Narrative Review Article

Sports-Related Spinal Cord Injuries in U.S. Youth Athletes: A Review of Recent Studies

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ABSTRACT

Sports-related spinal cord injury (SCI) remains a significant concern for youth athletes, particularly in sports with a high risk of collisions or falls such as football, wrestling, gymnastics, and cheerleading. This review examines recent literature on the epidemiology, on-field management, and acute care of these injuries, along with updates on emerging treatment strategies. National registry data indicate that youth and young adults face a disproportionately high risk of sports-related SCI despite a decline in overall incidence. Early management guidelines emphasize rapid stabilization, airway protection, and timely transport to appropriate medical facilities. Although current medical treatments primarily focus on stabilization and rehabilitation, recent research in biomaterials, drug-delivery systems, electrical stimulation, and cell-based therapies shows promise for enhancing neural repair. Most of these approaches remain in preclinical stages, but ongoing advances in the field suggest the potential for more effective interventions in the future.

Keywords: Spinal cord injury (SCI); Youth athletes; Sports-related injury; Cervical spine; Emergency management; Neural regeneration

INTRODUCTION

Spinal cord injury (SCI) is a neurological condition caused by traumatic or pathological damage to the spinal cord, leading to partial or complete disruption of motor and sensory pathways (1). Such injuries can lead to irreversible neurological deficits, including paraplegia (loss of function in the lower body) or quadriplegia (loss of function in all four limbs), and place significant physical, emotional, and financial burdens on both patients and their families. Common causes of SCI include motor vehicle accidents, falls, and sports-related injuries. In younger populations, a larger proportion of SCI cases are attributable to sports activities compared with other age groups (2). This trend is especially important because a large proportion of U.S. middle and high school students participate in sports such as football, ice hockey, cheerleading, wrestling, and diving, which are considered high-risk for spinal injuries (3, 4).

Recent surveillance data indicate that sports-related SCI occurs most frequently in youth and young adults (5). While some injuries involve minor neck strains or contusions that resolve with conservative treatment, others result in permanent paralysis due to vertebral fractures or direct spinal cord damage.

Although spontaneous neural regeneration is highly challenging, diverse experimental research efforts are actively underway across various fields to make functional regeneration possible. Given the current limitations in standard clinical treatment, prevention

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and optimal acute management remain the most critical strategies. Therefore, this review examines recent literature on sports-related spinal cord injuries in youth athletes, aiming not only to summarize relevant epidemiologic statistics but also to discuss prevention strategies, emergency management, and recent advances in emerging treatment approaches.

This narrative review examined English-language publications from 2000 to 2025 using PubMed and Google Scholar, with emphasis on studies published within the last five years. National registry data from the NSCISC and NCCSIR were also incorporated. Studies focusing on pediatric or adolescent populations, sports-related spinal injuries, acute medical care, and emerging regenerative treatments were prioritized, while single case reports and exclusively adult-focused studies were excluded.

BACKGROUND OF SPINAL CORD INJURY

To fully understand the clinical impact of sports-related spinal cord injuries on adolescent athletes, it is essential to first examine the foundational anatomy of the spine, the statistical prevalence of these injuries, and their underlying biological mechanisms.

Anatomy

Understanding spinal anatomy provides the foundation for interpreting injury patterns. The spinal cord is a soft, cylindrical column of nerve cells and fibers that connects the brain to the rest of the body. It is enclosed and protected by the vertebral column, which also provides structural support and is divided into four regions: the cervical, thoracic, lumbar, and sacral vertebrae. The spinal cord serves as the primary pathway for transmitting sensory information to the brain and carrying motor commands to the limbs and trunk. It also coordinates rapid reflexes and helps regulate involuntary functions such as heart rate, blood pressure, and digestion (1).

Because the spinal cord is vital for sensory processing, motor control, autonomic regulation, and reflex coordination, any injuries to this structure can lead to a wide range of neurological deficits. The severity of symptoms varies greatly depending on both the level and extent of the injury, ranging from mild sensory disturbances to paraplegia (paralysis of the lower body) or quadriplegia (paralysis of all four limbs) (6).

These clinical manifestations are highly dependent on the anatomical location of the trauma. For instance, with respect to vertebral level, injuries to the cervical region can interrupt both upper and lower limb motor pathways, often resulting in quadriplegia. In contrast, injuries at the thoracic level generally spare the nerves that supply the arms and more commonly lead to paraplegia. Although injuries involving the lumbar or sacral vertebrae have been documented, they are reported far less frequently in sports-related trauma (7).

Beyond the vertical level of the spine, symptoms also vary depending on the specific regions affected within the spinal cord cross-section. Damage to the ventral portion of the cord can disrupt motor function because it contains motor neuron cell bodies, whereas injuries involving the dorsal columns typically impair sensory modalities such as position and vibration (1). Given the devastating neurological consequences of these anatomical disruptions, it is crucial to understand how frequently and in what contexts these injuries actually occur, particularly among vulnerable populations like young athletes.

Epidemiology

School athletics play an important role in the physical and social development of students across the United States. During the 2023-24 season, data from the National Federation of State High School Associations reported that 8,062,302 students participated in organized sports programs, indicating that a large proportion of American high school students are involved in at least one athletic activity. Among boys, the most popular sports were football (1,031,508 participants), outdoor track and field (625,333), basketball (536,668), baseball (471,701), and soccer (467,483). Among girls, the leading sports were outdoor track and field (506,015), volleyball (479,125), soccer (383,895), basketball (367,284), and softball (345,451) (8).

Meanwhile, the National Center for Catastrophic Sport Injury Research documented 95 sport-related catastrophic injuries among high school and collegiate athletes during the same academic year (2023-24). The most frequently affected sports were football, baseball, basketball, track and field, and soccer. Excluding cardiac-related cases, spinal cord injuries (SCI) accounted for the largest proportion of catastrophic events (23%), highlighting their importance within traumatic sports injuries. Most incidents occurred during competition (56%), followed by practice (27%), and the male-to-female ratio was approximately 92:8 (9).

To examine the epidemiology of SCI among young athletes, Meron *et al.* (10) conducted a ten-year study analyzing cervical spine injuries in U.S. high school sports. Their investigation included 35,581,036 athlete exposures, corresponding to an overall injury rate of 3.04 per 100,000 athlete exposures. The highest injury rates were observed in football (10.10), wrestling (7.42), and girls' gymnastics (4.95). Among all cervical spine injuries reported, muscle injuries were most common (63.1%), followed by nerve injuries (20.5%) (10).

Another large-scale study by Alas *et al*. (11) examined 38,539 patients with sports-related cervical spine trauma. Adolescents showed the highest rates of cervical injuries, which included fractures, dislocations, and SCIWORA (spinal cord injury without radiographic abnormality). The high incidence of SCIWORA in this demographic is closely related to the developing anatomy of the adolescent spine. The inherent elasticity of ligaments and joint capsules allows for significant spinal deformation without bone fractures, ultimately exposing the spinal cord to severe injury. Football-related cervical spine injuries increased from 5.83% to 9.14% between 2009 and 2012, and football athletes were 1.56 times more likely to sustain an SCI compared with athletes in other sports. These results suggest that adolescents are especially vulnerable to cervical spine and spinal cord injuries in high-impact sports, reinforcing the need for strict safety measures in youth athletics (11).

While adolescent athletes face specific risks, broader national data provides context on how these sports-related injuries have trended over time. According to the NSCISC 2024 Annual Report, sports-related SCI has declined from 14.4% in the 1970s to 8.4% during 2020–2023, reflecting improved prevention strategies including enhanced equipment standards and rule modifications. The incidence remains higher in males (10.9%) than females (5.6%). Sports-related SCI cases are heavily concentrated within a narrow age window. The 16–30 age group accounts for 2,414 reported cases, which is nearly four times the number in the 31–45 group (637 cases) and about ten times the number reported in children under 15 (243 cases). After age 30, the case count drops steeply to 285 in the 46–60 range and only 9 in those aged 96–98 (Figure 1). This pattern coincides with the years of highest participation in competitive high school and collegiate athletics, suggesting that exposure to high-impact sports, rather than biological vulnerability alone, drives much of the observed injury frequency.

Carll *et al*. (3) identified football, cheerleading, wrestling, swimming and diving, and skiing or snowboarding as the primary high-risk sports for spinal cord injury. In contrast, the more recent NSCISC report identified skiing (229 cases), winter sports (191 cases), horseback riding (173 cases), football (162 cases), surfing (162 cases), wrestling (101 cases), trampoline use (84 cases), and gymnastics (61 cases) as the major sports-related causes of spinal cord injury. Sports such as baseball, basketball, volleyball, and track and field were also associated with spinal cord injury but were classified as relatively minor causes due to their lower incidence rates.

When NSCISC cases are broken down by sport and sex, football and wrestling cases are predominantly male. These distributions are consistent with the overall 92:8 male-to-female ratio reported in catastrophic sports injuries (9). Gymnastics shows a notably different pattern, with 40 male and 21 female cases, and trampoline injuries also show a higher female share than most contact sports (Figure 2). This likely reflects both the high female participation rate in these sports and their biomechanical demands, such as repeated cervical hyperextension and rotational landings, which place unusual stress on the developing spine. The pattern suggests that female athletes in rotation-based sports

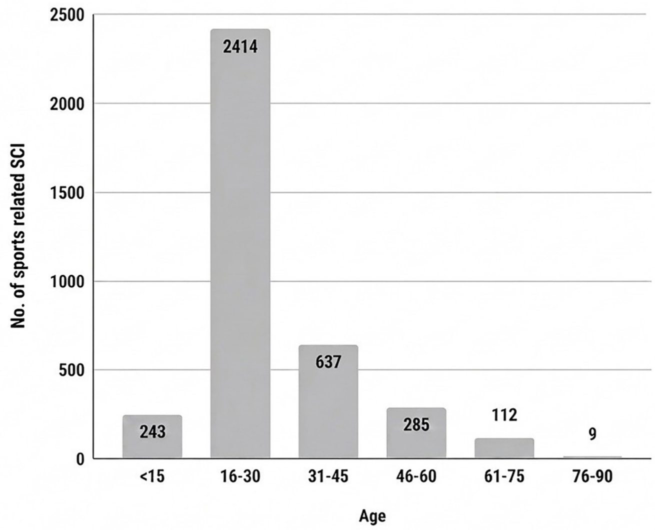

Figure 1. *Sports-related spinal cord injuries by age group. This figure presents the distribution of sports-related spinal cord injuries (SCI) across different age groups based on national registry data. The number of reported cases is highest among individuals aged 16–30, with more than 2,400 reported cases, followed by the 31–45 age group. Children under 15 account for 243 cases, while the numbers decrease steadily in older populations. This trend indicates that adolescents and young adults are at the greatest risk for sustaining sports-related SCIs, likely due to higher levels of participation in high-impact or high-velocity athletic activities.*

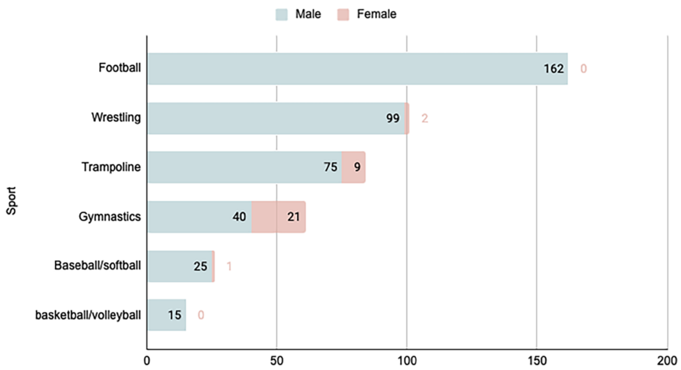

Figure 2. *Sports-Related Spinal Cord Injuries by Sport and Sex. This figure presents the number of sports-related SCIs reported to the NSCISC. Football accounts for the highest number of cases, and in most sports, males represent the clear majority. However, in gymnastics, the proportion of female cases is relatively higher compared with other sports.*

represent a meaningful subgroup that may need sport-specific prevention strategies.

The differences in the frequency and distribution of injury-causing sports between these two sources are likely due to differences in their analytical scope. The study by Carll *et al*. (3) focused exclusively on catastrophic spinal cord injuries occurring in high school, collegiate, and professional sports, whereas the NSCISC data include a broader range of spinal cord injuries across all age groups. In addition, the observed decline in severe sports-related spinal cord injuries in recent years may reflect the impact of improved safety regulations and increased awareness of spinal injury risks, which should also be taken into consideration.

Pathophysiology

While epidemiological data highlights the high incidence of SCI in youth sports, determining the severity and clinical outcomes of these injuries requires a closer look at the cellular and biological responses to spinal trauma. Spinal cord injury (SCI) can be classified according to the type and mechanism of neural damage. Based on the degree of pathway disruption, SCI is categorized as either complete or incomplete. A complete injury involves the total loss of motor and sensory function below the level of the lesion due to the absence of intact neural communication. In contrast, an incomplete injury preserves some neural transmission, allowing for partial sensation or voluntary movement below the affected segment (7).

Beyond classifying injuries by functional loss, it is also important to understand the biological changes that occur after injury.

The pathophysiological process of SCI involves two sequential phases: primary and secondary injury. The primary injury refers to the immediate mechanical insult to the spinal cord, which may include axonal shearing, hemorrhage, and tissue necrosis. This initial trauma directly disrupts neuronal integrity and vascular structures within the cord. The secondary injury develops over hours to days after the initial trauma and further amplifies tissue damage. It is characterized by inflammation, ischemia, excitotoxicity, intracellular calcium overload, and the production of reactive oxygen species (ROS). These mechanisms lead to neuronal apoptosis, demyelination, and the breakdown of neural networks responsible for sensory and motor function. As these secondary processes progress, chronic structural changes begin to appear, including glial scar formation and cystic cavity development (12). While the glial scar helps limit the spread of inflammation, it also inhibits axonal regeneration, restricting functional recovery (13). Understanding these pathological events has guided the development of early intervention strategies, such as neuroprotective agents, anti-inflammatory therapy, and experimental regenerative approaches.

These pathological features of SCI highlight its severity and indicate that some populations face greater risk. Notably, adolescents are susceptible to spinal cord injuries because their musculoskeletal systems are still developing. Incomplete ossification of vertebral structures and limited neuromuscular control may predispose them to greater risk of cervical injury during contact sports compared to adults. Studies of pediatric spinal anatomy also indicate that these anatomical characteristics are especially prominent in younger adolescents and children, contributing to an elevated risk of spine injuries in this age group (14). These developmental vulnerabilities underscore the need for targeted prevention strategies and age-appropriate management approaches, which will be discussed in the following section.

EMERGING TREATMENT STRATEGIES

Traditional medical care for spinal cord injury has tended to rely on surgery, corticosteroid treatment, physical therapy, and, in some cases, epidural electrical stimulation. Although these methods can stabilize the patient or provide temporary symptom relief, they do not regenerate damaged neural tissue. Given these limitations, recent research has increasingly focused on treatments that promote neural repair and functional recovery.

Recent literature describes four major categories of experimental approaches currently being explored for spinal cord injury (SCI): biomaterials, drug-delivery systems, electrical or mechanical stimulation, and cell-based therapies (Table 1). These strategies aim to create a more supportive biological environment that enhances neuronal survival, promotes tissue repair, and facilitates axonal regeneration. The following sections summarize the representative materials, mechanisms, and limitations of each strategy, drawing on insights from Bhatt *et al.* (15) and other recent studies.

Biomaterials

Biomaterials are being studied as a promising approach to support recovery after nerve injury. When nerves are damaged, the surrounding environment often becomes unfavorable for healing and limits the natural regrowth of nerve fibers. Biomaterials can help address this barrier by providing a stable structure that mimics the body's natural support system. This structure allows nerve cells to attach, survive, and extend new projections. These projections, called axons, are long, thin extensions that transmit signals between cells, and their regrowth is essential for restoring function. By providing both structural support and helpful biological signals, these materials can guide axons to grow across the injured area and help rebuild damaged nerve tissue. For this reason, such materials are considered an important approach in current nerve-repair research (16).

A study by Chen *et al.* (17) shows that biomaterials used for spinal cord injury repair can be broadly categorized into natural and synthetic types, each offering distinct advantages. Natural biomaterials, such as collagen, gelatin, chitosan, and hyaluronic acid, are derived from biological tissues and closely resemble the body's own extracellular matrix, making them highly biocompatible and supportive of cell attachment and growth. In contrast, synthetic biomaterials are artificially engineered and allow precise control over properties such as strength, structure, and degradation rate, although they often require additional surface modification to improve cell interactions. Hybrid materials that combine natural and synthetic components aim to balance biocompatibility with mechanical stability.

Despite these advantages, relying solely on biomaterials presents significant clinical challenges. Natural materials often degrade rapidly and vary between batches, which complicates standardized production. Conversely, synthetic materials can trigger immune responses in the body. Furthermore, matching the exact mechanical stiffness of the natural spinal cord is a major engineering difficulty, as materials that are too stiff can cause secondary compression to nearby healthy tissues (17).

Ultimately, biomaterials alone are rarely sufficient to achieve meaningful functional recovery after spinal cord injury. Although they provide important physical support and help stabilize the injured environment, they cannot replace lost neurons or supply the biological

Table 1. *Representative categories of emerging therapies for spinal cord injury. Summary of four major experimental approaches for SCI treatment—biomaterials, drug-delivery systems, electrical stimulation, and cell-based therapies—showing representative materials or techniques and their primary therapeutic functions. Abbreviations: PLGA = poly(lactic-co-glycolic acid); PCL = polycaprolactone; PEG = polyethylene glycol; rTMS = repetitive transcranial magnetic stimulation; CLV = closed-loop vagus nerve stimulation.*

Category	Representative Materials / Techniques	Primary Function
Biomaterials	Natural: Collagen, Gelatin, Chitosan, Hyaluronic acid Synthetic: PLGA, PCL, PEG Hybrid: Collagen + PLGA, Chitosan + PCL	Provide structural support and guide neural regeneration
Drug-Delivery Systems	Hydrogels, Polymeric Nanoparticles, Liposomes, Micelles, Exosomes	Enable localized delivery of therapeutic agents
Electrical Stimulation	Repetitive Transcranial Magnetic Stimulation (rTMS), Closed-Loop Vagus Nerve Stimulation (CLV)	Enhance neural signaling
Cell-Based Therapies	Bone marrow cells, Umbilical cord cells, adipose tissue-derived cells, embryonic cells, Neural stem cells / Mitochondrial transplantation	Replace damaged cells or restore cellular function

signals needed for regeneration. For this reason, most current research combines biomaterials with additional strategies such as stem cell transplantation, controlled drug delivery, or electrical stimulation.

Drug Delivery Systems

Drug delivery systems for spinal cord injury (SCI) are designed to deliver therapeutic molecules directly to the injured area in a controlled and long-lasting way. The main goal of these systems is to make treatments more precise and effective at the site of injury, overcoming the limitations of systemic drug administration, which often results in off-target side effects and poor penetration of the blood-spinal cord barrier.

Recent studies have shown that biomaterials such as hydrogels and engineered scaffolds can serve as carriers for drug delivery. These materials can be loaded with drugs, growth factors, or antibodies and release them slowly at the injury site, which helps reduce inflammation and supports tissue repair (18).

In addition to biomaterial-based carriers, other studies have explored nanoparticle and lipid-based systems such as liposomes and micelles. Because these particles are very small and their surfaces can be easily modified, they can move through biological barriers that larger molecules cannot. This allows them to deliver neuroprotective or anti-inflammatory drugs more precisely to the injured region of the spinal cord (19).

Recently, exosome-mediated drug delivery has gained attention as a potential treatment for spinal cord injury (SCI). Exosomes are tiny vesicles inside cells that normally carry proteins, lipids, and microRNAs. When used for therapy, they can transport these molecules directly to the injured area and help create conditions that support healing. Studies in animal models have shown that exosome-based delivery can reduce inflammation, protect nerve cells, improve blood vessel growth, and prevent cell death. Because exosomes can deliver therapeutic molecules precisely to specific target cells, many researchers now consider them a promising next-generation drug-delivery tool for promoting regeneration after SCI (18, 19).

Although biological delivery systems like exosomes offer high specificity and excellent biocompatibility, their application in clinical settings still faces major technical challenges. Currently, there is a lack of standardized methods for the extraction, purification, and efficient cargo loading of these vesicles. Furthermore, establishing consistent dosing, preventing rapid clearance from the injury site, and scaling up production remain primary barriers to regulatory approval and widespread clinical use (20).

Electrical and Mechanical Stimulation

Electrical and mechanical stimulation techniques are being explored as complementary strategies to enhance neural regeneration after spinal cord injury. These approaches aim to restore disrupted electrical signaling, promote axonal regrowth, and strengthen activity-dependent plasticity within damaged neural circuits.

One method involves the development of conductive biomaterials that can serve as both structural support and provide controlled electrical stimulation. Guo *et al.* (21) reported that conductive hydrogels, polymers, and nanocomposites help restore electrical communication across the lesion site while simultaneously supporting tissue regeneration. By combining physical support with electrical signaling, these materials can guide axonal recovery and improve functional outcome.

Another study by Benavides *et al.* (22) reviewed repetitive transcranial magnetic stimulation (rTMS), which uses magnetic pulses to activate neural pathways. Their findings indicate that rTMS can enhance neural plasticity in the spinal cord, leading to improvements in movement, reduced spasticity, and decreased pain. They also suggest that combining rTMS with neural cell transplantation may amplify therapeutic effects.

In addition, some studies have tested stimulation techniques that target nerves outside the spinal cord. Kilgard *et al.* (23) examined a method called closed-loop vagus nerve stimulation (CLV). The vagus nerve is a major nerve running from the brain to several organs, and it plays an important role in regulating many body functions. In this treatment, electrical pulses are delivered during specific motor actions. In a clinical trial, individuals who received CLV showed noticeable improvements in upper-limb strength, range of motion, and daily functional abilities.

Despite these promising results, these stimulation methods also present specific clinical challenges. Non-invasive techniques such as rTMS carry a risk of causing seizures and can produce mixed results depending on an individual patient's anatomy. On the other hand, invasive methods like closed-loop nerve stimulation require surgery, which increases the chances of infection, hardware failure, and additional tissue damage. Furthermore, finding the exact timing, frequency, and intensity of stimulation to maximize recovery without causing cell death from overstimulation remains a major challenge (22, 23).

Cell-Based Therapies

Cell-based therapies are being actively studied because they aim to restore damaged spinal cord tissue by adding new, healthy cells. Abraham *et al*. (24) reviewed recent clinical trials and reported that many types of stem cells—such as bone marrow, umbilical cord, adipose-derived, embryonic, and neural stem cells—are being tested for their potential to replace injured cells or release helpful molecules that support healing. Although most of these studies are still in the early stages, they show strong interest in the possibility of rebuilding neural tissue through cell transplantation.

Another new approach involves mitochondrial transplantation. Qin *et al*. (25) found that delivering healthy mitochondria to the injured spinal cord can improve cellular energy production, reduce inflammation, and help neurons survive. While it does not involve transplanting entire cells, mitochondrial delivery works toward the same goal of restoring cellular function.

Although replacing damaged tissue is theoretically promising, cell-based therapies face major safety and regulatory challenges. The inflammatory environment of an acute spinal cord injury (SCI) often leads to low survival rates for transplanted cells. Additionally, using stem cells carries a risk of uncontrolled cell growth, which can lead to tumor formation. Transplanting cells from a donor also usually requires long-term use of immunosuppressive drugs to prevent rejection, leaving patients more vulnerable to infections (24). While mitochondrial transplantation avoids whole-cell immune rejection, it still faces technical difficulties, such as efficiently delivering mitochondria into cells and keeping them alive outside the body (25).

Combined and Integrated Therapeutic Approaches

Recognizing that no single modality can overcome the complex pathology of SCI, recent research has shifted from examining the four approaches described earlier as separate strategies to developing combined or integrated treatment methods. Pairing cell-based therapies with electrical stimulation is one example, as electrical stimulation can enhance the activity while cell transplantation provides new cells that are required for regeneration (26). Another example of this combined approach is described by Chen *et al*. (27). Their study paired electrical stimulation with a medication that increases the excitability of nerve cells. Patients who received the combined treatment showed greater improvements in walking speed, endurance, sensory function, and corticospinal excitability compared with the control group (27).

Combining different treatments addresses the complex nature of spinal cord injuries better than using a single method. However, this approach also makes clinical application much more difficult. Testing the safety, potential combined side effects, and correct dosages of multiple treatments at the same time makes clinical trials and the FDA approval process highly complicated (28). Ultimately, no single approach among these four can be considered the most important, as meaningful recovery relies on their complementary effects. Therefore, future research is expected to advance toward integrated therapies that maximize these synergistic benefits, resolving the aforementioned limitations while ensuring strict safety and standardized clinical application.

PREVENTION AND EMERGENCY MANAGEMENT

Emergency On-Field Management

Sports-related spinal cord injury (SCI) is widely recognized as a major cause of trauma among young athletes, especially in high-impact sports such as football. These injuries have been documented steadily over several decades. Because such injuries often lead to severe and permanent neurological impairment, athletic programs and medical organizations have emphasized the need for strong awareness, preparation, and clearly defined emergency protocols during sports activities.

The guidelines outlined by Courson *et al*. (29) provide important context for understanding best practices for the initial management of suspected cervical spine injuries. These recommendations emphasize that, immediately after a suspected cervical spine injury, medical personnel must first secure the scene, stabilize the athlete's head and neck, and assess airway and breathing status. Airway access should usually be obtained by removing only the face mask, but if this is insufficient, helmet removal is also recommended. If high-quality chest compressions are indicated, removing the shoulder pads is also advised. These steps are intended to minimize spinal motion and should only be performed when enough trained responders are available.

The guidelines further specify that Spinal Motion Restriction (SMR) should be applied only when clear clinical indicators are present, such as altered consciousness after blunt trauma, spinal pain or tenderness, limited cervical range of motion, neurological symptoms affecting more than one limb, or visible deformity. Once stabilized, the athlete should be transported to a hospital capable of advanced imaging—

ideally within 30 minutes—to facilitate timely diagnosis and intervention.

Overall, Courson's protocol highlights how structured on-field procedures and consistent training help prevent secondary injury, reduce mortality risk, and improve outcomes, reinforcing the importance of preparedness and coordinated emergency response in youth sports settings.

Prevention Strategies

The most effective prevention strategy has been the modification of rules and tackling techniques to prevent axial loading. Axial loading occurs when the cervical spine is slightly flexed and a high-velocity impact is delivered directly to the crown of the head, causing the vertebrae to compress and potentially fracture or dislocate. To combat this primary mechanism of injury, strict rule modifications have been implemented. One of the most important steps in preventing SCI was the 1976 rule change that banned 'spearing'—the dangerous practice of using the top of the helmet as the initial point of contact in high school and college football. Similar rule modifications have proven crucial across other contact sports, such as the strict penalization of 'checking from behind' in ice hockey (30) and the restructuring of scrum engagement sequences in rugby (31), both of which significantly reduced catastrophic cervical injuries. However, recent epidemiological data emphasizes that while incidence rates have dropped historically, catastrophic spine injuries remain prevalent in school contact sports due to increased game speeds and persistent technique errors, highlighting that rule changes alone are insufficient (32). To continue this progress, various youth contact sports programs have introduced further regulations, such as severe penalties and automatic ejections for targeting defenseless players, forcing a continuous behavioral shift on the field.

Alongside rule enforcement, safety education programs play a crucial role. Programs such as 'Heads Up Football' emphasize proper tackling mechanics, training athletes to keep their heads up and make contact with their shoulders rather than their helmets, which has been shown to significantly reduce unsafe head impacts during play. A 2024 study on youth football safety highlights that the success of these programs heavily depends on the beliefs and self-efficacy of leaders and coaches. Therefore, educating these leaders and coaches to recognize and correct dangerous contact postures during practice is the critical first line of defense against cervical trauma (33).

Finally, while protective equipment standards are continuously updated by organizations like the National Operating Committee on Standards for Athletic Equipment (NOCSAE), their limitations regarding the spinal cord must be clearly communicated. Recent biomechanical research consistently shows that standard testing protocols for modern helmets emphasize cranial acceleration to prevent skull fractures and brain injuries, but fail to account for cervical spine load transmission (34, 35). Therefore, prevention strategies cannot rely on equipment alone. A comprehensive approach must integrate strict officiating, mandatory coaching education on safe contact techniques, and the presence of certified athletic trainers at youth sporting events to ensure a safe athletic environment.

Limitations and Future Direction

Despite advances in prevention and emergency management, a fundamental challenge remains: neurons of the central nervous system cannot spontaneously regenerate, making full recovery from SCI extremely difficult. Several promising research directions aim to address this problem. These include biomaterials that support axonal regrowth, drug-delivery systems that enhance the molecular environment for healing, stem cell transplantation to replace damaged neural tissue, and electrical or magnetic stimulation techniques designed to promote neuroplasticity. Although these strategies show potential, most remain in animal studies or early-phase human trials. As of 2025, nearly all clinical investigations are still in Phase I. Another limitation of the existing research is the lack of large-scale, long-term clinical trials that specifically focus on school-aged athletes, despite their heightened vulnerability to sports-related SCI.

Recent advances in artificial intelligence have accelerated early-stage drug discovery and predictive modeling, offering new hope that neuroregenerative therapies may emerge more rapidly in the future. Continued monitoring of developments in this area will be important as the field evolves. Future research should place greater emphasis on continuous monitoring of serious sports-related SCI cases, expand development of rehabilitation strategies tailored to youth athletes, and investigate how promising preclinical therapies might be combined to support better recovery outcomes.

CONCLUSION

While the overall incidence of sports-related spinal cord injury (SCI) in middle- and high-school athletes is relatively low, the potential for severe, lifelong disability demands a paradigm shift from reactive treatment to proactive prevention. Despite an overall decline in SCI incidence since the 1970s, adolescents aged 16–30 still account for nearly four times the cases of any other age group, reflecting both high sports participation and the anatomical immaturity of the developing spine.

To effectively address these risks, prevention strategies must recognize that protective equipment alone is insufficient, as modern gear can inadvertently transfer damaging forces directly to the cervical spine. Therefore, a comprehensive approach is required, integrating strict rule enforcement, proactive coaching education on safe contact mechanics, and the presence of qualified medical personnel at youth sporting events. Furthermore, when injuries do occur, structured on-field emergency protocols that emphasize spinal motion restriction (SMR) and rapid transport to capable medical facilities are essential to prevent secondary neurological damage.

Because current medical treatments focus primarily on stabilization and rehabilitation, research priorities must transition from conventional stabilization strategies toward restorative and regenerative therapies. Future investigations should specifically focus on translating promising preclinical modalities, such as targeted biomaterial drug-delivery systems, neuromodulation via electrical stimulation, and cellular therapies, into robust clinical trials. Crucially, these advanced treatments must be investigated and optimized for the unique neurodevelopmental physiology of the adolescent spinal cord. Ultimately, bridging the gap between experimental neuroregeneration and accessible clinical applications stands as the most critical mandate for the future of adolescent SCI management.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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