recovery. These hormones may influence neuroplasticity—the

brain’s ability to reorganize following trauma^{21,22}. Yet evidence remains mixed, as several studies have failed to replicate strong hormonal effects, suggesting that endocrine factors alone cannot fully account for observed sex differences. 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 duration²³. Recovery estimates, however, differ widely across the literature due to heterogeneity in outcome measures, sample characteristics, and follow-up duration.

Biomechanical differences also play a role. Female athletes generally have less neck strength and smaller cervical spine muscle mass relative to body size, reducing head stabilization upon impact. This 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 under equivalent force, largely due to reduced neck stiffness²⁴. Still, translating biomechanical findings to real-world concussion risk is challenging, as on-field impacts vary in magnitude and direction, and many studies use laboratory simulations that may not fully reflect real-world sports conditions. Sports involving high rates of falls or collisions, such as American football, cheerleading, or basketball, may amplify these vulnerabilities.

Symptom expression patterns also differ between sexes. Female athletes tend to report more emotional and cognitive symptoms, such as anxiety, sadness, and sleep disruption, while males more often report physical symptoms like headaches or sensitivity to light⁸. However, these patterns may be influenced by gendered social norms, differences in willingness to report emotional symptoms, and stigma around emotional experience and expectations around athletic performance. Disentangling biological sex effects from gender related influences should remain an active area of research. Recognizing these nuances is crucial for tailoring post concussion care, so that both male and female athletes receive accurate diagnoses and appropriate support.

Despite these disparities, no formal concussion guidelines currently differentiate protocols by sex, even though evidence tends to indicate variability in symptom burden and recovery duration. Guideline development is limited by inconsistent findings, variability in study quality, and the lack of adolescent specific normative data. Female athletes may be cleared prematurely or may hesitate lingering symptoms if their experience does not match the expected presentation. Addressing this gap may require a more individualized approach informed by emerging evidence rather than rigid sex-based protocols. Current data support the need for greater awareness of sex-related symptom patterns, but further research is required before establishing formal sex-specific guidelines.

Beyond the physical and cognitive effects, concussions can disrupt key aspects of identity formation in adolescence. Many student-athletes strongly associate their identity and social belonging with sport participation. Injury related withdrawal from team activities, combined with academic or emotional challenges, can threaten 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. These impacts intersect with the biological and biomechanical differences described above, underscoring the importance of integrated and informed management approaches across sexes.

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, low-magnitude blows to the head that do not cause immediate symptoms but may contribute to long term 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. High school football players, for example, experience an average of 652 head impacts during a 14-week season, with linemen reporting up to 868 hits, often without formal diagnosis or intervention²⁵. However, reported impact counts vary substantially across studies due to differences in sensor technology, threshold settings, and device compatibility, making it difficult to establish precise exposure levels.

Unlike a single concussive event, subconcussive trauma often goes unrecognized due to its subtlety and lack of observable symptoms. Advanced imaging technology, particularly diffusion tensor imaging (DTI), have demonstrated measurable microstructural changes in white matter even in the absence of diagnosed concussion²⁶. In adolescent athletes, DTI studies show reduced fractional anisotropy (an indicator of white matter health) following seasons of repetitive head impacts²⁷. These imaging findings, however, are not always consistent across research groups, and interpretation is limited by small sample sizes, variability in protocol, and the absence of long term follow-up and longitudinal design in many studies.

Functional MRI (fMRI) studies have shown disrupted connectivity between the prefrontal cortex and limbic regions that are responsible for attention, impulse control, and emotional regulation²⁸. Yet the functional significance of these changes remains uncertain, as altered connectivity patterns do not always correlate directly with behavioral symptoms, and many studies lack adolescent specific normative baselines. Nonetheless, such disruptions raise concerns about potential effects on academic performance and social behavior in youth athletes.

Adolescents may be especially vulnerable to cumulative

neurological disruption because their brains are still undergoing myelination, cortical thinning, and synaptic pruning to optimize cognitive processing. Disruption to gray matter regions such as the cerebrum, hippocampus, and amygdala may have lasting consequences for memory, emotion, decisionmaking, and sensory processing. A longitudinal study found that concussed adolescents showed prolonged deficits in attention and executive function, such as slower reaction times and reduced task switching ability, persisting up to two months following injury²⁹. These impairments occurred even without overt physical symptoms, emphasizing the potential for subtle but sustained cognitive effects. However, other longitudinal studies report more rapid recovery trajectories, indicating that the long-term cognitive impact of both concussive and subconcussive trauma in adolescents remains uncertain.

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 symptom based monitoring gap limits the effectiveness of current protocols, which largely rely on self-report and often do not account for physiological changes that develop undetected. The lack of accessible and objective monitoring tools in high school sports remains a major barrier to identifying cumulative exposure risk.

To address this gap, researchers have proposed expanding education on subconcussive exposure, improving access to head-impact monitoring technologies, and advancing experimental diagnostic tools such as portable EEG systems. However, most of these approaches remain in the early stages of development, and their feasibility in adolescent sports programs, particularly those with limited resources, has not been established. Rather than emphasizing specific policy actions, current evidence suggests that greater awareness of cumulative exposure risk may help inform safer training practices while further research clarifies long term outcomes. The cumulative risks also overlap with developmental vulnerability, sex related symptom patterns, and healthcare disparities.

Conceptual Framework for 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. As shown in Table 1, the recovery process is typically divided into immediate, acute, subacute, and

Table 1 Concussion Recovery Phases in Adolescents

Recovery Phase	Timeframe	Description
Immediate Phase	0–24 hours	Acute symptoms such as headache, confusion, and light sensitivity driven by neuro-metabolic disruption and impaired cerebral blood flow ² .
Acute Phase	1–14 days	Persistent cognitive and emotional symptoms. Relative rest is recommended, with gradual reintroduction of light cognitive and physical activity ¹⁹ .
Subacute Phase	15 days–3 months	Emerging or intensifying deficits in attention, memory, and executive function, often overlapping with academic challenges ^{19,30} .
Chronic Phase / PCS	3+ months	Persistent symptoms including sleep disturbances, mood changes, and cognitive impairments that require ongoing clinical and academic support ³¹ .

chronic phases.

It is important to note that most recovery-based frameworks are adapted from adult literature, and empirical validation in adolescent populations remains limited. Recovery trajectories in youth are highly variable, and studies often differ in their definitions of recovery time, symptom thresholds, and measurement tools. As a result, these phases should be viewed as general guides rather than strict, developmentally validated stages.

Memory Domains Affected by Concussion

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. Table 2 outlines several memory domains commonly affected by brain trauma.

Although these domains are widely referenced in clinical neuropsychology, many of the assessment tools used to measure them, such as working memory or prospective memory tasks, have not been extensively validated in the context of concussion in adolescent populations. Variability in testing procedures, baseline cognitive differences, and inconsistent follow-up intervals may limit the interpretability of results. Thus, these domains should be interpreted as conceptual areas of vulnerability rather than definitive diagnostic categories.

Linking Concussion Phases and Memory Domains

Taken together, these recovery phases and memory vulnerabilities highlight how neurological disruption in adolescents intersects with developmental timing, symptom expression, and disparities in access to monitoring tools discussed in later sections.

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; delayed recall may persist weeks post-injury.	Hippocampus and medial temporal lobes ³²
Semantic Memory	Challenges with general knowledge and factual recall, potentially impairing academic performance in subjects such as vocabulary or history.	Lateral temporal lobe ³³
Working Memory	Impaired ability to hold and manipulate information, such as remembering instructions or performing mental calculations; deficits may persist after mTBI.	Prefrontal cortex ³⁴
Prospective Memory	Reduced ability to remember future intentions, such as submitting assignments or attending practice sessions; rarely assessed but critical for daily functioning.	Right dorsolateral and medial prefrontal cortex ³⁵

Disparities in Management Resources

While concussion protocols and recovery guidelines have advanced significantly at the collegiate and professional levels, these advancements are not consistently implemented across high school sports. 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 infrastructure³⁶. These inequities are especially concerning in adolescents, whose developing brains may be more susceptible to the cognitive and emotional consequences of delayed diagnoses or insufficient follow-up care.

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 reported that ~31% of public high schools in the United States lack a full time athletic trainer, with rates disproportionately higher in low income, rural areas. 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 coverage³⁷. Without trained personnel to identify, assess, and monitor concussions, many injuries go unnoticed or are evaluated by untrained coaches, teachers, or even peers. However, estimates of access vary depending on survey methods, and not all schools without ATCs lack alternative supports (e.g., school nurses), highlighting need for more precise data on resource distribution.

Geographic differences also play a significant role. Athletes in urban or suburban districts may have access to neurologists,

neuropsychologists, and concussion clinics, whereas adolescents in rural or under-resourced communities often rely on primary care providers with limited specialization³⁸. Barriers such as transportation, limited clinic availability, and socioeconomic constraints can delay or prevent follow-up care. These gaps are particularly consequential for adolescents, as prolonged symptoms may impair academic performance, emotional regulation, and social development at a critical developmental stage.

Students without timely evaluation may return to play or school prematurely, increasing their risk for additional injuries or prolonged symptoms³⁹. A survey found that 43.5% of athletes post-concussion returned to their sport too early, and 44.7% returned to school before full recovery. Premature return to action is associated with higher rates of subsequent concussions or musculoskeletal injury, with one study reporting a 34% increased risk. Causal pathways remain difficult to establish clearly, as premature return may also reflect underlying differences in school culture, coaching expectations, or societal pressure from peers or parents. Inconsistent use of baseline testing, limited access to imaging or diagnostic tools, and variability in follow-up protocols further widen the disparity in outcomes between resource-rich and resource-limited schools.

Disparities also intersect with race, language access, and school culture. Students in predominantly minority districts may be less likely to receive formalized care or concussion education, exacerbating existing health inequities³⁸. The lack of culturally responsive educational materials and limited representation of minority adolescent populations in concussion research restricts the generalizability of current management guidelines. This gap underscores the importance of tailoring educational strategies and clinical outreach to diverse communities.

Addressing these disparities will require comprehensive solutions rather than isolated policy changes. Sustainable progress depends on increased investment in school-based medical infrastructure, funding for certified athletic trainers, and the development of mobile or telehealth-based concussion support services for rural districts. Because adolescent recovery is influenced not only by biological factors but also by access to monitoring, diagnostic tools, and academic accommodations, addressing structural disparities is integral to improving long-term outcomes.

These disparities also interact with the neurodevelopmental and sex-related vulnerabilities discussed in earlier sections, illustrating how structural inequities can amplify individual risk factors in adolescent concussion. Because adolescents are still undergoing maturation of executive, emotional, and white matter systems, delays in evaluation or inconsistent follow-up can further disrupt recovery and magnify the neurocognitive consequences of concussion.

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 axonal damage and remains elevated for weeks	Correlates with axonal injury severity and recovery time; useful for long-term tracking but less effective for acute diagnosis ⁴¹ .
Tau protein (t-tau)	Neurons (microtubules)	Stabilizes neuronal structure	Linked to cognitive, memory, and attention deficits	Associated with post-injury cognitive deficits; findings remain inconsistent and diagnostic utility is still under investigation ⁴⁰ .
Glial fibrillary acidic protein (GFAP)	Astrocytes	Repair and inflammatory response	Suggests blood-brain barrier disruption and inflammation	Reliable marker of astrocyte activation and BBB disruption; typically elevated in moderate to severe brain injuries ⁴⁰ .
S100B	Astrocytes	Calcium-binding protein	Helps rule out the need for CT imaging	Useful for excluding serious brain injury but lacks specificity, as levels may rise following non-neurological trauma such as bone fractures ⁴⁰ .
Ubiquitin C-terminal hydrolase L1 (UCH-L1)	Neurons	Protein degradation enzyme	Used in acute screening in combination with GFAP	May exhibit sex-specific post-injury patterns; currently an emerging biomarker and not part of standard diagnostic practice ^{40,41} .

Exosomal Biomarkers and Emerging Diagnostic Tools

Accurately diagnosing concussion remains challenging because current methods rely heavily on subjective symptom reporting and clinician judgment, both of which are vulnerable to bias. In adolescents, these limitations may be intensified by fear of removal from play, social pressure, or limited symptom awareness. For this reason, researchers have increasingly explored biologically based diagnostic tools, particularly fluid-based biomarkers, to provide more objective evidence of injury.

Among the most promising developments in this area are exosomal biomarkers, which have shown utility in adult TBI research. However, most adolescent studies still focus on plasma-based biomarkers, as standardized protocols for isolating neuron-derived exosomes are still emerging. Exosomes are small vesicles containing proteins and microRNAs that reflect the physiological state of their originating cells⁴⁰. Although exosomal assays offer high biological specificity, their use in adolescent concussion remains experimental, and existing studies typically include small sample sizes and limited time points.

Recent work has highlighted several neuronal and glial biomarkers, including neurofilament light chain (NFL), tau protein, glial fibrillary acidic protein (GFAP), S100B, and ubiquitin C-terminal hydrolase L1 (UCH-L1), as potential indicators of mild traumatic brain injury. As shown in Table 3, these markers reflect a range of injury processes, such as axonal damage, neuroinflammation, and blood-brain barrier disruption. However, diagnostic accuracy across studies varies considerably, and many findings have not been replicated in adolescent-specific cohorts. Changes in biomarker concentration can also result from non-neurological factors such as exercise, systemic inflammation, or musculoskeletal injury, which complicates interpretation in school sports settings.

Compared with subjective symptom checklists or sideline evaluations, biomarker analysis offers the potential for noninvasive, longitudinal tracking of recovery. Nevertheless, most biomarker thresholds lack clinical standardization, and no biomarker currently offers sufficient sensitivity or specificity

for routine use in secondary school settings. Their utility may be greatest when combined with cognitive testing, neuroimaging, or machine-based learning models⁴⁰, though such approaches remain early in development.

In addition to biomarker research, several emerging technologies show potential for improving concussion assessment:

- Oculomotor screening (e.g., King-Devick Test), which assesses saccadic (rapid or jerky) eye movements
- Quantified vestibular testing, which measures balance and spatial orientation
- Portable EEG systems, which detect real time neural activity patterns

*While these tools may help identify deficits not captured by subjective symptom reporting, most have limited adolescent validation and show variable reliability across studies. Many also require specialized training or hardware, reducing feasibility in under-resourced schools.*⁴¹

Parallel advances in artificial intelligence (AI) offer long-term potential for improving access to objective diagnostic support. Machine learning models trained on impact telemetry, biomarker panels, or cognitive performance could help flag athletes that are at risk of prolonged recovery. However, most AI tools remain conceptual or preliminary, and their accuracy is highly dependent on the quality and representativeness of training datasets, a major limitation in adolescent research, where large-scale data remain limited.

Although advanced diagnostics may initially be adopted by well-funded programs, future development will need to prioritize affordability, ease of use, and equitable implementation to avoid widening existing disparities in concussion care. Technology-driven approaches could help reduce reliance on in-person specialists, but only if paired with sustainable policy support and validation in diverse adolescent populations.

These emerging tools complement, but do not replace, the need for developmentally informed clinical evaluation, highlighting the importance of integrating biological, behavioral, and contextual indicators when assessing concussion in adolescents.

Current Concussion Management Protocols

Over the past two decades, concussion management has become more structured, especially in collegiate and professional athletics. Tools such as the Sport Concussion Assessment Tool (SCAT), 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 have important limitations when applied to adolescents.

The Sport Concussion Assessment Tool – 5th Edition (SCAT5) is a widely used sideline screening tool combining symptom checklists, balance testing, 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 especially unreliable in adolescents. A recent study of over 2,800 high school athletes found that SCAT5 scores varied significantly by age, sex, and medical history⁴². These findings suggest that baseline SCAT5 performance is influenced by demographic and clinical factors unrelated to concussion itself. Even in high school populations, SCAT5 shows limited test-retest reliability and lacks developmental sensitivity, raising concerns about its utility for tracking adolescents' recovery.

In 2023, SCAT6 and Child SCAT6 were released to address several well-documented issues with SCAT5⁴³. SCAT6 introduces clearer instructions, expanded cognitive/neurological domains, and greater emphasis on serial assessments, while Child SCAT6 (ages 8–12) includes developmentally tailored symptom ratings and simplified tasks. These updates aim to improve sensitivity and reduce variability, but early validation studies indicate that robustness in adolescent samples remains limited, and baseline influences such as mood, sleep, and stress continue to affect results. As a result, SCAT6 should be interpreted cautiously until more data become available.

ImPACT (Immediate Post-Concussion Assessment and Cognitive Testing) is a computerized test used to assess memory, processing speed, and reaction time. Ideally, it is administered pre-season to establish a baseline and repeated after injury. However, baseline testing is inconsistent in high schools, especially in underfunded programs. A study of nearly 9,000 high school athletes found that more than 54% produced at least one questionable or invalid baseline score, with only a small fraction flagged by the test's internal validity checks⁴⁴. Poor engagement, limited understanding, or environmental distractions may compromise baseline accuracy. When baselines are unreliable, post-injury comparisons can be misleading, reducing the diagnostic value of ImPACT in adolescents unless interpreted cautiously and in combination with other assessments.

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: BESS can miss subtler balance impairments⁴⁵ King-Devick scores can be influenced by fatigue and attention, and both offer limited insight into long term cognitive or emotional outcomes. These tools function best as part of a broader assessment system, which many secondary schools lack.

Most screening tools are embedded within protocols such as Graduated Return-to-Play (GRTP) and Return-to-Learn (RTL) frameworks, which provide stepwise guidance for reintroducing physical and academic activity⁴. These models are major improvements over outdated “rest only” strategies, but they depend on consistent monitoring and access to trained personnel. Current CDC guidelines emphasize 24 to 48 hours of relative rest followed by gradual return to school, and recommend delaying return to athletics until the student is back to full academic participation and symptom-free with exertion. Similarly, the most recent international consensus from Amsterdam⁴⁶ and European guidance recommend staged progression with close monitoring, avoidance of prolonged strict rest, and individualized pacing based on symptoms and exertional tolerance.

Another concern is that many existing protocols are not tailored to the developmental needs of adolescents. As the adolescent brain is still undergoing synaptic pruning, myelination, and maturation of executive functions, teens may exhibit longer recovery trajectories, more variable symptom presentation, and reduced accuracy in self-reporting. Social pressures, stigma, and limited insight further undermine the reliability of symptom-based tools. Taken together, these factors indicate that while current recovery frameworks provide useful structure, adaptations are likely needed to better reflect adolescent neurodevelopment and the resource constraints present in many high school environments.

Taken together, these findings illustrate how adolescent neurodevelopment, sex-related symptom patterns, cumulative subconcussive exposure, diagnostic limitations, and structural disparities interact to shape concussion presentation and recovery. These domains operate not as isolated risk factors but as overlapping influences that affect symptom reporting, access to evaluation, and the accuracy of available assessment tools. Understanding these factors as an interconnected system helps explain why adult-derived protocols often underperform in youth populations and underscores the need for adolescent-specific diagnostic models that integrate biological, cognitive, and contextual considerations. This multidimensional perspective provides a foundation for strengthening concussion identification, monitoring, and management in high school settings.

Limitations in Current Research and Future Directions

Despite growing research on concussion over the past two decades, key limitations continue to constrain understanding of the topic, particularly in adolescent populations.

First, much of the concussion literature remains focused on adults, drawing data from collegiate or professional athletes. While these studies offer insight into underlying injury mechanisms, they may not generalize well to adolescents,

whose brains are still undergoing substantial developmental changes. This gap is especially pronounced in biomarker research, where adolescent-specific studies, particularly involving exosome-based markers, remain sparse. Youth studies are frequently underfunded, rely on small convenience samples, or combine adolescents with younger children, which obscures age-specific developmental patterns and reduces the precision of findings.

Many tools still rely heavily on subjective symptom reporting. Assessments like SCAT and ImpACT depend on athlete self-report, which is often biased or incomplete. Adolescents may underreport symptoms due to social pressure, fear of being removed from play, or limited awareness of what constitutes a concussion symptom. These reporting biases complicate efforts to evaluate diagnostic accuracy or estimate true recovery trajectories, and they contribute to the difficulty of validating tools that rely heavily on self-reporting.

There is also a shortage of longitudinal research. Most studies are cross-sectional or short-term, restricting our ability to track the cognitive, academic, or emotional consequences of concussion or subconcussive trauma over time. Without long-term follow-up, it remains difficult to determine which adolescents are most vulnerable to lasting deficits. To address this gap, future research should prioritize efforts to create longitudinal databases that follow adolescent athletes over multiple seasons. Programs like TRACK-TBI and the CARE Consortium, which have generated foundational data on adult and collegiate populations, could serve as models for youth-focused registries. Integrating school-based academic records, cognitive assessments, and injury history into a national adolescent concussion registry would offer substantial benefits. However, such a registry would need to address significant feasibility challenges, including data privacy protections (e.g., FERPA, HIPAA), standardized data collection procedures, and sustainable funding models.

Population representation remains limited. Many studies fail to report race, socioeconomic status, or geographic region, which restricts the generalizability of findings. A 2020 survey found that 21.9% of youth with brain injuries did not receive timely medical care, illustrating disparities in access to follow-up⁴⁷. A 2024 review found that 84.4% of concussion studies did not report race or ethnicity⁴⁸. Because large datasets often draw disproportionately from suburban or private school athletes, current evidence may underestimate risks or outcomes in marginalized groups. This lack of representation contributes to gaps in culturally responsive education materials and may perpetuate inequities in diagnosis and care.

Fifth, methodological inconsistencies limit comparability across studies. Definitions of concussion, diagnostic criteria, and outcome measures vary widely, creating substantial heterogeneity in the literature. Differences in imaging protocols, biomarker assay platforms, and neurocognitive test scoring

further complicate synthesis efforts. This variability weakens the evidence base for clinical recommendations and underscores the need for greater standardization in adolescent-focused research.

Lastly, funding and publication bias likely shape the field. Commercially marketed tools, such as baseline testing platforms, tend to receive more visibility and financial support, which may skew the literature toward proprietary solutions rather than low-cost, community-based interventions. At the same time, emerging technologies like biomarkers, portable EEG devices, and AI-based classifiers often require specialized equipment and expertise, raising concerns about scalability, cost-effectiveness, and equitable implementation in real-world high school settings. Future research should evaluate not only scientific accuracy but also feasibility, affordability, and accessibility in under-resourced environments.

Taken together, these limitations highlight the need for more inclusive, developmentally informed research that prioritizes longitudinal follow-up, methodological consistency, and equitable access. Addressing these gaps will be essential for improving adolescent concussion care and ensuring that emerging innovations translate into real-world benefits.

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. These interacting vulnerabilities make timely recognition and appropriate management particularly challenging in this age group.

Current tools such as SCAT, ImpACT, and Graduated Return-to-Play (GRTP) protocols offer a useful foundation but rely heavily on self-reported symptoms and were primarily designed around adult populations. 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. These structural inequities can amplify underlying developmental and biological risks, highlighting the need for systems-level improvements.

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 may ultimately

enhance live clinical decision-making in sideline or school-based settings. However, clinical validation in adolescents is still limited, and feasibility challenges remain, including cost, assay standardization, and the need for trained personnel. Without addressing these practical constraints, the promise of biomarker-driven diagnostics may not translate effectively to high school environments.

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 become more inclusive and longitudinal, tracking outcomes across diverse populations to better understand risks and inform tailored recovery strategies.

Emerging technologies—including portable EEG systems, digital symptom monitoring, and AI-based decision support—may also help translate advanced science into more accessible tools. However, equitable implementation will require careful attention to cost, data privacy, and the risk of widening existing disparities if such tools become concentrated in well-resourced schools. When designed with scalability, fairness, and adolescent-specific validation in mind, these innovations could meaningfully support clinicians and improve care in under-resourced areas.

Policy-level interventions are equally important. These may include requiring full-time athletic trainers in public high schools, mandating baseline testing for high-impact sports, expanding telehealth services, and investing in culturally responsive concussion education. Such systemic changes are essential to reducing preventable harm and ensuring that advances in diagnosis or treatment do not bypass the communities that need them most.

Clarifying the role of plasma and exosomal biomarkers in youth populations will also be crucial to bridging the translational gap between laboratory discovery and practical school-based implementation. Ultimately, improving adolescent concussion care will require coordinated action across research, clinical practice, education, and policy. Only by advancing diagnostic accuracy, ensuring equitable access to resources, and expanding inclusive research can we build a concussion care system that truly meets the developmental and practical needs of adolescent athletes.

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