Current Concepts Review

Catastrophic Sports Injuries

Causation and Prevention

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➤ Catastrophic injuries in U.S. high school and college athletes are rare but devastating injuries.

➤ Catastrophic sports injuries are classified as either traumatic, caused by direct contact during sports participation, or nontraumatic, associated with exertion while participating in a sport.

➤ Football is associated with the greatest number of traumatic and nontraumatic catastrophic injuries for male athletes, whereas cheerleading has the highest number of traumatic catastrophic injuries and basketball has the highest number of nontraumatic catastrophic injuries for female athletes.

➤ The incidence of traumatic catastrophic injuries for all sports has declined over the past 40 years, due to effective rule changes, especially in football, pole-vaulting, cheerleading, ice hockey, and rugby. Further research is necessary to reduce the incidence of structural brain injury in contact sports such as football.

➤ The incidence of nontraumatic catastrophic injuries has increased over the last 40 years and requires additional research and preventive measures. Avoiding overexertion during training, confirming sickle cell trait status in high school athletes during the preparticipation physical examination, and developing cost-effective screening tools for cardiac abnormalities are critical next steps.

Sports participation has many physical, psychological, and social benefits. However, there is always the risk of a rare but devastating catastrophic injury. For the purpose of this review, catastrophic sports injury is defined as any severe spinal, spinal cord, cerebral (excluding concussion), or internal organ injury or systemic failure incurred while participating in a sport in the United States unless otherwise specified[1]. Traumatic catastrophic injuries (e.g., spinal or structural brain injury) are caused by direct contact. Nontraumatic catastrophic injuries result from sports-related exertion (e.g., sudden cardiac death, exertional heat stroke, exertional red blood-cell sickling)[1,2]. The mechanisms for nontraumatic catastrophic injuries tend to be consistent across sports, whereas traumatic catastrophic injury mechanisms tend toward being sport-specific. Both types of injuries can be fatal.

Catastrophic sports injuries occur more frequently in male athletes (Table I), currently tend to be nontraumatic (Fig. 1), and cluster in specific sports (Table I)[1]. For U.S. high school and college athletics, U.S. football (referred to in this article as "football") is associated with the greatest number of traumatic and nontraumatic catastrophic injuries in male athletes (Table I)[1,3,4]. For female athletes, the greatest number of traumatic catastrophic injuries are associated with cheerleading and the greatest number of nontraumatic catastrophic injuries are associated with basketball (Table I)[1,5]. Although sports-related traumatic catastrophic injuries have declined over the past 40 years, both in number and incidence, nontraumatic catastrophic injuries have been rising (Fig. 1)[1]. From 2016 to 2021, nontraumatic injuries were 1.5 to 2.3 times higher, on average, than traumatic catastrophic injuries[1] (Table II). Although the total

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TABLE I High School and College Catastrophic Injuries in 1982-1983 through 2020-2021*

	High School		College	
	Traumatic	Nontraumatic	Traumatic	Nontraumatic
All sports†	1,423	820	326	257
Male	1,291 (90.7%)	721 (87.9%)	302 (92.6%)	218 (84.8%)
Female	132 (9.3%)	99 (12.1%)	24 (7.4%)	39 (15.2%)
Male sports‡				
Football	991 (76.8%)	319 (44.2%)	223 (73.8%)	95 (43.6%)
Female sports‡				
Cheerleading	69 (52.3%)	12 (12.1%)	0 (0%)	0 (0%)
Basketball	7 (5.3%)	22 (22.2%)	1 (4.2%)	8 (20.5%)

*These data are obtained from Tables 9 and 10 in the 2021 National Center for Catastrophic Sport Injury Research Annual Report[1] †The percentage is the number of injuries for that sex divided by the number of injuries for all sexes (the All sports row) ‡Information is shown for the sports with the greatest number of traumatic injuries (football and cheerleading) and nontraumatic injuries (football and basketball) for each sex. The percentages are relative to the numbers for that gender. For example, female cheerleading had 69 traumatic injuries at the high school level, which is 52.3% of the 132 female traumatic injuries at this level of play.

number of injuries was 2.7 times higher in high school, compared with college, the incidence was 5.7 times higher for college athletes from 2016 to 2021 due to the higher participation in high school sports (Table II)[1].

Sports fatalities[6,7] are primarily caused by sudden cardiac death, structural brain injury, and exertional heat stroke (Fig. 2)[3,6-8]. The mean fatality incidence has been 3.8 to 7.1 times higher for nontraumatic injuries, compared with traumatic injuries (2016 to 2021)[1] for all U.S. high school and college sports (Table II). The highest number of traumatic and nontraumatic fatalities occur in football[1,3]. Since the 1960s, the incidence of traumatic football fatalities has declined fourfold to fivefold (Fig. 3)[9]. Conversely, the incidence of nontraumatic football fatalities has remained constant, with current (2000 to 2018) rates higher than traumatic fatalities at 2 times for high school levels and 4 times for college levels[9]. Thus, prevention strategies for traumatic injuries and fatalities are effective, but greater efforts are necessary to prevent nontraumatic injuries and fatalities.

This review summarizes the advances that likely contributed to the decline in catastrophic injuries over the last 40 years. These advances are being accomplished through surveillance, a better understanding of injury mechanisms, subsequent educational efforts, protective policy changes, and equipment redesigns (Table III). This review focuses on U.S. high school and college sports, where clear epidemiological studies fostered

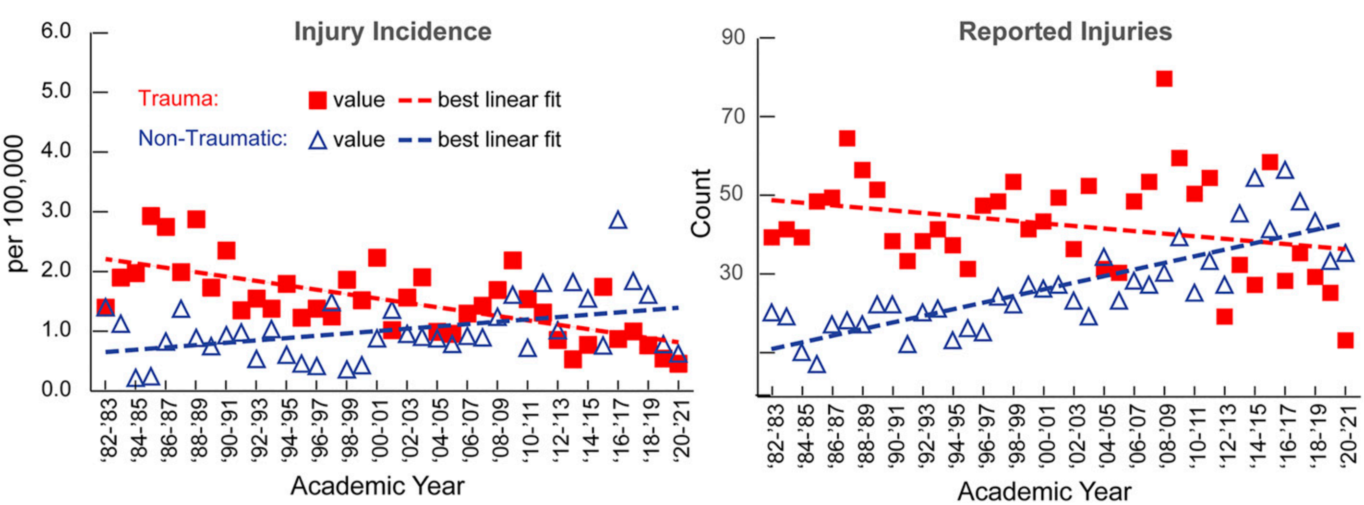

Fig.1

Reported injuries for high school athletes (based on Tables 7 and 8 in the 2021 National Center for Catastrophic Sport Injury Research [NCCSIR] Annual Report[1]). *Left:* Incidence per 100,000 for all injuries (fatal, nonfatal, and serious), averaged for high school. *Right:* Number of reported injuries, summed for high school.

TABLE II Ratio of Nontraumatic to Traumatic Injuries from 2016-2017 to 2020-2021*

	High School					College				
	Traumatic		Nontraumatic		Ratio of Nontraumatic to Traumatic Injuries	Traumatic		Nontraumatic		Ratio of Nontraumatic to Traumatic Injuries
	No. of Injuries	Incidence/ 100,000	No. of Injuries	Incidence/ 100,000		No. of Injuries	Incidence/ 100,000	No. of Injuries	Incidence/ 100,000	
All injuries	106	0.28	154	0.41	1.5	29	1.17	66	2.68	2.3
Fatalities	17	0.05	64	0.17	3.8	3	0.12	21	0.85	7

*Data are from the most recent 5 years available, as reported in Tables 9 and 10 of the 2021 National Center for Catastrophic Sport Injury Research Annual Report[1].

rule changes and follow-up studies have evaluated their effectiveness.

Catastrophic Nontraumatic Sports Injuries

Sudden Cardiac Death

Sudden cardiac death is the leading cause of death across all sports (incidence, 0.6 to 2.9/100,000 in high school and college athletes)[1,3,8,10-14]. The majority of cases occur in males (84%)[10], most frequently during basketball, soccer, and football[8,10-13]. Hypertrophic cardiomyopathy is the most commonly reported etiology of sudden cardiac death in athletes <35 years of age[15-18]. However, some fatalities thought to be hypertrophic cardiomyopathy may be due to other causes (e.g., unexplained autopsy-negative sudden death, myocarditis, and coronary arthrosclerosis)[11,18].

The foundation of cardiac disease screening remains a complete personal and family history and physical examination[18,19]. Preparticipation cardiac screening should be performed prior to training and competition. In the National Collegiate Athletic Association (NCAA), guidelines[19,20] have recommended repeating such screening annually. At the high school level, each state sets its own requirements[21].

The role of electrocardiography in preparticipation screening is controversial[18]. An 89% decrease in athlete sudden cardiac death was demonstrated after instituting screening including 12-lead

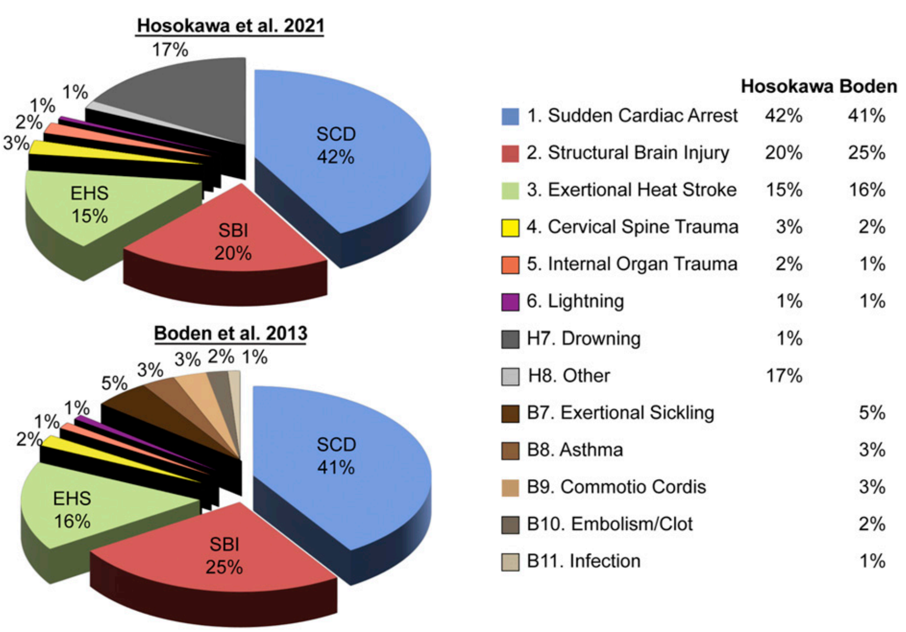

Fig. 2

Causes of fatalities by diagnosis in Japanese middle school and high school sports[7] (top) and American high school and college football[3] (bottom). Both studies showed fatalities from injury categories labeled 1 to 6 (shown on the pie chart as the pieces separated from their neighbors). Injury categories labeled H7 and H8 were only reported in the study by Hosokawa et al.[7], and 17% of the fatalities in that study were uncategorized. Injury categories labeled B7 to B11 were only reported in the study by Boden et al.[3]. Despite the 2 studies evaluating very different populations (United States compared with Japan), levels of play (middle school and high school compared with high school and college), and sports (27 varied sports compared with American football), all injury categories leading to fatalities are within 1 percentage point of each other except structural brain injury (SBI) (5 percentage point difference). EHS = exertional heat stroke, and SCD = sudden cardiac death.

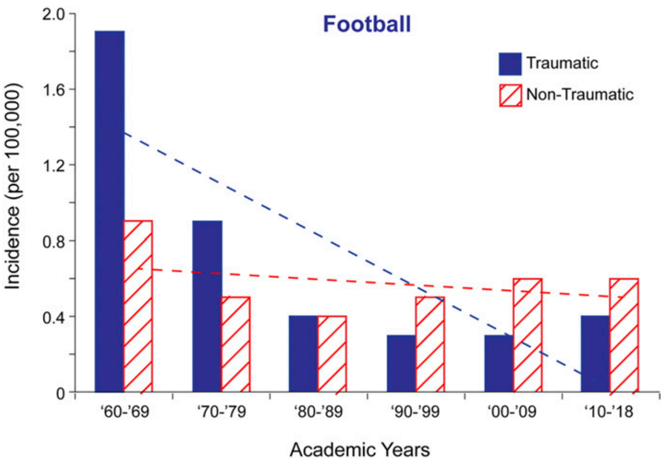

Fig. 3
Incidence of traumatic and nontraumatic football fatalities in high school football by decade, 1960 to 2018. The dotted lines are the linear best-fit lines for each injury type by year. (Adapted from: Boden BP, Fine KM, Breit I, Lentz W, Anderson SA. Nontraumatic exertional fatalities in football players, part 1: epidemiology and effectiveness of National Collegiate Athletic Association bylaws. Orthop J Sports Med. 2020 Aug 19;8(8): 2325967120942490[8], published by Sage under Creative Commons License CC BY-NC-ND 4.0.)

electrocardiography interpreted by physicians[22]. However, electrocardiographic screening has been criticized for false-positive results, unnecessary disqualifications, and lack of cost-effectiveness[23,24]. Although electrocardiographic screening is employed by most professional leagues, there are no mandatory universal electrographic screening recommendations for nonprofessional U.S. athletes. Cardiac screening tests, with higher sensitivity rates and improved cost-effectiveness, at the nonprofessional levels are critical next steps for reducing sudden cardiac death[18,25].

In the event of sudden cardiac arrest, the survival rate is highest (89% in 1 study[26]) when cardiopulmonary resuscitation (CPR) and an automated external defibrillator are readily available for use within 1 to 3 minutes[3,6,27-31]. For each minute of delay, the survival rate decreases approximately10%[6]. Along with automated external defibrillator availability, a documented emergency action plan, regularly rehearsed and reviewed prior to competitions, is critical for minimizing deaths[28,32].

Exertional Heat Stroke

Exertional heat stroke remains a persistent problem across several sports[6,33,34]. For the NCAA, it was the third greatest sports-related cause of death from 2002 to 2011[9,13]. In football, the primary sport in which these deaths occur, exertional heat stroke has been recognized since the 1950s, with a mean of 1.9 fatalities per year from 1990 to 2010[3]. In 2003, the NCAA mandated the out-of-season model with acclimatization rules for the first 5 days of preseason football practices that placed restrictions on the equipment worn and the duration and number of practices[35]. However, the NCAA's 5-day acclimatization period failed to substantially reduce football-related exertional heat stroke fatalities[8]. Even as high schools adopted similar strategies intended to prevent exertional heat stroke, the overall number of exertional heat stroke fatalities increased to 2.4 per year (2017 to 2021), with a peak of 9 deaths in 2021[1].

A recent report[9] identified several important risk factors for football exertional heat stroke fatalities (Table IV), including overexertion during conditioning and training sessions. This usually involves high-intensity drills, exertion as

TABLE III Grades of Recommendation: Summary of Effective Prevention and Treatment Strategies

Sport	Prevention Strategy	Grade of Recommendation*†
Any sport, sudden cardiac arrest	Automated external defibrillator[6,27,30,31]	C
Football, exertional sickling with sickle cell trait	Sickle cell trait screening with targeted education[8]	C
Football, structural brain injury	Improved football helmet[52]	C
Football, cervical spine injury	Ban on spear tackling[60]	C
Pole-vaulting	Increase in minimum dimensions of landing pad[69]	C
Cheerleading, pyramid	Limit height of pyramid, sufficient spotters[5]	C
Cheerleading, basket toss	Hardwood court basket toss ban; mat requirement[74]	C
Baseball	Regulations on bat[1,76]	C
Ice hockey	Ban on checking from behind near boards[98]	C
Rugby	Sequential or uncontested scrum[105,106,112,113]	C
Any sport, commotio cordis	Automated external defibrillator[83,91]	C

*According to Wright[116], grade A indicates good evidence (Level-I studies with consistent findings) for or against recommending intervention; grade B, fair evidence (Level-II or III studies with consistent findings) for or against recommending intervention; grade C, poor-quality evidence (Level-IV or V studies with consistent findings) for or against recommending intervention; and grade I, insufficient or conflicting evidence not allowing a recommendation for or against intervention. †All studies were Level-IV (Grade C) cohort studies due to the unethical nature of performing randomized studies on potential catastrophic injuries.

punishment, or conditioning tests[9], all with no consideration of body habitus (obesity), the demands of the position played, and baseline fitness level[9]. Linemen are the at-risk population and constitute 97% of cases (34 of 35)[9]. Common scenarios involve coaches pushing players to complete excessive conditioning and toughness drills despite demonstrating signs of a medical crisis[9]. In 2 case reports of an exertional heat stroke fatality in football, linemen (mean body mass index [BMI], 33.7 kg/m^2) were required to run repetitive sprints that were 68.5% higher than the safe suggested starting speed[36]. The pattern is similar to overexertion exercise programs resulting in rhabdomyolysis, exertional sickling, and other nontraumatic exertional syndromes[37-40].

Historic exertional heat stroke prevention strategies in football (e.g., avoiding a full uniform, limiting the number [1 to 2] and duration [2 to 3 hours] of practices per day, practicing in a safe climate, and an emphasis on hydration) alone have limited effectiveness in reducing exertional heat stroke death in high school and college football, as exertion intensity and the at-risk population (lineman) are not addressed[9]. A large athlete with a high body-fat percentage can die during a brief conditioning session from no more than 10 repeat sprints, even without wearing protective equipment[9]. Although heat and humidity are important risk factors and critical components in a prevention strategy, exertional heat stroke has been reported in many athletes when the maximum daily temperature was below 90°F (32.2°C)[9,41,42]. A paradigm shift is recommended, with the focus changing from the uniform worn and dehydration to the population at risk (linemen) and exertion intensity (Table V), which are the primary determinants of heat production and subsequent fatalities[9]. Exertional heat stroke is preventable by tailoring training and conditioning to be sport-specific and position-specific based on competition demands. Exercise programs must be established on the basis of exercise science principles, BMI[36], or a 50/30/20/10 reduction in training at the beginning of the season (the first week of training is reduced by 50% of the highest conditioning volume on file for the individual and is adjusted accordingly in subsequent weeks) (Table V)[8,9,28,32,36,43,44].

TABLE IV Risk Factors for Exertional Heat Stroke in Football

High-intensity exertion and/or overexertion[9,40]
Excessive conditioning and/or sprinting in relation to game demands
Fitness or conditioning tests (timed runs, especially during preseason)
Conditioning as a team
Failure to accommodate position-specific game demands
Failure to accommodate for body habitus
Failure to accommodate for medical conditions (ES)[6]
Improper conditioning sessions
100% of exertional heat stroke and ES deaths in 1 report[9]
Linemen[9]
Body habitus: large body with high percentages of both lean muscle mass and body fat
Exercise as punishment[9]
Transition period (preseason, offseason, return after injury)[9]
Lack of knowledge of baseline fitness[36]
Culture of football[9]
Focus on toughness rather than exercise physiology
Medical personnel being employees of the university and/or coaching staff[9]

Exertional Sickling with Sickle Cell Trait (ES)

The primary cause of ES is sustained intense exertion in athletes with 1 abnormal sickle gene[9]. ES potential exists in all populations, but predominantly occurs in African American athletes[45]. Athletes with the sickle cell trait have a 10 to 37 times higher risk of sudden death compared with athletes without the sickle cell trait[8,9,45,46].

From 1998 to 2010, there were 10 deaths due to ES in NCAA Division-I football[3]. In response, in 2020, the NCAA mandated preparticipation sickle cell trait status identification for all Division-I athletes via testing or prior testing documentation, or signing of a waiver[32]. This rule promoted sickle cell trait awareness, provided targeted education and physician counseling during the pre-participation physical[47], and tailored precautions during conditioning[3,48]. The primary precaution is diminished exercise intensity, especially in the presence of modifiers (e.g., ambient heat stress, newness to altitude, uncontrolled asthma)[49,50]. Subsequently, NCAA Division-I football deaths declined 84% (0.83 to 0.13 per year) (Fig. 4)[6,9]. The NCAA eliminated the waiver option in 2022[51]. There are no mandatory testing requirements for high school sports, where the risk of ES fatalities increased 3.5-fold since 2010[9]. Based on the NCAA's success, college guidelines for ES are recommended at the high school level[8].

Catastrophic Traumatic Sports Injuries

Football: Structural Brain Injuries

From 1945 to 1975, there were a mean of 9.5 brain injury-related fatalities annually in high school and college football[1,52,53]. This decreased to 5 per year in the 1980s[54] and then to 3 per year in the 1990s and early 2000s[3]. This reduction was most likely due to improvements in football helmet design, which have been associated with a lower prevalence of skull fractures, and due to advances in game-day medical coverage and treatment for major brain injuries[52-54].

In high school and college football (1989 to 2002), structural brain injuries were 3.5 times more common during games than during practices, with a disproportionate number occurring during special teams' plays[53,55]. Over 50% of athletes with a structural brain injury had a prior concussion, with 71% of the prior concussions occurring within the same season as the catastrophic event[53]. Responding to the risk of structural brain injury after incomplete recovery, Washington State passed the Lystedt Law in 2009, requiring any youth athlete demonstrating concussion symptoms to be examined and cleared by a licensed health-care provider before return to play[53]. Within 5 years, all

TABLE V Prevention Strategies for Exertional Heat Stroke in Football

Conditioning programs based on exercise science[9,36]
Conditioning consistent with game demands for each position
Conditioning based on individual fitness level, when known[36]
Performance tests (e.g., timed miles) should be avoided, as they lack sensitivity to fitness and specificity to sport[9]
Conditioning programs should be developed in conjunction with an exercise physiologist or health-care personnel[32]
Work levels should range from 50% to 85% of the maximum level[36]
Work to rest ratios should be no greater than 1:5 for sprints lasting <15 seconds (phosphagen system)[36]
Work to rest periods should be no greater than 1:4 for sprints lasting between 15 and 30 seconds (anaerobic glycolysis)[36]
Submaximal aerobic conditioning at distances over 1 to 2 minutes requires a recovery period of at least 3 minutes[36]
Conditioning programs should be adjusted for individuals with medical conditions[6,9,32]
Linemen should receive separate conditioning programs than skill players[9,36]
Linemen rarely run >30 to 40 yards (>27 to 36.5 meters) during a game with 35 to 55-second breaks and should not be required to exceed these demands during practice sessions[9,36]
Linemen should not be required to run serial sprints exceeding game requirements[9]
Consider training linemen in air-conditioned venues in hot and/or humid conditions
Exercise should never be employed as a punishment drill[9,32]
Transition periods lasting a minimum of 7 to 10 days are required to acclimatize with decreased intensity of training (reduced work to rest ratios)
The 50/30/20/10 conditioning rule provides guidelines during transition periods; the first week of training is reduced by 50% of the highest conditioning volume on file for the individual and adjusted accordingly in subsequent weeks[43]
When the prior fitness level is unknown, BMI or grouping by body habitus can provide an estimate of baseline fitness and a foundation for prescribing safe exercise regimens[36]
Adjust exertion to heat and humidity[44]
The culture in football needs to change from teaching mental toughness to developing rational conditioning based on exercise science[9,36]
Educating team coaches, strength and conditioning coaches, athletic trainers, physicians, and administrators on risk factors and proper conditioning programs
Educational efforts, in collaboration with the NCAA, NFHS, and other sports organizations, are necessary to disseminate appropriate conditioning information
Conditioning programs should be available for review on request[32]
Compliance with current athlete health and welfare policies and consensus statements that include safe environmental conditions for conditioning[28]
Health-care workers should be independent from the coaching staff, to allow autonomy with medical care and authority to intervene if punishment drills are suspected[9,36]

50 states and the District of Columbia adopted the Lystedt Law's core principles. Despite the Lystedt Law and the NCAA targeting rules in 2008, a marked increase in structural brain injuries and fatalities was reported from the 1989 to 2002 period[53] to the 2002 to 2020 period, with no change in incidence within the 2002 to 2020 period[56].

This increase in structural brain injuries and fatalities may be due to more structural brain injuries occurring during the initial brain injury (without a prior predisposing concussion) and/or poor compliance with concussion reporting and medical clearance[56]. Alternatively, there may have been an increase in the rate of other risk factors such as undiagnosed inherent abnormalities that predispose to a brain bleed (e.g., brain aneurysms and bleeding disorders) or failure to enforce rules of play designed to reduce risk[56]. This trend reversal is concerning and warrants further research, particularly regarding why the new rules and education are not having the intended effect[56].

Football: Cervical Injuries

In the United States, approximately 7% to 10% of all new cases of spinal cord injury are secondary to athletic activities[57], with football having the highest number[1,4,58]. After the improved modern football helmet was introduced, the number of quadriplegic events increased, peaking at 34 cases in 1976[59]. These events were caused by an axial cervical spine compression injury resulting from spear tackling[59,60]. The 1976 ban on spear tackling[59] substantially reduced quadriplegia injuries, which dropped to 6 per year on average (1989 to 2002)[54,58,59]. Nonetheless, quadriplegic events persisted[58]. Thus, the NCAA in 2005 and the National Federation of State High School Associations (NFHS) in 2007 strengthened the spear-tackling rule[61], as penalties for spear tackling were rarely called[61,62]. Although preliminary data revealed a slight drop in catastrophic cervical injuries since the most recent rule change[54], the key to further prevention is renewed educational efforts (e.g., teaching proper tackling

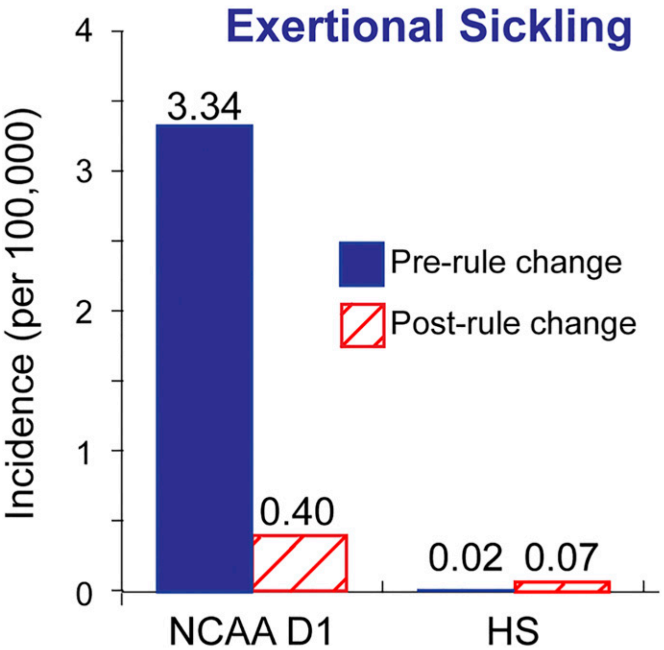

Fig. 4
Fatality incidence per 100,000 athletes due to exertional sickling with sickle cell trait (ES), in NCAA Division 1 (D1) athletes and high school students (HS), before and after the NCAA 2010 sickle cell trait screening policies. (Adapted from: Boden BP, Fine KM, Breit I, Lentz W, Anderson SA. Nontraumatic exertional fatalities in football players, part 1: epidemiology and effectiveness of National Collegiate Athletic Association bylaws. Orthop J Sports Med. 2020 Aug 19;8(8):2325967120942490[8], published by Sage under Creative Commons License CC BY-NC-ND 4.0.)

techniques) and rule enforcement[61]. In response to the disproportionate number of catastrophic cervical[58] and brain[53] injuries during special team plays, the National Football League (NFL) and NCAA (2011)[63] moved the kickoff 5 yards (4.6 meters) forward to reduce injuries during kickoff returns. Preliminary (college) results revealed a sharp decline in the number of concussions during kickoffs[63]. However, definitive data on catastrophic injuries have been lacking.

Cervical cord neurapraxia is an acute, transient neurologic episode due to spinal cord trauma[59,64] involving hyperextension[59], hyperflexion, or excessive axial loads[58]. The incidence ranges from 1.3 to 6/10,000 athletes and is most common in football[64]. A cervical cord neurapraxia episode is not an absolute contraindication to return to play[59]. The overall risk of a recurrent cervical cord neurapraxia episode following return to play is approximately 56% and is correlated with canal stenosis[59]. To our knowledge, there have been no reported cases of quadriplegia following cervical cord neurapraxia. However, due to the low number of players returning to football after cervical cord neurapraxia and the extremely small risk of quadriplegia, a definitive statement concerning risk cannot be made[58]. Although the risk is likely quite low, at least 2 players sustained an incomplete permanent neurologic deficit after return to play following a cervical cord neurapraxia episode[54,58]. Thus, individualized counseling on the known and potential risks when returning to football after cervical cord neurapraxia is recommended.

Recent consensus statements[65,66] on the pre-hospital care of the spine-injured athlete emphasize the importance of the emergency action plan, a pre-event medical timeout, scene control, and knowledge of athletic equipment removal and spinal motion restriction techniques[65]. Airway access should always be achieved prior to transport[65,67]. In cases where CPR and/or an automated external defibrillator are necessary, new recommendations allow for removing the helmet and shoulder pads, and not just the face mask, prior to transport[65,67].

Pole-Vaulting

Prior to 2003, pole-vaulting had the highest incidence of traumatic catastrophic injury and the second highest number of fatalities across high school and college sports[68]. From 1982 to 1998[68], 97% of injuries resulting in a structural brain injury led to either a fatality (50%) or permanent neurologic disability. The primary injury mechanism (69%) was the vaulter's body landing completely or partially off the landing pad, resulting in the head striking the surrounding hard surface (asphalt or concrete). The second most common mechanism (25%) was the vaulter landing in or around the vault box[13]. Therefore, the NCAA, NFHS, and USA Track & Field mandated new rules in 2003. The most important rule was a 68% increase in the minimum landing pad dimensions behind the vault box[69], with all hard surfaces adjacent to the landing pad removed or padded (with a minimum 2 inches [5.08 cm] of dense foam)[69].

Comparing 17-year epochs (Fig. 5), the annual number of catastrophic pole-vault injuries declined 88% from the pre-rule change (1986 to 2003) of 0.94 per year, compared with the post-rule change (2003 to 2020) to 0.12 per year. These rule changes have likely saved approximately 17 lives since the rule change (2003 to 2023), with no fatalities over the last 13 years[69].

Despite the dramatic reduction in fatalities, the mean number of catastrophic injuries from landing in the vault box area increased from 0.5 per year (1982 to 1998) to 1.6 per year (2003 to 2011)[68,69], with 1 fatality. In a survey study, 80% of vaulters reported landing in or directly around the vault box during their career[70]. An inspection of 533 vault boxes and 4,512 pole-vault poles revealed that 97% of the vault boxes would likely result in a fatal injury if an unprotected fall from 12 feet and 5 inches (3.71 meters) occurred[71]. In addition, 41% of the vault boxes had an elevated front lip, which can cause the vaulter to lose his or her grip, and 96% of the poles demonstrated degradation from rubbing against the vault box, which can result in pole breakage[70,71]. Therefore, new vault boxes were developed to improve shock absorption, reduce pole abrasion, and ensure that the front lip is flush with or lower than the runway. The effectiveness of these new vault boxes is currently being investigated.

Cheerleading

The majority of high school and college catastrophic cheerleading injuries (1982 to 2002) have resulted from pyramid and basket toss maneuvers[5,72]. A location at the top of a pyramid and poor flyer (thrown athlete) spotting[5,73] were the largest risk factors. Half

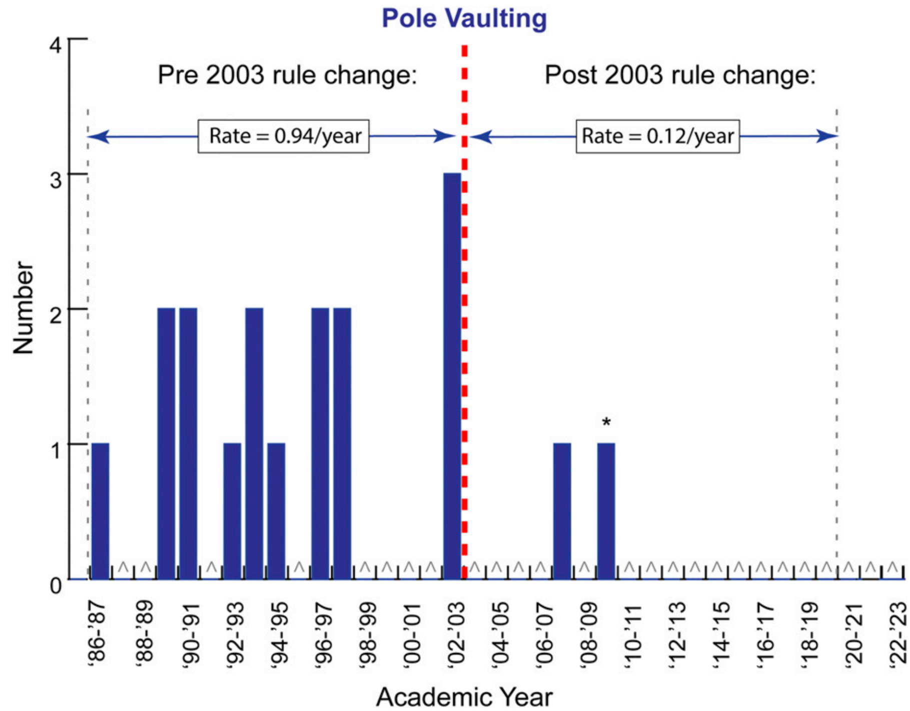

Fig. 5

Number of direct pole-vaulting fatalities per year in high school and college athletes in the 1986-1987 through 2022-2023 academic years. The dotted red line indicates the 2003 rule changes. ^No fatalities occurred in this academic year. *This fatality involved noncompliance with the 2003 rule change. Comparing equal 17-year time periods, the annual incidence dropped 88% from 0.94 in the period before the rule change (1986 to 2003) to 0.12 in the period after the rule change (2003 to 2020). When the post-rule-change period is extended to 20 years (2003 to 2023), the annual rate decreased to 0.10. No fatalities have been reported since the 2010-2011 academic year. (This figure incorporated data from the previous articles by Boden et al.[68,69], with 2018 to 2023 data provided by Jan Johnson at the National Pole Vault Safety Center.)

of the injuries occurred indoors on hard gym surfaces without a soft landing mat[5]. The number of catastrophic injuries rose in the 2000s, with a peak of 10 injuries per year (2005-2006) (Fig. 6)[74,75].

In the early 1990s, the NFHS and USA Cheer restricted the height of pyramids to 2 body lengths in high school and 2.5 body lengths in college[5]. After the rise of injuries in the early 2000s, the governing bodies implemented several additional safety measures in 2006 to 2007. The most important rule eliminated performing the basket toss on any hardwood court unless it was on a mat (minimum thickness 1⅜ inches [3.49 cm]) and during the halftime or postgame (i.e., not during high-risk, quick timeouts) in an area free of obstruction[76]. In the same year, USA Cheer mandated 2 spotters for each individual at the 2.5-person height in a pyramid in college cheerleading.

Since the 2006 to 2007 rule changes, there has been a 63% overall reduction in the number of catastrophic basket toss injuries (Fig. 6)[75]. Impressively, there have been no collegiate basket toss injuries reported since the rule change[1,75]. For high school, the number of basket toss injuries declined from 2007 to 2010, with no injuries over the last 11 years of reported data (2010 to 2021)[1,75].

Baseball

The majority of catastrophic high school and college baseball injuries were structural brain injuries, followed by cervical injuries, commotio cordis, and facial fractures[77,78]. Collisions between fielders or between a base runner and a fielder, typically the catcher, were the most common mechanisms[77]. Runners diving headfirst, especially at home plate, were at risk for an axial compression cervical injury, potentially resulting in quadriplegia[77]. After identifying this mechanism, the NFHS mandated that runners are not allowed to collide with the catcher[77].

A batted ball hitting the pitcher was the next most common catastrophic injury mechanism[77]. A ball hit by an aluminum bat was responsible for all injuries to pitchers[77]. This raised concerns with regard to non-wooden bats, because they may be lighter and more compliant, resulting in a higher ball exit velocity[79]. In 2003, the NCAA and NFHS mandated bat certification, ensuring that the bat cannot weigh >3 ounces (>85 grams) less than the length of a bat (e.g., a 34-inch [86-cm] bat cannot weigh <31 ounces [85 grams])[77]. Later, the NCAA in 2011 and the NHFS in 2012 strengthened the bat rules, ensuring that non-wooden and wooden bats perform comparably. Additionally, protective L-screens during batting practice, helmets, and decreased ball hardness and weight may reduce injury severity[77,80]. The mean number of catastrophic traumatic injuries declined in both high school (2.8 to 1.3 per year) and college (1.5 to 1.0 per year) between the periods before (1985 to 2011) and after (2014 to 2021) the bat rule change[1,77].

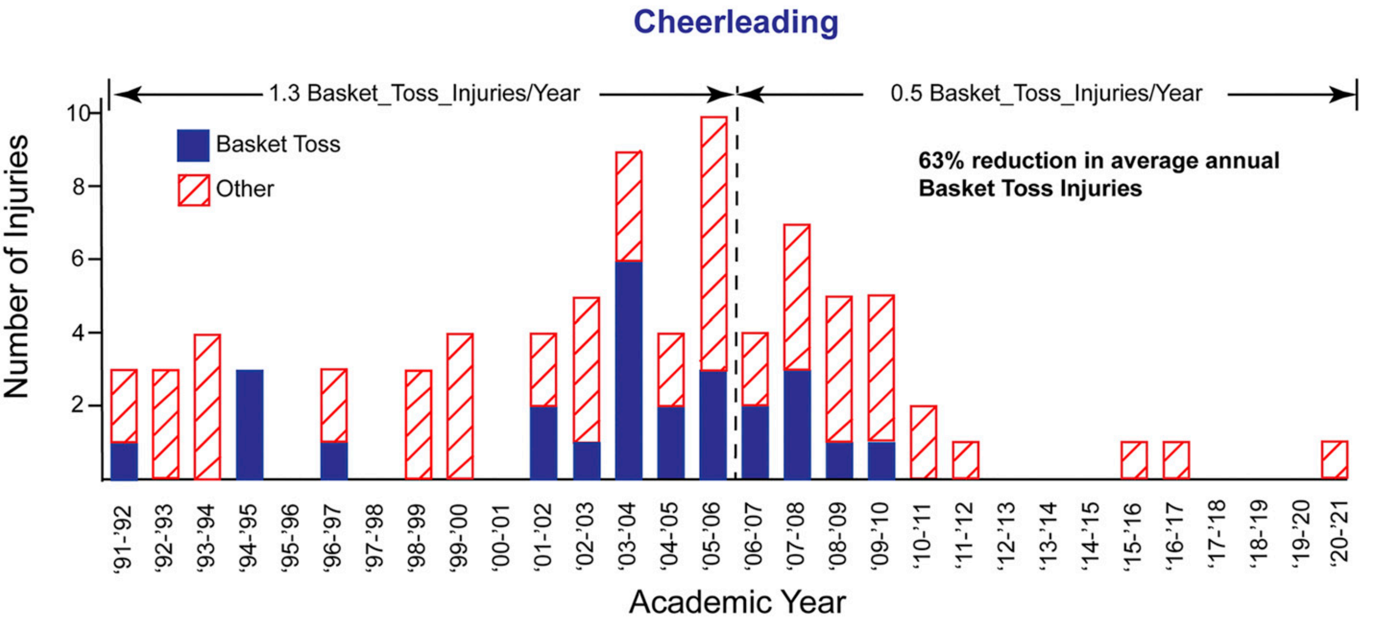

Fig. 6

Catastrophic cheerleading injuries from 1992 to 2020. The 15 years after the major rule changes demonstrated a 63% reduction in the rate of basket toss injuries, compared with the 15 years prior. No catastrophic basket toss injuries have occurred after the 2009-2010 academic year. (This figure incorporated data from the previous articles by Boden et al.[5] and Yau et al.[75] and from Cheerleading Safety Data and Research - USA Cheer, with data for the 2017-2018 through 2020-2021 academic years derived from personal conversation with Jim Lord at USA Cheer.)

Commotio cordis causes arrhythmia or sudden death from low-impact blunt trauma to the chest in individuals with no preexisting cardiac disease[81-83]. The condition occurs most frequently in baseball, but is also reported in lacrosse, softball, football, rugby, and other sports[84-87]. The proposed mechanism is impact just prior to the T-wave peak, inducing ventricular fibrillation. The pediatric population may be most susceptible because of a thinner soft-tissue layer in the chest wall, increased rib cage compliance, and slower protective reflexes[84]. The use of chest protectors and safety balls show promise in reducing the risk of commotio cordis[83,88-91]. Both the NFHS in 2020 and the NCAA in 2021 have mandated chest protectors meeting the National Operating Committee on Standards for Athletic Equipment (NOCSAE) standards for all catchers and players at other positions choosing to wear chest protectors. Automated external defibrillators are the most successful technique for resuscitating athletes with commotio cordis and increasing survival rates[82,83,92-94].

Ice Hockey

Although the number of catastrophic cervical injuries in Canadian ice hockey is lower than that in football, the incidence is 3 times higher[95,96]. Ice hockey injury studies have evaluated all ages and found the majority of injuries (69.4%) occurring in players 11 to 20 years of age[97]. Boys and men have the highest injury incidence during games, with the cervical spine being the most often affected[98-100]. Goalpost injuries have been rare since displaceable goalposts were introduced. Checking from behind, which may subject the neck to an excessive axial load when the top of the head contacts the boards, is the most frequent mechanism resulting in neurologic injury[95,101]. The peak of severe spinal injuries (16.6 per year) occurred between 1982 and 1993[95]. To curtail these injuries, in 1985, the Canadian Amateur Hockey Association established a 10-minute major penalty for checking from behind[95]. By 1994, a worldwide ban on checking from behind while the opponent is in a vulnerable position was implemented[102]. Since the rule changes, the number of severe spinal injuries in Canadian ice hockey dropped to 7 per year on average[97,99,103].

Rugby

Worldwide, rugby has the highest proportion of spinal cord injuries caused by an individual sport[104]. Cervical spine injuries occur most frequently in front-row players (especially the hooker or central position) during the scrum, when the opposing sides come forcibly together (engagement), generating up to 1.5 tons (0.91 metric tons) of force[105-107]. An axial compression injury with quadriplegia may result from improper engagement or employing the head as a weapon (i.e., with the neck flexed during contact)[105]. Preventive strategies include avoiding a mismatch in hookers' physical size, prohibiting unskilled players in the front row, and disallowing tackling with the top of the head[4,105]. New internationally mandated rules requiring a sequential scrum engagement (crouch-touch-prebind-set) demonstrate reduced biomechanical load on the front-row players[107,108]. During prebind, the front-row players are required to bind opposing players with the head facing the opposing players' shoulders and hip and knee angles at 120° (more vertical position). The prebind position reduces the distance between packs, the speed at impact, and the risk of head-to-head contact[108,109]. Following the scrum rule changes and educational efforts, a marked reduction of catastrophic cervical spine injuries (1.8 to 1.0/100,000 from 2006 to 2013[110]) was reported[110-114].

Wrestling

Cervical injuries during match competitions constitute the majority of traumatic catastrophic wrestling injuries[72,115]. The defensive position during the takedown maneuver, especially when the wrestler's arms are constrained, is most vulnerable for injury due to the risk of initial head contact as the wrestler is slammed to the mat[72,115]. Prevention strategies rely on referees enforcing penalties for slams and stopping matches when an obvious mismatch exists. The incidence of catastrophic wrestling injuries has held fairly steady over the past 40 years[1], indicating a further need for prevention strategies.

Overview

Although catastrophic sports injuries may not be 100% preventable, tremendous strides have been made in substantially reducing these tragic events. Epidemiology and etiology-based studies identified key injury patterns and mechanisms. This provided the impetus for developing and implementing multiple sports-specific and cross-sport safety rules, which not only drastically reduced injuries but prevented many sports-related fatalities. Although rule and policy changes dramatically reduced traumatic catastrophic injuries in football, pole-vaulting, cheerleading, and other sports, research is still necessary to reduce the incidence in gymnastics, wrestling, lacrosse, female field hockey, and many other sports. Further work is necessary to develop and reach consensus on a cost-effective screening program for detecting preexisting cardiac abnormalities, especially in female basketball players. Educating coaches on the basics of exercise science and position-specific conditioning programs is critical to prevent exertional heat stroke fatalities. Identification of sickle cell trait status in high school athletes and rules to promote precautions during conditioning are recommended. Lastly, mandatory injury reporting and universal databases that provide the number of injuries and incidence values across all levels of play are important next steps.

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