Journal of Athletic Training 2017;52(11):1028–1034
doi: 10.4085/1062-6050-52.11.22

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Lower Extremity Musculoskeletal Injury Risk After Concussion Recovery in High School Athletes

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Context: Although an association between concussion and musculoskeletal injury has been described in collegiate and professional athletes, no researchers have investigated an association in younger athletes.

Objective: To determine if concussion in high school athletes increased the risk for lower extremity musculoskeletal injury after return to activity.

Design: Observational cohort study.

Setting: One hundred ninety-six high schools across 26 states.

Patients or Other Participants: We used data from the National Athletic Treatment, Injury and Outcomes Network surveillance system. Athletic trainers provided information about sport-related concussions and musculoskeletal injuries in athletes in 27 sports, along with missed activity time due to these injuries.

Main Outcome Measure(s): Three general estimating equations were modeled to predict the odds of sustaining (1) any lower extremity injury, (2) a time-loss lower extremity injury, or (3) a non–time-loss lower extremity injury after concussion. Predictors were the total number of previous injuries, number of previous concussions, number of previous lower extremity injuries, number of previous upper extremity injuries, and sport contact classification.

Results: The initial dataset contained data from 18 216 athletes (females = 39%, n = 6887) and 46 217 injuries. Lower extremity injuries accounted for most injuries (56.3%), and concussions for 4.3% of total injuries. For every previous concussion, the odds of sustaining a subsequent time-loss lower extremity injury increased 34% (odds ratio [OR] = 1.34; 95% confidence interval [CI] = 1.13, 1.60). The number of previous concussions had no effect on the odds of sustaining any subsequent lower extremity injury (OR = 0.97; 95% CI = 0.89, 1.05) or a non–time-loss injury (OR = 1.01; 95% CI = 0.92, 1.10).

Conclusions: Among high school athletes, concussion increased the odds of sustaining subsequent time-loss lower extremity injuries but not non–time-loss injuries. By definition, time-loss injuries may be considered more severe than non–time-loss injuries. The exact mechanism underlying the increased risk of lower extremity injury after concussion remains elusive and should be further explored in future research.

Key Words: mild traumatic brain injuries, adolescents, functional movement, dynamic balance

Key Points

- Among high school athletes, we observed an increased risk of musculoskeletal injury after concussion for time-loss lower extremity injuries but not non–time-loss injuries.
- The results of this first investigation of the musculoskeletal injury risk after concussion in high school athletes were similar to those from a larger body of literature studying the same outcomes in collegiate and professional athletes.
- The exact mechanism(s) leading to an increased musculoskeletal injury risk after concussion is (are) unclear. More research that combines functional movement and dynamic balance outcomes postconcussion with longitudinal assessment of musculoskeletal injuries is needed.

Traditional concussion management involves assessments of symptoms, neurocognition, and static balance along with a gradual return-to-activity protocol.[1] This broad assessment battery allows clinicians to better understand the myriad of potential deficits after concussion, leading to more complete and safe return-to-activity decisions. Although this broad approach is certainly preferred to assessment of only a single domain,[2] the assessment battery may be incomplete. Dynamic balance deficits during gait have been observed to linger beyond the recovery of clinically measurable symptoms, neurocognition, and static balance.[3,4] These reports are compelling and suggest the need for alterations to the currently recommended concussion-assessment battery, but the clinical implications of lingering dynamic balance deficits are unclear.

One potential consequence of decreased dynamic balance and altered gait mechanics may be a higher risk of musculoskeletal injury after return to activity from concussion. An increased musculoskeletal injury risk after concussion has been observed in collegiate[5–8] and professional athletes.[9,10] Similar observations have been reported in both sexes and across a variety of sports, demonstrating the robustness of these findings.

The exact mechanism for this increased risk of musculoskeletal injury after concussion is unclear. Recent evidence[11] suggested that neuromuscular function, specifically altered lower extremity muscle stiffness, may play a role in the musculoskeletal injury risk after concussion. Previous authors[5] also hypothesized that relatively small-magnitude dynamic balance deficits may be exacerbated in the highly dynamic sport environment with significant motor and cognitive demands. Lingering dynamic balance deficits have been observed in high school and collegiate athletes, suggesting that high school athletes may be at an increased risk of musculoskeletal injury after concussion, similar to findings in collegiate athletes.[12] Despite these reports and potential concussion-recovery differences based on age,[13,14] no publications have addressed the musculoskeletal injury risk after concussion in high school athletes. Understanding the potential consequences of concussion may better inform development of the most effective postconcussion-management strategies across the athlete age spectrum, leading to safer return-to-activity protocols and a reduced risk of subsequent musculoskeletal injury.

The purpose of our investigation was to determine if sustaining a concussion puts high school athletes at greater risk for lower extremity musculoskeletal injury after return to activity. Based on previous documentation of an increased risk of musculoskeletal injury after concussion in older athlete cohorts,[5–10] we hypothesized that high school athletes would have a greater risk of lower extremity musculoskeletal injury after concussion.

METHODS

Data collected from the National Athletic Treatment, Injury and Outcomes Network (NATION) were used for this study. The NATION is a high school injury-surveillance program that has captured data for 27 high school sports from 196 high schools across 26 states. Data originated from the 2011–2012 through 2013–2014 academic years. The NATION protocol was reviewed and deemed exempt by the Western Institutional Review Board (Puyallup, WA).

The NATION methods have been described in detail.[15] All injury data were recorded during school-sanctioned practices and competitions by athletic trainers (ATs) working directly with participating sport programs. Individual weight-lifting and conditioning sessions were excluded. The ATs reported injuries through their organizations' electronic health record applications. The surveillance system also captured other sport-related adverse health events, such as illness, heat-related conditions, general medical conditions, and skin infections. The ATs completed a detailed report of each injury, including diagnosis, body site, activity, injury mechanism, and event type (ie, competition or practice). The ATs could review and update the injury data as needed, such as when the athlete returned to sport participation, over the course of a season.

From the electronic health record applications, common data elements were stripped of all identifiers; only relevant variables and values were retained. This common data element standard allowed ATs to record injury information as they normally would in their daily clinical practice. The use of data collection through preexisting electronic health record applications helped ensure that as many injuries as possible of those detected and managed by the team ATs were being captured and reported to the NATION.

All data underwent a validation certification process in which a series of consistency checks was conducted. Data were reviewed and flagged for invalid values. The ATs and data quality-assurance staff were notified about any flagged data and worked together to resolve the concern. Only data that successfully passed the verification process were placed into datasets.

The NATION database includes the injury histories of athletes in participating schools during our timeframe of interest. These data do not include injuries that occurred before or after high school. Thus, we sought to analyze the odds of sustaining a lower extremity musculoskeletal injury after concussion as well as the odds of sustaining a lower extremity musculoskeletal injury after a lower extremity injury or an upper extremity injury.

Data and Measures

The primary outcome was a dichotomous variable that indicated if a given injury was a *lower extremity injury* (defined as an injury occurring at or inferior to the hip joint). Our models consisted of the following predictors: total number of previous injuries, number of previous concussions, number of previous lower extremity injuries, number of previous *upper extremity injuries* (defined as injuries to the neck, shoulder, arm, or hand), and sport contact classification. The *total number of previous injuries* was the number of injuries sustained by the athlete that were reported in the dataset before the index injury. *Number of previous lower extremity injuries* was the number of lower extremity injuries sustained by the athlete before the identified index injury of interest (ie, concussion, lower extremity injury, upper extremity injury). The *number of previous upper extremity injuries* was the number of injuries that occurred to the upper extremity before a given injury of interest. These outcomes were included in the model because previous musculoskeletal injury is a primary risk factor and predictor for future musculoskeletal injury.[16–18] The *number of previous concussions* was the number of diagnosed concussions an athlete had received before the current injury of interest.

A *time-loss injury* was defined as any injury that was evaluated or treated by an AT or physician and resulted in restriction from participation beyond the day of injury. A *non–time-loss injury* was defined as any injury that was evaluated or treated by an AT or physician but did not result in restriction from participation beyond the day of injury.[19]

Sport contact classification was according to the American Academy of Pediatrics Classification of Sports by Contact.[20] All sports were classified into 4 categories based on the amount of contact anticipated during play: football, contact/collision, limited contact/impact, and noncontact. The original classification system did not separate football from other contact/collision sports, but

Table 1. Descriptive Statistics[a]

Variable	All Injuries (n = 46 217), % (n)	Time-Loss Injuries (n = 8064), % (n)	Non–Time-Loss Injuries (n = 38 153), % (n)
Sex			
Male	67.4 (31 165)	72.2 (5826)	66.4 (25 339)
Female	32.5 (15 023)	27.4 (2213)	33.6 (12 810)
Missing	0.1 (29)	0.3 (25)	0.01 (4)
Class year of injury			
Freshman	29.8 (13 754)	28.8 (2326)	30.1 (11 428)
Sophomore	28.2 (13 043)	25.3 (2038)	28.8 (11 005)
Junior	20.7 (9568)	22.0 (1778)	20.4 (7790)
Senior	20.7 (9562)	22.0 (1773)	20.4 (7789)
Missing	0.6 (290)	1.8 (149)	0.4 (141)
Sport contact classification			
Football	36.3 (16 762)	45.0 (3626)	34.4 (13 136)
Contact/collision	23.5 (10 884)	23.4 (1889)	23.6 (8995)
Limited contact/impact	20.7 (9548)	21.7 (1750)	20.4 (7798)
Noncontact	19.5 (9023)	9.9 (799)	21.6 (8224)
Concussions	4.3 (2004)	24.7 (1988)	0.04 (16)
Lower extremity injuries	56.3 (26 010)	42.4 (3416)	59.2 (22 594)
Upper extremity injuries	13.9 (6437)	11.3 (914)	14.5 (5523)

[a] Individuals injured multiple times appeared once for each injury.

because of the high number of concussions reported during football in our study cohort, we decided to treat football as its own sport classification. Also, although the original pediatric classification system further categorizes noncontact sports based on how strenuous the activity was, we chose not to use these subclassifications in our analyses as those sports generally have low concussion frequencies and would have resulted in categories with low cell counts.

Statistical Analysis

Both descriptive and inferential statistics are presented. Descriptive statistics are reported as means for continuous variables and frequencies for categorical data. Three generalized estimating equations (GEEs) were used to test if concussions predicted subsequent lower extremity injuries. A GEE can be thought of as a repeated-measures logistic regression and is an extension of the generalized linear model for longitudinal or clustered data.[21] The data were structured such that injuries were nested within athletes. A logistic regression could be used if the analysis was limited to examining only 1 subsequent injury per athlete. But because many athletes had more than 2 injuries, the GEE model was used. The advantage of using a GEE model is that it provides unbiased marginal regression coefficients, regardless of the correlation structure of the errors.[22] This procedure allows for the specification of a working correlation matrix to account for the lack of independence in the observations from the athletes' varying numbers of injuries.[23] We performed analyses using the binomial distribution, the logit link function, and an independent working correlation matrix. One model included all time-loss and non–time-loss injuries as the outcome, the second model included only time-loss injuries as the outcome, and the third model included only non–time-loss injuries as the outcome.

Sport contact classification was entered as a nominal variable, and, if it was significant, we conducted post hoc comparisons using the Fisher least significant difference test. The additional covariates of sex and class year (a proxy for age) were not significant and thus removed from the final model. For significance, the Wald χ^2 test was used with an a priori α of .05; additionally, effect sizes are reported as odds ratios (ORs) with corresponding 95% confidence intervals (CIs). Any CIs not containing 1.0 were considered statistically significant.

An important limitation was that only injured athletes' data were included. Therefore, multiple statistical models were run to verify our findings. Using only the data for athletes who incurred multiple injuries within the larger dataset produced results that were the same as from the models presented here. Models that used dichotomized predictors (ie, having a concussion before the injury instead of the number of previous concussions) resulted in similar findings. An alternative outcome, predicting illness or infection, was used to see if a spurious relationship might have occurred due to this study's relatively large sample size. No predictors in that model were significant. Additionally, we performed an analysis with stricter inclusion and exclusion criteria, which considered only injuries directly after a concussion or upper extremity injury. Unfortunately, this analysis greatly reduced the sample size, and though concussions were not a significant factor, they had a larger effect size than in the models reported here.

RESULTS

The initial dataset contained 18 216 athletes (females = 39%, n = 6887) and 46 217 injuries. Nearly half the sample (47.5%; 8646) sustained only 1 injury, and the majority of the injuries that occurred were non–time loss (82.6%; 38 153). Descriptive statistics for all injuries, time-loss injuries, and non–time-loss injuries are reported in Table 1. Most injuries overall occurred in football (36.3%): 45.0% of all time-loss injuries and 34.4% of all non–time-loss injuries. Lower extremity injuries accounted for the majority of the total injuries (56.3%) and non–time-loss injuries (59.2%) but

Table 2. Statistical Models Predicting Lower Extremity Injury: Outcomes Reported for the All Injuries, Time-Loss Injuries Only, and Non–Time-Loss Injuries Only Models

Outcome	Predictor	β	Standard Error	Wald χ^2 Value	Odds Ratio (95% Confidence Interval)
Any lower extremity injury	No. of previous concussions	–0.03	0.04	0.58	0.97 (0.89, 1.05)
	No. of previous LEIs	0.11	0.01	57.45	1.12[a] (1.09, 1.15)
	Number of previous UEIs	0.01	0.02	0.28	1.01 (0.97, 1.05)
	Total No. of previous injuries	–0.07	0.01	41.89	0.93[a] (0.92, 0.95)
	Sport contact classification[b]			2810.72	
Time-loss lower extremity injuries	No. of previous concussions	0.29	0.09	11.16	1.34[a] (1.13, 1.60)
	No. of previous LEIs	0.12	0.04	8.64	1.13[a] (1.04, 1.23)
	No. of previous UEIs	0.08	0.05	2.05	1.08 (0.97, 1.20)
	Total No. of previous injuries	–0.10	0.03	10.89	0.90[a] (0.85, 0.96)
	Sport contact classification[b]			369.49	
Non–time-loss lower extremity injuries	No. of previous concussions	0.01	0.05	0.02	1.01 (0.92, 1.10)
	No. of previous LEIs	0.11	0.02	47.35	1.12[a] (1.08, 1.15)
	No. of previous UEIs	–0.00	0.02	0.006	0.99 (0.96, 1.04)
	Total No. of previous injuries	–0.07	0.01	36.43	0.93[a] (0.91, 0.96)
	Sport contact classification[b]			2436.47	

Abbreviations: LEI, lower extremity injury; UEI, upper extremity injury.

[a] Indicates statistical significance.

[b] Post hoc sport contact classification results are presented separately in Table 3.

fewer than half of the time-loss injuries (42.4%). Concussions were a small percentage of total injuries (4.3%) but almost a quarter of all time-loss injuries (24.7%).

All-Injuries Outcome

The number of previous lower extremity injuries, total number of any previous injuries, and sport contact classification were significant (Table 2) predictors of subsequent lower extremity injury. For every previous lower extremity injury, the odds of sustaining a subsequent lower extremity injury increased by 12% (OR = 1.12; 95% CI = 1.09, 1.15). Conversely, the total number of any injuries was a protective factor. With each previous injury, the odds of sustaining a subsequent lower extremity injury decreased by 7% (OR = 0.93; 95% CI = 0.92, 0.95). The number of previous concussions had no effect on the odds of sustaining subsequent lower extremity injuries (OR = 0.97; 95% CI = 0.89, 1.05).

Time-Loss Injuries Outcome

The number of previous concussions, number of previous lower extremity injuries, total number of any previous injuries, and sport contact classification were significant predictors of subsequent time-loss lower extremity injury (Table 2). For every previous concussion, the odds of sustaining a subsequent time-loss lower extremity injury increased 34% (OR = 1.34; 95% CI = 1.13, 1.60). For every previous lower extremity injury, the odds of sustaining a subsequent time-loss lower extremity injury increased by 13% (OR = 1.13; 95% CI = 1.04, 1.23). Again, the total number of injuries was a protective factor. With each previous injury, the odds of sustaining a subsequent time-loss lower extremity injury decreased by 10% (OR = 0.90; 95% CI = 0.85, 0.96).

Non–Time-Loss Injuries Outcome

The number of previous lower extremity injuries, total number of any previous injuries, and sport contact classification were significant predictors of subsequent non–time-loss lower extremity injuries (Table 2). For every previous lower extremity injury, the odds of sustaining a subsequent non–time-loss lower extremity injury increased 12% (OR = 1.12; 95% CI = 1.08, 1.15). As with the previous models, the total number of previous injuries was a protective factor. With each previous injury, the odds of sustaining a subsequent non–time-loss lower extremity injury decreased by 7% (OR = 0.93; 95% CI = 0.91, 0.96). Number of previous concussions had no effect on the odds of sustaining subsequent non–time-loss lower extremity injuries (OR = 1.01; 95% CI = 0.92, 1.10).

Sport Contact Classification

Sport contact classification post hoc results for all models are presented in Table 3. In the models that included all injuries and non–time-loss injuries, all pairwise comparisons for sport classification were significant. Injuries incurred while playing a noncontact sport ($\pi = 0.83$, SE = 0.004) were more likely to be lower extremity injuries than when playing contact/collision sports ($\pi = 0.60$, SE = 0.005), limited contact/impact sports ($\pi = 0.49$, SE = 0.005), or football ($\pi = 0.44$, SE = 0.004). In the model that included only time-loss injuries, all sport contact classification pairwise comparisons, except between football and contact, were significant. The highest proportion of lower extremity injuries resulted from playing a noncontact sport ($\pi = 0.77$, SE = 0.016), followed by limited contact/impact sports ($\pi = 0.46$, SE = 0.013); the least likely were contact/collision sports ($\pi = 0.37$, SE = 0.012) and football, ($\pi = 0.35$, SE = 0.009). In the model that included only non–time-loss injuries, all sport contact classification pairwise comparisons were significant. Injuries sustained while playing a noncontact sport ($\pi = 0.84$, SE = 0.005) were more likely to be lower extremity injuries than when playing contact/collision sports ($\pi = 0.65$, SE = 0.006), limited contact/impact sports ($\pi = 0.50$, SE = 0.006), or football ($\pi = 0.46$, SE = 0.004).

Table 3. Proportion of Lower Extremity Injuries Stratified by Sport Contact Classification: Outcomes Reported for the All Injuries, Time-Loss Injuries Only, and Non–Time-Loss Injuries Only Models[a]

Model	Sport Contact Classification	Proportion (95% Confidence Interval)	Standard Error
Any lower extremity injury	Football	0.44 (0.43, 0.44)	0.004
	Contact/collision	0.60 (0.59, 0.61)	0.005
	Limited contact/impact	0.49 (0.48, 0.50)	0.005
	Noncontact	0.83 (0.82, 0.84)	0.004
Time-loss lower extremity injuries	Football	0.35 (0.33, 0.37)	0.009
	Contact/collision	0.37 (0.35, 0.40)	0.012
	Limited contact/impact	0.46 (0.44, 0.49)	0.013
	Noncontact	0.77 (0.73, 0.80)	0.016
Non–time-loss lower extremity injuries	Football	0.46 (0.45, 0.47)	0.004
	Contact/collision	0.65 (0.64, 0.66)	0.006
	Limited contact/impact	0.50 (0.49, 0.51)	0.006
	Non-contact	0.84 (0.83, 0.85)	0.005

[a] All pairwise comparisons were significant except football versus contact/collision in the time-loss injuries only model.

DISCUSSION

The main finding of this study was that in high school male and female athletes, concussion increased the risk of incurring a subsequent time-loss lower extremity injury but not a non–time-loss lower extremity injury. Previous authors[5–10] have explored the association between concussion and the risk of musculoskeletal injury at various levels of play, but our data represent the first investigation of this association at the high school level. Close to 8 million children play high school sports in the United States alone.[24] Concussion rates[25] and recoveries[14] appear to differ in this population compared with older cohorts. Thus, understanding the musculoskeletal injury risk after concussion in this age group is important.

The discrepancy in findings between time-loss and non–time-loss injuries is interesting. Although the distinction is not perfect, these 2 injury types may be surrogates for injury severity, with time-loss injuries leading to a greater number of missed practices and competitions and likely having a greater effect on activities of daily living, thus being more severe than non–time-loss injuries. Accounting for non–time-loss injuries is important: observing all injuries offers more detail about the overall injury burden in high school sports. Using these injury outcome criteria as surrogates for injury severity, we suggest that concussion increased the risk of more severe time-loss lower extremity injuries but did not affect the risk for less severe non–time loss lower extremity injuries in high school athletes. This finding was similar to that of a previous report[26] detailing an association between concussion and more severe, traumatic lower extremity injuries.

Previous authors have varied in how they accounted for the differences between time-loss and non–time-loss injuries when exploring the association between concussion and musculoskeletal injury. At the professional sports level, Cross et al[10] analyzed only time-loss injuries and reported a significantly greater injury risk (60%) after concussion compared with any other injury. At the collegiate level, Lynall et al[5] did not distinguish between time-loss and non–time-loss injuries and noted significantly higher injury rates after concussion compared with the rates for nonconcussed control participants. In contrast, Herman et al[6] studied only time-loss injuries and found increased odds of sustaining a lower extremity musculoskeletal injury for those who had sustained a concussion compared with a matched nonconcussed control group. To our knowledge, we are the first to analyze injury severities separately within a single investigation. This method may offer more detail as to the musculoskeletal injury burden after concussion.

The majority of injuries we observed were non–time-loss injuries (82.5%). This is in contrast to the findings of previous authors[5,10] who either included only time-loss injuries or did not distinguish between time-loss and non–time-loss injuries. This methodologic difference may account for why the risk of lower extremity musculoskeletal injury after concussion was tempered in our study compared with earlier studies. Furthermore, most time-loss injuries (57.6%) did not affect the lower extremity. When we assessed only time-loss injuries, the athletes might not have been at increased risk for lower extremity injury because their previous injury affected an unrelated body region; thus, there was no increased risk for lower extremity injury. The total number of time-loss injuries could have been protective because the athletes who sustained these injuries participated in fewer days of athletic activity and therefore had less of an opportunity to be injured. We could not account for the time missed due to injury in our statistical models. This is evidenced by the findings of our non–time-loss injuries model. Unlike concussions[5–10] and previous lower extremity injuries,[16–18] which increase the risk of future lower extremity injury, no evidence indicates that prior upper extremity injury influences the risk of future lower extremity injury. Hence, these time-loss upper extremity injuries resulted in less available time for sport participation without a known subsequent increase in lower extremity injury risk.

Despite further evidence of an increased risk of musculoskeletal injury after concussion as presented here, the mechanism for this elevated risk remains unclear. Reports continue to emerge suggesting that dynamic balance deficits linger beyond return to activity after concussion[27,28] and that these effects may differ among concussed athletes of different ages.[12] This is concerning as current return-to-activity guidelines recommend only static balance assessments.[1] Tandem gait has been suggested as a potential means of evaluating dynamic balance after concussion,[29,30] but more work in this area is needed before a valid and reliable tandem-gait assessment can be recommended for clinical use. Beyond more dynamic movement tasks in isolation, adding a cognitive task to the motor task may increase the overall difficulty and make the assessment more sensitive to lingering postconcussive impairments.[3,12,31]

Several limitations exist that should be considered when interpreting our findings. Concussion severity and symptoms were not considered but may be important contributors to the musculoskeletal injury risk after return to activity. Further, player exposure (eg, starter versus reserve, total playing time) was not accounted for yet was deemed unlikely to influence outcomes based on previous research.[6,7] Both chronic and acute lower extremity injuries were included in our analyses. Because concussion may cause lingering deficits in postural control,[27,28] we felt including these injuries in our analyses was the most appropriate course of action at this time. Future researchers should investigate differences in injury risk after concussion based on the chronic or acute nature of the lower extremity injury. In some cases, ATs may have relied on athlete self-reports to initiate injury evaluation. This may be especially true for more minor injuries (non–time loss) that would not be apparent to the AT without reporting by the athlete. As discussed in the Methods section, a limitation to our study was that athletes' data were only included if they incurred an injury. To test the robustness of our findings, multiple statistical models were run to verify findings, as noted at the end of the Methods section.

CONCLUSIONS

Among high school athletes, concussions increased the risk of more severe time-loss lower extremity injuries but not less severe non–time-loss lower extremity injuries. These findings are consistent with the previous literature,[5–10] which described an overall increased risk for musculoskeletal injury after concussion in older athlete cohorts. Further research is needed to determine the neuromotor-control mechanism behind this increased risk of musculoskeletal injury and how functional movement outcomes can be objectively quantified and incorporated in return-to-activity assessment protocols.

ACKNOWLEDGMENTS

Funding for this study was provided by the National Athletic Trainers' Association Research & Education Foundation and BioCrossroads in partnership with the Central Indiana Corporate Partnership Foundation. The funding organizations had no role in the design and conduct of this study; the collection, management, analysis, or data interpretation; the preparation, review, or manuscript approval; or the decision to submit the manuscript for publication. The content of this manuscript is solely the responsibility of the authors and does not necessarily represent the official views of the study sponsors. We thank the many athletic trainers who have volunteered their time and efforts to submit data to the NATION. Their efforts are greatly appreciated and have had a tremendously positive effect on the safety of high school student-athletes.

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