Original Research

Incidence, Mechanisms, and Severity of Game-Related High School Football Injuries Across Artificial Turf Systems of Various Infill Weights

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Investigation performed at Idaho State University, Pocatello, Idaho, USA

Background: Artificial turf surfaces are developed to duplicate playing characteristics of natural grass. With the newer generations of sand and rubber infill systems, the infill is a common component that varies between fields and is a critical factor that could influence the player-surface interaction. Because the influence of infill weight on sport trauma is unknown, this study quantified football trauma in high schools in the United States across artificial turf systems of various infill weights.

Hypothesis: Athletes would not experience differences in game-related injuries across artificial turf systems of various infill weights.

Study Design: Cohort study; Level of evidence, 2.

Methods: Artificial turf systems were divided into 4 sand/rubber infill weight groups by pounds per square foot: ≥9.0, 6.0-8.9, 3.0-5.9, and 0.0-2.9. A total of 57 high schools in 4 states participated over the course of 5 seasons. Outcomes of interest included injury severity, as a function of infill weight, across head, knee, and shoulder traumas; injury category; primary type of injury; tissue type; specific body location of injury; cleat design; environmental factors; and turf age. Data were subject to multivariate analyses of variance (MANOVAs) and Wilks λ criteria through use of general linear model procedures.

Results: Of 1837 games documented, 528 games were played on infill weights of ≥9.0 lb/ft^2, 521 on 6.0-8.9 lb/ft^2, 525 on 3.0-5.9 lb/ft^2, and 263 on 0.0-2.9 lb/ft^2, with 4655 total injuries reported. MANOVAs indicated significant infill weight effects across injury severity ($F_{2,4648}$ = 5.087; P = .0001), with significant main effects also observed by injury category, tissue injured, lower extremity joint and muscle, cleat design, environmental factors, and turf age. Post hoc analyses indicated significantly lower ($P < .05$ to .0001) total and substantial traumas, concussions, shoe-surface interaction during contact trauma, surface impacts, muscle-tendon overload, cleat design influence, adverse weather trauma, lower extremity injuries, and turf age effect while athletes were competing on the 6.0 to ≥9.0 lb/ft^2 infill weight systems compared with the lighter infill weight systems.

Conclusion: As infill surface weight decreased, football trauma significantly increased across numerous playing conditions. Based on findings, high school football fields should minimally contain 6.0 pounds of infill per square foot.

Keywords: artificial surface; knee; turf; trauma

Today's new generations of artificial turf infill systems are increasingly being installed to duplicate or exceed the playing characteristics of natural grass. Although components vary, in most cases these synthetic surfaces are composed of a polyethylene slit-film or monofilament/polypropylene fiber blend, stabilized with a 2- or 3-layer infill made of sand and ground ambient styrene-butadiene rubber and laid over a crushed rock base for stability and drainage. Lighter weight infill systems often incorporate poured or interlocking polypropylene or thermoelastomer pad systems under the fiber-infill layers, reportedly to reduce shock and enhance shoe-surface stability. The infill weight (in lb/ft^2) can vary between fields, which could be a critical factor influencing the player-surface interaction. Combined with the increasing size, strength, and speed of these

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athletes,[20] the lighter infill weight surfaces may result in less dispersal of effective force and greater potential for surface impact trauma than provided with the heavier infill weight systems. Some investigators have concluded that the significantly lower incidence of leg trauma documented in prior studies on heavier infill weight may be related to the lower shoe-surface contact time usually associated with a more consistent, firmer surface,[4,36,39,44] supported by earlier summations noting an inverse relationship between surface integrity and the incidence of muscle, tendon, and ligament trauma.[31]

Prior studies have indicated no significant differences between artificial turf and natural grass in the incidence of anterior cruciate ligament and lower extremity injuries during American football competition.[7,10,22,36,39,49] Similar nonsignificant findings involving lower leg trauma have been reported in soccer.[4,5,15,37,38] At this time, however, the long-term effects of the surface infill weight on football trauma, during actual game conditions over several seasons of competition, are unknown.

Identifying the numerous factors that contribute to injury has become a priority to enhance player safety,[3,16,27,55] for several reasons: more than 1 million athletes play competitive football[42]; the number of injuries is increasing, with the costs of knee surgeries and rehabilitation alone reaching into the millions of dollars each year[16,21,35,41]; and athletes typically experience psychological trauma and setbacks in training after a significant injury.[1,19,23,40] Therefore, the purpose of this study was to quantify the incidence, causes, and severity of game-related high school football injuries in the United States across artificial turf systems of various infill weights. It was hypothesized that high school football athletes would not experience any difference in game-related injury when competing on artificial turf infill systems of various weights.

METHODS

Population

A total of 57 high schools in 4 states (Montana, Pennsylvania, Southern California, and Texas) were evaluated for game-related football injuries sustained on various artificial turf infill systems over the course of 7 competitive seasons from 2010 to 2016. The specific schools were selected based on availability of artificial playing surfaces during the competitive season, uniformity of school size based on each school's state classification, and the presence of a full-time certified athletic trainer (ATC) on the staff. A full-time ATC was required to ensure a uniform level of professional knowledge among those evaluating and reporting injuries for the study.[9,51]

The study initially started with 28 high schools over the first year, with the remaining high schools added by year 3, resulting in an initial total of 2008 seasonal games. With the exception of excluding games played on natural grass (n = 171), selection bias was avoided by reporting all remaining games and subsequent injuries on all remaining artificial turf infill systems. This resulted in 1837 games played across the country over the 7-year period. Artificial turf systems were divided into 4 sand/rubber infill weight groups based on pounds per square foot: $\geq$9.0, 6.0-8.9, 3.0-5.9, and 0.0-2.9. Low-weight infill systems ($<$6.0 lb/ft^2) are less expensive and are promoted by various turf manufacturers as having safety equal to that provided by heavier surface infill systems, whereas heavier weight infills are widely used at high levels of competition, such as in the National Collegiate Athletic Association and National Football League. The infill weight was recorded on the specification sheet that is submitted to each school district prior to installation. Various stadiums were used by all 57 high schools during home and away games. All teams had facilities with an artificial turf infill system.

Procedures

Based on paradigms suggested in prior research,[3,29,55] it was decided that a comprehensive approach that encompassed teams playing on all surfaces during the same time period, using a definitive but brief injury surveillance, would provide several advantages. These included gaining a better comparison of the possible nuances of each surface's influence on injury, avoiding limitations in data collection (eg, seasonal variation, participant randomization by surface), and minimizing difficulties in analyses and interpretation of findings that have affected former studies.[3,50] For this prospective cohort study, a 2-sided, single-page injury surveillance form was developed based on prior criteria recommended and established in the literature.[24,29,36,44,48] Demographic features and predictors included athletic identification number, ATC, date of injury, personnel determining the injury, athlete weight, high school, type of playing surface, surface quality, time period of injury, year and skill level of athlete, and game location where the injury occurred. Outcomes of interest included injury severity, injury category, primary type of injury, specific body location of injury, player position, cleat design, turf age, and environmental factors. The injury surveillance form was initially emailed to the head ATCs during the summer prior to the start of the football season. Communication was maintained by the author to discuss potential concerns and ensure accuracy of collection, comprehensiveness of information, and ease of application.

The respective ATCs for each high school were initially approached because of their daily interaction with the athletes and coaches during and after sport trauma and their expertise in injury recognition.[9,23,39] During the summer prior to the football season, all ATCs were provided with an overview of the purpose and procedures of the study, copies of the injury surveillance form, and detailed instructions for completion to avoid the potential for performance and detection biases.[50,51] The protocol was approved by the institutional review board at the university in which the study was based, and the study was conducted in accordance with the guidelines for use of human subjects as stipulated by the American College of Sports Medicine.[2]

All regular season district, nondistrict, and postseason playoff games were included. Injury data were recorded after game completion, with additional support from ATC notes to avoid lapse of memory leading to inaccuracy or response distortion.[39,50] All game-related injuries were evaluated by the attending head ATC and team physicians on-site and subsequently in the physician's office when further follow-up and treatment were deemed necessary. Any sport trauma that occurred toward the end of the competitive schedule was monitored beyond the player's specific season to determine date of recovery and functional return to play.[39,48]

Completed injury surveillance forms were faxed to the author within 7 working days after a game and were processed before the next game. A follow-up telephone visit was used to obtain any additional information pertaining to any changes or additions in diagnosis, treatment, or time to return to play. To avoid the potential for on-the-field detection bias,[51] a double-blind outcome approach was maintained throughout the study period, whereby the surface infill weights were unknown to the ATCs collecting the injury data, and total data compilation and analyses were limited to the data coordinator.

Definitions

The definition of injury was based on a combination of functional outcome, observation, and treatment.[9,39,44] A *reportable injury* was defined as any game-related football trauma reported or treated by the ATC or physician that resulted in an athlete missing all or part of a game.[21,38,39] Injury severity was based on the number of days absent from practice or game competition (time loss). As previously described, any trauma that required 0 to 6 days of time loss was considered a *minor injury*, an injury that required 7 to 21 days of time loss resulting in the athlete being unable to return to play at the same competitive level was considered a *substantial injury*, and trauma that required 22 or more days of time loss was considered a *severe injury*.[36,39]

Injury category was quantified by player-to-player collision, player-to-turf collision, injuries attributed to shoe-surface interaction during player contact, injuries attributed to shoe-surface interaction without player contact, and muscle- or tendon-related overload. Regarding stage of injury, acute trauma was delineated from recurrent acute injury according to criteria previously published[37-39]: Acute trauma was linked to an incident that specifically occurred during a competitive game, whereas recurrent trauma was linked to repetitive exposure resulting in symptoms and injury to the same location during the season.

To optimize cell size and enhance interpretation, the 23 player positions were condensed and analyzed by offense, defense, and special teams and by specific positions (quarterback, backfield, offensive line, tight end, receiver, defensive line, linebacker, secondary).[8,36] Primary type of injury was combined into the following categories: surface or epidermal injury (abrasion, laceration, puncture wound), contusion, concussion, inflammation (bursitis, tendinitis, fasciitis, synovitis, capsulitis, apophysitis), ligament sprain, ligament tear, cartilage tear, muscle-tendon strain or tear, hyperextension, neural injury (burner, brachial plexus), subluxation or dislocation, and fracture (standard, epiphyseal, avulsion, stress, osteochondral).

Specific body location of injury was condensed to 25 anatomic sites. Type of tissue injured was analyzed by bone, joint, muscle, neural, and other. Cranial/cervical trauma included simple and complex concussions, hematoma, postconcussion and second-impact syndromes, neurological sequelae (eg, stingers and burners, transient quadriplegia), vascular or dental injury, or associated fractures, sprains, and strains.[33,36,39] Neural trauma was restricted to any injury involving only concussion, associated syndromes, and neurological sequelae. Head, knee, and shoulder traumas were specifically identified for further analyses.

Each team's ATC documented type of cleat design (7-studded and 12-studded cleats, molded or hybrid cleats, edge or blade-style cleats, turf or elastomeric short rubber cleats) and age of the playing surface.[56] Environmental factors such as field conditions (no precipitation/dry field, rain, snow, sleet, no precipitation/wet field, adverse conditions combined) and environmental temperature were obtained before game time and whenever an injury occurred; these data were obtained by the ATCs and/or through the local airport climatic data.[27,36,38,39,45]

Statistical Analyses

Data were grouped by playing surface infill weight ($\geq$9.0, 6.0-8.9, 3.0-5.9, 0.0-2.9 lb/ft^2), and tabular-frequency distributions were computed by use of SPSS software (v 15.0; IBM Corp), with 95% confidence intervals (95% CIs) determined as described elsewhere.[54] Because most high schools played approximately 10 games each season, the injury incidence rate (IIR) was expressed as injuries per 10 team games, calculated as (*number of injuries/number of team games*) $\times$ 10, as previously reported.[36,39,55] When appropriate, the denominator was adjusted to reflect the number of athletes playing in each specific cleat type as well as the number of matches played in adverse weather conditions or on a dry field.

Data were then subjected to multivariate analyses of variance (MANOVAs) and the Wilks λ criteria using general linear model procedures.[32] Data screening indicated no violations of multivariate normality, linearity, outliers, homogeneity of variance, multicollinearity, or singularity.[54] When significant main effects were observed, univariate post hoc procedures were performed within each dependent variable based on the total percentage of injuries reported on each artificial turf infill weight. An experimentwise type I error rate of 0.05 was established a priori, and least squared means procedures were required because of the uneven number of observations on which to compare differences between variables. Statistical power analyses were performed, and *P* values were determined a priori at the .05 level of significance.

Although the number of games played on the lightest infill weight (0.0-2.9 lb/ft^2) was less than that for the other groups, the number of documented injuries provided adequate statistical power for analyses ($1 - \beta = .778$ to 1.000). Because of the increasing popularity of base pads or e-layers (poured pads) being installed as an alternative to heavier infill

TABLE 1
Incidence of Game-Related High School Football Injuries Between Artificial Turf Infill Systems by Infill Weight[a]

Variable	Infill Weight				Total/Mean
	≥9.0 lb/ft^2	6.0-8.9 lb/ft^2	3.0-5.9 lb/ft^2	0.0-2.9 lb/ft^2	
Games evaluated, n (%)	528 (28.8)	521 (28.4)	525 (28.6)	263 (14.2)	1837 (100.0)
All injuries					
n (%)	917 (19.7)	1324 (28.4)	1590 (34.2)	824 (17.7)	4655 (100.0)
IIR (95% CI)	17.4 (16.9-17.7)^{b,f,h}	25.4 (24.8-25.8)^{c,d}	30.3 (29.9-30.5)^{e,g}	31.3 (30.7-31.8)^{e,i}	25.3
Minor injuries					
n (%)	666 (72.6)	884 (66.8)	1054 (66.3)	488 (59.2)	3092 (66.4)
IIR (95% CI)	12.6 (12.2-13.0)^{f,h}	17.0 (16.5-17.3)^{b,g}	20.1 (19.8-20.2)^{c,i}	18.6 (18.0-18.9)^{c,i}	16.8
Substantial injuries					
n (%)	168 (18.3)	322 (24.3)	405 (25.5)	263 (31.9)	1158 (24.9)
IIR (95% CI)	3.2 (2.8-3.6)^{f,h}	6.2 (5.8-6.6)^{b,g}	7.7 (7.3-8.1)^{c,i}	10.0 (9.9-10.0)^{c,i}	6.3
Severe injuries					
n (%)	83 (9.1)	118 (8.9)	131 (8.2)	73 (8.9)	405 (8.7)
IIR (95% CI)	1.6 (1.3-1.9)^{b}	2.3 (1.9-2.6)^{b}	2.5 (2.1-2.9)^{c}	2.8 (2.3-3.3)^{c}	2.2

[a]Wilks λ severity of injury ($F_{2,4648} = 5.087$; $P = .0001$). IIR, injury incidence rate (calculated as [*number of injuries/number of team games*] × 10). Minor injury, 0-6 days of injury time loss; substantial injury, 7-21 days of injury time loss; severe injury, ≥22 days of injury time loss.
Statistically significant at $^{b,c}P < .05$, $^{d,e}P < .01$, $^{f,g}P < .001$, $^{h,i}P < .0001$.

weights, injuries reported on this lighter infill weight were presented to provide insight into the potential influence of this practice on the incidence of injury.

RESULTS

Total Injury Frequency and Severity

Over the 7-season study, 4655 game-related injuries, or 11.7 injuries per high school per season, were recorded among 57 high schools competing on all surfaces, with a significant main effect ($F_{2,4648} = 5.087$; $P = .0001$) observed between infill weight. Post hoc analyses indicated a significantly lower total incidence of injuries ($P < .05$ to .0001) documented on the heaviest (≥9.0 lb/ft^2) infill weight when compared with all other descending infill weights (Table 1). Although all injuries were acute, the incidence of recurrent cases over 7 seasons ranged from 8.1% to 13.1%. The incidence of injury attributed to foul play or illegal action was 1.5% of the total trauma reported.

When severity of injuries was compared between types of playing surface, a significantly lower incidence of substantial injuries ($P < .05$ to .0001) was found for ≥9.0 lb/ft^2 infill weight compared with all other infill weight categories. Although severe trauma was minimal, a significantly lower incidence of severe trauma was observed among 6.0 to ≥9.0 lb/ft^2 infill weight systems compared with the lighter infill weight systems.

Head, Knee, and Shoulder Trauma

As shown in Table 2, significant main effects were found between infill weights by head ($F_{5,4646} = 3.577$; $P = .0001$) and knee injuries ($F_{9,4642} = 1.715$; $P = .009$). A nonsignificant main effect ($F_{6,4644} = 1.426$; $P = .093$) between infill weights by shoulder injury, however, was observed. Post hoc analyses indicated a significantly lower ($P < .05$) incidence of complex concussions on 6.0 to ≥9.0 lb/ft^2 infill systems compared with 3.0 to 5.9 lb/ft^2 surfaces. A significantly lower ($P < .05$ to .001) incidence of patellar tendon/syndrome was documented on ≥9.0 lb/ft^2 infill compared with all lower infill weights.

Injury Category

As shown in Table 3, a significant main effect was found by injury category ($F_{4,4646} = 4.959$; $P = .0001$). Post hoc analyses indicated a significantly lower incidence of muscle-tendon overload injuries reported on the 6.0 to ≥9.0 lb/ft^2 infill compared with the lighter infill weight systems ($P <$ .05 to .01), as well as injuries resulting from shoe-surface interaction during physical contact on the heaviest infill compared with 0.0 to 8.9 lb/ft^2 surfaces ($P < .05$ to .001). More important, significantly fewer player-turf injuries combined were reported for the heavier (≥6.0 lb/ft^2) infill surfaces (IIR, 4.8; 95% CI, 6.0-7.6) than for the lighter (<6.0 lb/ft^2) infill systems (IIR, 12.0; 95% CI, 11.0-13.0) ($P < .001$).

Primary Type of Injury

As shown in Table 3, a significant main effect ($F_{16,4635} = 3.039$; $P = .0001$) by primary type of injury was noted between infill weight, with post hoc analysis revealing a significantly lower incidence of contusions, inflammations, and ligament sprains reported on ≥9.0 lb/ft^2 than across other infill weights ($P < .05$ to .0001). Of special note were the significantly lower incidences of muscle and tendon strains or tears observed on the heavier infill weight systems compared with the lighter infill weight systems ($P < .01$ to .001).

TABLE 2
Frequency and Rate of Game-Related High School Football Injuries Between Artificial Turf Infill Systems by Head, Knee, and Shoulder Trauma[a]

	Infill Weight							
	≥9.0 lb/ft² (n = 528)		6.0-8.9 lb/ft² (n = 521)		3.0-5.9 lb/ft² (n = 525)		0.0-2.9 lb/ft² (n = 263)	
Variable	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)
Head injury								
Simple concussions	42	0.8 (0.6-1.1)	16	0.3 (0.2-0.5)	21	0.4 (0.3-0.6)	8	0.3 (0.2-0.6)
Complex concussions	31	0.6 (0.4-0.8)[b]	54	1.0 (0.8-1.3)[b]	69	1.3 (1.1-1.6)[c]	28	1.1 (0.7-1.5)[b]
Post syndromes/epistaxis	3	0.1 (0.0-0.2)	1	0.0 (0.0-0.1)	8	0.2 (0.1-0.3)	1	0.0 (0.0-0.2)
Concussion combined	73	1.4 (1.1-1.7)	70	1.3 (1.1-1.7)	90	1.7 (1.4-2.1)	36	1.4 (1.0-1.8)
Knee injury								
Medial/lateral collateral	45	0.9 (0.6-1.1)	58	1.1 (0.9-1.4)	51	1.0 (0.7-1.3)	34	1.3 (0.9-1.8)
Anterior cruciate	13	0.3 (0.1-0.4)	11	0.2 (0.1-0.4)	12	0.2 (0.1-0.4)	7	0.3 (0.1-0.5)
ACL and associated tissue	23	0.4 (0.3-0.6)	22	0.4 (0.3-0.6)	17	0.3 (0.2-0.5)	16	0.6 (0.4-1.0)
PCL and associated tissue	0	0.0 (0.0-0.0)	4	0.1 (0.0-0.2)	6	0.1 (0.1-0.2)	3	0.1 (0.0-0.1)
Arcuate-popliteal complex	7	0.1 (0.1-0.3)	6	0.1 (0.1-0.2)	1	0.0 (0.0-0.1)	1	0.0 (0.0-0.2)
Medial/lateral meniscus	9	0.2 (0.1-0.3)	20	0.4 (0.3-0.6)	10	0.2 (0.1-0.3)	4	0.2 (0.1-0.4)
Plica syndrome	2	0.0 (0.0-0.1)	1	0.0 (0.0-0.1)	0	0.0 (0.0-0.0)	0	0.0 (0.0-0.0)
Patellar tendon/syndrome	18	0.3 (0.2-0.5)[b,d]	39	0.7 (0.6-1.0)[c]	42	0.8 (0.6-1.1)[c]	31	1.2 (0.8-1.6)[e]
ACL injuries combined	36	0.7 (0.5-0.9)	33	0.6 (0.5-0.9)	29	0.6 (0.4-0.8)	23	0.9 (0.6-1.3)
Shoulder injury								
AC separation	33	0.6 (0.4-0.9)	42	0.8 (0.6-1.1)	46	0.9 (0.7-1.1)	25	1.0 (0.7-1.4)
Rotator cuff tear/strain	4	0.1 (0.0-0.2)	13	0.3 (0.1-0.4)	24	0.5 (0.3-0.7)	17	0.6 (0.4-1.0)
Dead arm syndrome	13	0.3 (0.1-0.4)	22	0.4 (0.3-0.6)	21	0.4 (0.3-0.6)	18	0.7 (0.4-1.1)
GH subluxation/dislocation	37	0.7 (0.5-1.0)	34	0.7 (0.5-0.9)	51	1.0 (0.7-1.3)	20	0.8 (0.5-1.1)
Impingement syndrome	0	0.0 (0.0-0.0)	1	0.0 (0.0-0.1)	11	0.2 (0.1-0.4)	3	0.1 (0.0-0.3)
SLAP lesion	11	0.2 (0.1-0.4)	13	0.3 (0.1-0.4)	16	0.3 (0.2-0.5)	9	0.3 (0.2-0.6)
Hill-Sachs lesion	0	0.0 (0.0-0.0)	1	0.0 (0.0-0.1)	2	0.0 (0.0-0.1)	0	0.0 (0.0-0.0)
Bankart lesion	2	0.0 (0.0-0.1)	0	0.0 (0.0-0.0)	4	0.1 (0.0-0.2)	1	0.0 (0.0-0.2)

[a]Wilks λ head injury ($F_{5,4646} = 3.577$; $P = .0001$); knee injury ($F_{9,4642} = 1.715$; $P = .009$); shoulder injury ($F_{6,4644} = 1.426$; $P = .093$). AC, acromioclavicular; ACL, anterior cruciate ligament; GH, glenohumeral; IIR, injury incidence rate (calculated as [*number of injuries/number of team games*] × 10); PCL, posterior cruciate ligament; SLAP, superior labrum anterior-to-posterior.
Statistically significant at [b,c]$P < .05$, [d,e]$P < .001$.

Type of Tissue Injured

Significant main effects were observed by stage of injury ($F_{2,4650} = 6.585$; $P = .0001$) and tissue type ($F_{4,4647} = 5.160$; $P = .0001$). A significantly lower incidence of joint and muscle injuries was reported on the ≥9.0 lb/ft² infill compared with all other infill weight surfaces ($P < .05$ to .0001) (Appendix Table A1).

Specific Body Location of Injury

With a significant main effect ($F_{38,4612} = 2.132$; $P = .0001$) observed by specific body location of trauma (Appendix Table A2), post hoc findings indicated a significantly lower incidence of shoulder girdle and ankle injuries on the heaviest infill weight (≥9.0 lb/ft²) compared with all lower infill weight surfaces ($P < .05$ to .001). Significantly lower incidences of upper arm, forearm, hand, finger, and knee-patella trauma were reported on ≥9.0 lb/ft² infill than were reported across most 0.0 to 5.9 lb/ft² infill surfaces ($P < .05$ to .0001), as well as a lower incidence of neck and lower leg trauma on the 6.0 to ≥9.0 lb/ft² infill surfaces compared with the lighter weight systems ($P < .05$ to .0001). Significant lower extremity muscle trauma ($F_{7,4644} = 3.013$; $P = .0001$) was also evident in cases involving flexor, extensor, gastrocnemius/soleus/plantaris, and combined muscles on the heavier surfaces (Appendix Table A3).

Cleat Design

Results indicated a significant main effect ($F_{4,4646} = 15.570$; $P = .0001$) by cleat design (Appendix Table A4), with a significantly lower incidence of injuries reported while players were wearing 7- and 12-studded removable cleats on ≥9.0 lb/ft² infill versus 3.0 to 5.9 lb/ft² infill surfaces ($P < .05$ to .01). A significantly lower incidence of injuries was also documented on the ≥9.0 lb/ft² infill versus most lower infill weights while players were wearing the most popular molded or hybrid, edge or blade-style, and traditional turf or elastomeric short rubber cleats ($P < .01$ to .0001).

Environmental Factors

Significant main effects were found by field conditions ($F_{4,4646} = 6.184$; $P = .0001$) and environmental temperature

TABLE 3
Frequency and Rate of Game-Related High School Football Injuries Between Artificial Turf Infill Systems by Injury Category, Injury Time Loss, and Primary Type of Injury[a]

	Infill Weight							
	≥9.0 lb/ft² (n = 528)		6.0-8.9 lb/ft² (n = 521)		3.0-5.9 lb/ft² (n = 525)		0.0-2.9 lb/ft² (n = 263)	
Variable	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)
Injury category								
Player-to-player collision	446	8.4 (8.1-8.7)[d,f]	570	10.9 (10.6-11.2)[b,e]	767	14.6 (14.1-15.0)[c,g]	337	12.8 (12.2-13.4)[c,g]
Player-to-turf collision	120	2.3 (1.9-2.6)[d,h]	236	4.5 (4.1-5.0)[b,e]	293	5.6 (5.2-6.0)[c,i]	169	6.4 (5.8-7.0)[c,i]
Shoe surface (contact)	223	4.2 (3.8-4.6)[d,f]	360	6.9 (6.5-7.3)[b,e]	321	6.1 (5.7-6.5)[e]	242	9.2 (8.8-9.5)[c,g]
Shoe surface (noncontact)	53	1.0 (0.8-1.3)	63	1.2 (1.0-1.5)	58	1.1 (0.9-1.4)	39	1.5 (1.1-2.0)
Muscle-tendon overload	75	1.4 (1.1-1.7)[b,d]	95	1.8 (1.5-2.2)[b]	151	2.9 (2.5-3.3)[c,e]	37	1.4 (1.0-1.9)[b]
Primary type of injury								
Surface/epidermal	33	0.6 (0.4-0.9)[f]	28	0.5 (0.4-0.8)	93	1.8 (1.5-2.1)[g]	16	0.6 (0.4-1.0)
Contusion	191	3.6 (3.2-4.0)[f,h]	379	7.3 (6.9-7.6)[g]	449	8.6 (8.2-8.8)[i]	230	8.7 (8.3-9.1)[i]
Concussion	73	1.4 (1.1-1.7)	70	1.3 (1.1-1.7)	90	1.7 (1.4-2.1)	36	1.4 (1.0-1.8)
Inflammation	16	0.3 (0.2-0.5)[b]	39	0.7 (0.6-1.0)[c]	47	0.9 (0.7-1.2)[c]	27	1.0 (0.7-1.5)[c]
Ligament sprain	268	5.1 (4.7-5.5)[b,d]	388	7.4 (7.1-7.8)[c]	438	8.3 (8.0-8.6)[e]	216	8.2 (7.7-8.6)[e]
Ligament tear	45	0.9 (0.6-1.1)	50	1.0 (0.7-1.2)	55	1.0 (0.8-1.3)	28	1.1 (0.7-1.5)
Cartilage tear	14	0.3 (0.2-0.4)[f]	25	0.5 (0.3-0.7)	14	0.3 (0.2-0.4)	6	0.2 (0.1-0.5)
Muscle-tendon strain/tear	145	2.8 (2.3-3.3)[d,f]	195	3.7 (3.1-4.4)[d]	272	5.2 (4.6-5.8)[e]	161	6.1 (5.3-7.1)[e,g]
Hyperextension	10	0.2 (0.1-0.3)	16	0.3 (0.2-0.5)	7	0.1 (0.1-0.3)	10	0.4 (0.2-0.7)
Herniation	3	0.1 (0.0-0.2)	0	0.0 (0.0-0.0)	0	0.0 (0.0-0.0)	1	0.0 (0.0-0.2)
Neural	28	0.5 (0.4-0.8)	26	0.5 (0.3-0.7)	31	0.6 (0.4-0.8)	16	0.6 (0.4-1.0)
Subluxation/dislocation	37	0.7 (0.5-1.0)	42	0.8 (0.6-1.1)	41	0.8 (0.6-1.0)	36	1.4 (1.0-1.8)
Fracture	54	1.0 (0.8-1.3)	66	1.3 (1.0-1.6)	53	1.0 (0.8-1.3)	41	1.6 (1.2-2.0)

[a]Wilks λ injury category ($F_{4,4646} = 4.959$; $P = .0001$); primary type of injury ($F_{16,4635} = 3.039$; $P = .0001$). IIR, injury incidence rate (calculated as [*number of injuries/number of team games*] × 10).

Statistically significant at [b,c]$P < .05$, [d,e]$P < .01$, [f,g]$P < .001$, [h,i]$P < .0001$.

($F_{2,4649} = 7.520$; $P = .0001$) (Appendix Table A4). Post hoc analyses indicated a significantly lower incidence of injury from no precipitation–dry field conditions, adverse field conditions combined, and across all temperatures while athletes were playing on the ≥9.0 lb/ft² infill compared with all lower weight infill surfaces ($P < .01$ to .001).

Age of Playing Surface

In this study, a significant main effect ($F_{3,4649} = 21.621$; $P = .0001$) by turf age (Appendix Table A4) was found, with post hoc analyses indicating a significantly lower incidence of injury on new fields ($P < .05$ to .01), on 1- to 3-year-old fields ($P < .01$ to .0001), and on 4- to 7-year-old fields ($P < .001$ to .0001) containing the heaviest infill weight. Injury rates were also significantly lower on ≥8-year-old fields containing the heavier 6.0 to ≥9.0 lb/ft² infill compared with the lighter infill weight systems ($P < .0001$).

DISCUSSION

Prior studies have compared injuries sustained by athletes while competing on artificial and natural grass surfaces. The current research, however, was focused on sport trauma during seasonal play comparing artificial turf systems of various infill weight. Although some similarities in injury characteristics did exist, significant differences in sport trauma were observed between the heavier and lighter infill weight systems.

Head, Knee, and Shoulder Injuries

Although significant differences in head trauma were found across artificial turf infill weight groups, findings were primarily attributed to player-to-player contact, with 5.8% of concussions attributed to player-to-turf cases. Regardless of the incidence of head-to-surface impacts in this study, caution is advised when equating head trauma with surface infill weight, as infill weight does not infer shock attenuation performance (Gmax). High-quality, heavy weight fields can easily be installed within recommended Gmax guidelines below 165*g* to reduce the potential for head-to-surface trauma.[53] With proper maintenance of the surface, shock attenuation performance should stay below excessive levels of hardness over the life of the surface. That being said, research quantifying the optimal Gmax value resulting in the lowest incidence of sport trauma remains elusive at this time.

The significantly lower incidence of patellar tendon/syndrome injuries documented on the 6.0 to ≥9.0 lb/ft² infill surfaces may reflect less cleat contact time and less surface deformation with concomitantly greater impact energy absorption and dissipation when playing on the heavier surfaces.[12,39] Of primary concern, however, was the anterior cruciate ligament and associated tissue trauma across all surfaces, which comprised 23.4% of all knee injuries and 2.6% of all injuries reported. This reiterates the ever-increasing level of severe trauma observed during high school competition across any surface,[36,39] leading to future diminished health-related quality of life.[1,6,19,43,52]

Injury Category

Given that maintenance and consistency of artificial turf surfaces pose a budgetary challenge with multipurpose fields at the high school level, combined with the increasing size, strength, and speed of high school athletes,[20] the significantly higher injury rates with lighter infill weight may reflect less margin of error than provided with the heavier infill weight systems. This was especially evident during player-to-turf collisions and injuries attributed to shoe-surface interaction during player contact as infill weight declined.

Primary Type of Injury

The significantly lower incidence of ligament sprains, muscle and tendon strains, and joint inflammation documented on the heaviest infill weight may be related to the lower shoe-surface contact time usually associated with a more consistent, firmer surface,[36,39,44] supported by earlier summations noting an inverse relationship between surface integrity and the incidence of muscle, tendon, and ligament trauma.[31] As reported by others, results may also be a function of varying shoe-surface peak torque and rotational stiffness across various artificial surfaces.[11,14,30,56,57] These studies, however, were conducted under noncompetitive, laboratory conditions using traditional mechanical simulations that lacked environmental variability, player contact, and the anatomic and neuromuscular complexities that occur during actual sport performance, thus limiting comparison with on-the-field sport activity.[20,26]

Type of Tissue Injured

As previously mentioned, the significantly lower incidence of joint and muscle injury reported on the heaviest infill weight may indicate an inverse relationship between a playing surface's energy absorbency or compliance and the degree of fatigue and tissue trauma.[3,26,34] Although the coefficient of restitution or degree of rebound was not established in this study, when compared with the polyethylene/cryogenic rubber composition of the heavy 3-layer system, findings on lower weight 2-layer infill may reflect a less compliant surface and lower energy absorption at ground impact. In this case, the energy of impact is subsequently transferred back to the lower extremity region, increasing the potential for trauma.[3,31] This finding is substantiated by the significant effect of infill weight on lower extremity trauma in this study, especially involving the significantly higher incidence of patellofemoral injuries and combined lower extremity joint injuries reported on fields with infill weight lower than 9.0 lb/ft^2. The prevalence of significant muscle trauma to the lower leg and combined lower extremity musculature when athletes play on the lighter weight infill surfaces also lends support to this theory.

Cleat Design

The effect of the type of shoe-surface interface with playing surface has become an increasing concern within the medical community. The majority of cleat designs associated with injuries in this study reflected a significant effect of infill weight on shoe-surface interaction, which is in contrast to prior work assessing cleat effect on lower extremity trauma[20] and in-shoe foot loading patterns during maximal sprint effort in male high school athletes.[14] The significantly lower incidence of trauma across most cleat designs as infill weight increased may simply reflect more optimal stability and warrants further research.

Environmental Factors

Limited attention has been directed toward the potential influence of weather conditions on injury during competition in American football.[17,20,27,36,39] In this study, the majority of play and injuries occurred during conditions of no precipitation, therefore minimizing the opportunity to extensively ascertain possible influences under various field conditions. The significantly lower incidence of injury as infill weight increased during play across adverse weather conditions combined and across temperatures, however, may reflect the more consistent surface that the heavier infill weight provides during most environmental conditions.

Age of Playing Surface

As existing artificial surfaces continue to mature, conjecture has arisen as to the influence of surface age on injury, with the scant information in the literature primarily focusing on artificial turf versus natural grass.[36-39] The recent explosion in artificial turf systems, however, has brought the effect of surface age and maintenance to the forefront. The significantly lower number of injuries reported in this study on the $\geq$9.0 lb/ft^2 new to 7-year-old infill surfaces, and especially injuries reported on the $\geq$8-year-old surfaces of 6.0 to $\geq$9.0 lb/ft^2 infill compared with 0.0 to 5.9 lb/ft^2 surfaces, is of clinical concern, reflecting decreasing long-term protection as well as increasing medical costs for those athletes playing on lighter infill surfaces. Unfortunately, the limited research on the influence of turf age on sport trauma prevents further comparison and merits further research at all levels and types of sport competition.

Limitations

This study had several potential limitations that may have influenced the type and number of injuries reported. These included the inability to determine and control the inherent random variation in injury typically observed in high-collision team sports[8,32]; the strength and conditioning status of the athletes and variations in the type of equipment used[3,19,28,48]; weather conditions and variations in field conditions[3,45-47]; differences in postural and joint integrity, musculoskeletal structure, and biomechanics of movement[3,8,18,19,28,34,35]; time of year[12,28]; coaching style, experience, and play calling[17,25,48]; quality of officiating and foul play[48,56]; actual versus average time of exposure to injury[9,23-25]; sport skill level, intensity of play, and fatigue level at time of injury[13,16,23,25,28]; an athlete's ephemeral response to help seeking, injury, and subsequent pain[34,40,50]; unreported congenital or developmental factors predisposing an athlete to additional injury[3,8,23,28,48]; or simply unforeseen mishap.[32,39,48] There is also the opportunity for an injury to go unreported despite the comprehensive nature of any reporting system.[21,27]

Key strengths of the study were the opportunity to evaluate a large number of high schools across the country during a 7-year period, which prevented seasonal injury fluctuations and individual team effect and enhanced the ability to identify differences and trends in surface effect. In addition, the combined method of assessing functional outcome, time loss, direct observation, and treatment records, as well as the daily interactions of ATCs and players evaluated in this study, minimized the potential for transfer bias and unreported injuries throughout the season.[26,39]

The influence of risk factors, other than simply surface type, cannot be overlooked. Because of the inherent challenges of collecting data on multiple indices and on numerous teams and players over an extended period of time, the degree of influence from these risk factors remains a limitation that can only be acknowledged at this time.[25,26] The prospective cohort multivariate design, however, enhanced sample size, resulted in randomization of play on all surfaces, controlled for seasonal and team variation, and allowed for greater insight into both significant and subtle differences across artificial turf systems of various infill weight.

CONCLUSION

Although similarities in injury characteristics were found across various infill weight systems over the 7-year period of competitive play, significant differences were found in injury incidence between infill weights related to severity of injury, knee trauma, injury category, primary type of injury, type of tissue injured, lower extremity joint and muscle trauma, cleat design, injuries under various environmental conditions, and age of playing surface. All infill weight surfaces, from a statistical and clinical standpoint, exhibited unique injury causes that should be addressed to reduce the number of game-related, high school football injuries.

The hypothesis that high school athletes would not experience any difference in the incidence, causes, and severity of game-related football injury across artificial turf systems of various infill weight was not supported. In most cases, injury incidence across all infill weights increased as infill weight decreased, with numerous similarities observed between the 2 heaviest infill surfaces. Based on the findings of this study, it is recommended that high school football fields contain a minimum of 6.0 lb/ft^2 of infill weight to optimize player safety.

Rectifying low infill weight ($<$6.0 lb/ft^2) on fields presently under use, however, will pose significant challenges. Because the amount of infill will dictate the blade height of the grass, the opportunity to add additional infill weight will mitigate original blade height, ultimately leading to higher infill splash, excessive infill migration, uneven surface depth, and poorer drainage. Therefore, ensuring optimal infill weight should be considered prior to future field installations.

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APPENDIX

TABLE A1
Frequency and Rate of Game-Related High School Football Injuries Between Artificial Turf Infill Systems by Stage of Trauma and Type of Tissue Injured[a]

	Infill Weight							
	≥9.0 lb/ft² (n = 528)		6.0-8.9 lb/ft² (n = 521)		3.0-5.9 lb/ft² (n = 525)		0.0-2.9 lb/ft² (n = 263)	
Variable	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)
Stage of injury								
Acute injury—no prior history	796	15.1 (14.6-15.5)[d,f]	1198	23.0 (22.4-23.4)[b,e]	1368	26.1 (25.4-26.5)[c,g]	754	28.7 (28.0-29.0)[c,g]
Acute injury—recurrent history	121	2.3 (2.0-2.7)[b]	126	2.4 (2.1-2.8)[b]	222	4.2 (3.8-4.7)[c]	70	2.7 (2.2-3.2)[b]
Type of tissue injured								
Bone	54	1.0 (0.8-1.3)	65	1.2 (1.0-1.6)	53	1.0 (0.8-1.3)	41	1.6 (1.2-2.0)
Joint	393	7.4 (7.1-7.8)[b,d]	566	10.9 (10.6-11.1)[c]	609	11.6 (11.2-11.9)[c]	331	12.6 (12.0-13.1)[e]
Muscle	333	6.3 (5.9-6.7)[h]	565	10.8 (10.5-11.1)[i]	715	13.6 (13.1-14.0)[i]	384	14.6 (13.9-15.2)[i]
Neural	101	1.9 (1.6-2.3)	95	1.8 (1.5-2.2)	118	2.2 (1.9-2.6)	53	2.0 (1.6-2.5)
Other	36	0.7 (0.5-0.9)[d]	33	0.6 (0.5-0.9)[d]	95	1.8 (1.5-2.2)[e]	15	0.6 (0.3-0.9)[d]

[a]Wilks λ stage of injury ($F_{2,4650} = 6.585$; $P = .0001$); type of tissue injured ($F_{4,4647} = 5.160$; $P = .0001$). IIR, injury incidence rate (calculated as [*number of injuries/number of team games*] × 10).

Statistically significant at [b,c]$P < .05$, [d,e]$P < .01$, [f,g]$P < .001$, [h,i]$P < .0001$.

TABLE A2
Frequency and Rate of Game-Related High School Football Injuries Between Artificial Turf Infill Systems by Specific Location of Body Trauma[a]

	Infill Weight							
	≥9.0 lb/ft² (n = 528)		6.0-8.9 lb/ft² (n = 521)		3.0-5.9 lb/ft² (n = 525)		0.0-2.9 lb/ft² (n = 263)	
Variable	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)
Specific body location								
Head	76	1.4 (1.2-1.8)	73	1.4 (1.1-1.7)	93	1.8 (1.5-2.1)	40	1.5 (1.1-2.0)
Face/oral and maxillofacial	7	0.1 (0.1-0.3)[b]	22	0.4 (0.3-0.6)[b]	27	0.5 (0.4-0.7)[c]	8	0.3 (0.2-0.6)[b]
Neck	22	0.4 (0.3-0.6)[b,h]	23	0.4 (0.3-0.7)[b]	48	0.9 (0.7-1.2)[c]	50	1.9 (1.5-2.4)[i]
Shoulder girdle	136	2.6 (2.2-3.0)[d,f]	217	4.2 (3.7-4.6)[e]	271	5.2 (4.7-5.6)[g]	148	5.6 (5.0-6.2)[g]
Upper arm	19	0.4 (0.2-0.6)[b]	22	0.4 (0.3-0.6)[b]	49	0.9 (0.7-1.2)[c]	20	0.8 (0.5-1.1)[b]
Elbow	25	0.5 (0.3-0.7)	35	0.7 (0.5-0.9)	49	0.9 (0.7-1.2)	23	0.9 (0.6-1.3)
Forearm	28	0.5 (0.4-0.8)[b,f]	62	1.2 (0.9-1.5)[c]	87	1.7 (1.4-2.0)[g]	24	0.9 (0.6-1.3)[b]
Wrist	12	0.2 (0.1-0.4)	29	0.6 (0.4-0.8)	13	0.2 (0.1-0.4)	12	0.5 (0.3-0.8)
Hand	25	0.5 (0.3-0.7)	44	0.8 (0.6-1.1)	50	1.0 (0.7-1.2)	25	1.0 (0.7-1.4)
Finger	18	0.3 (0.2-0.5)[b]	29	0.6 (0.4-0.8)[b]	43	0.8 (0.6-1.1)[c]	11	0.4 (0.2-0.7)[b]
Thumb	32	0.6 (0.4-0.8)[b]	38	0.7 (0.5-1.0)[b]	61	1.2 (0.9-1.5)[c]	23	0.9 (0.6-1.3)[b]
Upper back/spine	9	0.2 (0.1-0.3)	10	0.2 (0.1-0.4)	6	0.1 (0.1-0.2)	7	0.3 (0.1-0.5)
Lower back	27	0.5 (0.4-0.7)	40	0.8 (0.6-1.0)	34	0.6 (0.5-0.9)	14	0.5 (0.3-0.9)
Chest/sternum/ribs	17	0.3 (0.2-0.5)[b]	28	0.5 (0.4-0.8)[b]	38	0.7 (0.5-1.0)[b]	22	0.8 (0.6-1.2)[c]
Abdomen	6	0.1 (0.1-0.2)	3	0.1 (0.0-0.2)	7	0.1 (0.1-0.3)	1	0.0 (0.0-0.2)
Pelvis/hips/buttocks	19	0.4 (0.2-0.6)	26	0.5 (0.3-0.7)	24	0.5 (0.3-0.7)	23	0.9 (0.6-1.3)
Groin	7	0.1 (0.1-0.3)	9	0.2 (0.1-0.3)	5	0.1 (0.0-0.2)	1	0.0 (0.0-0.2)
External genitalia	2	0.0 (0.0-0.1)	2	0.0 (0.0-0.1)	0	0.0 (0.0-0.0)	0	0.0 (0.0-0.0)
Upper leg	61	1.2 (0.9-1.5)	76	1.5 (1.2-1.8)	79	1.5 (1.2-1.8)	48	1.8 (1.4-2.3)
Knee/patella	116	2.2 (1.9-2.6)[b]	162	3.1 (2.7-3.5)[c]	142	2.7 (2.3-3.1)[b]	96	3.7 (3.1-4.2)[c]
Lower leg	88	1.7 (1.4-2.0)[d,f]	121	2.3 (2.0-2.7)[d]	184	3.5 (3.1-3.9)[e]	112	4.3 (3.7-4.9)[g]
Ankle	123	2.3 (2.0-2.7)[d]	192	3.7 (3.3-4.1)[e]	190	3.6 (3.2-4.0)[e]	90	3.4 (2.9-4.0)[e]
Heel/Achilles tendon	3	0.1 (0.0-0.2)	5	0.1 (0.0-0.2)	11	0.2 (0.1-0.4)	1	0.0 (0.0-0.2)
Foot	27	0.5 (0.4-0.7)	34	0.7 (0.5-0.9)	49	0.9 (0.7-1.2)	19	0.7 (0.5-1.1)
Toe	12	0.2 (0.1-0.4)	22	0.4 (0.3-0.6)	30	0.6 (0.4-0.8)	6	0.2 (0.1-0.5)

[a]Wilks λ specific body location of trauma ($F_{38,4612} = 2.132$; $P = .0001$). IIR, injury incidence rate (calculated as [*number of injuries/number of team games*] × 10).

Statistically significant at [b,c]$P < .05$, [d,e]$P < .01$, [f,g]$P < .001$, [h,i]$P < .0001$.

TABLE A3
Frequency and Rate of Game-Related High School Football Injuries Between Artificial Turf Infill Systems by Lower Extremity Joint and Muscle Trauma[a]

	Infill Weight							
	≥9.0 lb/ft² (n = 528)		6.0-8.9 lb/ft² (n = 521)		3.0-5.9 lb/ft² (n = 525)		0.0-2.9 lb/ft² (n = 263)	
Variable	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)
Lower extremity—joint								
Hip and associated joints	1	0.0 (0.0-0.1)	6	0.1 (0.1-0.2)	10	0.2 (0.1-0.3)	12	0.5 (0.3-0.8)
Tibiofemoral	99	1.9 (1.6-2.2)	124	2.4 (2.0-2.8)	98	1.9 (1.6-2.2)	66	2.5 (2.0-3.1)
Patellofemoral	18	0.3 (0.2-0.5)[b,d]	38	0.7 (0.5-1.0)[b]	42	0.8 (0.6-1.1)[c]	30	1.1 (0.8-1.6)[e]
Proximal tibiofibular	7	0.1 (0.1-0.3)	7	0.1 (0.1-0.3)	8	0.2 (0.1-0.3)	9	0.3 (0.2-0.6)
Distal tibiofibular	35	0.7 (0.5-0.9)	52	1.0 (0.8-1.3)	63	1.2 (0.9-1.5)	27	1.0 (0.7-1.5)
Talocrural	49	0.9 (0.7-1.2)[b]	84	1.6 (1.3-2.0)[c]	61	1.2 (0.9-1.5)[b]	30	1.1 (0.8-1.6)[b]
Subtalar	22	0.4 (0.3-0.6)	24	0.5 (0.3-0.7)	25	0.5 (0.3-0.7)	15	0.6 (0.3-0.9)
Talocalcaneonavicular	12	0.2 (0.1-0.4)	25	0.5 (0.3-0.7)	27	0.5 (0.4-0.7)	9	0.3 (0.2-0.6)
Calcaneocuboid	0	0.0 (0.0-0.0)	2	0.0 (0.0-0.1)	10	0.2 (0.1-0.3)	6	0.2 (0.1-0.5)
Intertarsal	1	0.0 (0.0-0.1)	0	0.0 (0.0-0.0)	1	0.0 (0.0-0.1)	0	0.0 (0.0-0.0)
Transverse/midtarsal	0	0.0 (0.0-0.0)	2	0.0 (0.0-0.1)	4	0.1 (0.0-0.2)	2	0.1 (0.0-0.3)
Tarsometatarsal	3	0.1 (0.0-0.2)	4	0.1 (0.0-0.2)	6	0.1 (0.1-0.2)	1	0.0 (0.0-0.2)
Intermetatarsal	1	0.0 (0.0-0.1)	2	0.0 (0.0-0.1)	2	0.0 (0.0-0.1)	1	0.0 (0.0-0.2)
Metatarsophalangeal	7	0.1 (0.1-0.3)	13	0.3 (0.1-0.4)	17	0.3 (0.2-0.5)	5	0.2 (0.1-0.4)
Proximal/distal interphalangeal	2	0.0 (0.0-0.1)	3	0.1 (0.0-0.2)	9	0.2 (0.1-0.3)	1	0.0 (0.0-0.2)
Lower extremity—joint combined	257	4.9 (4.4-5.3)[d,f]	386	7.4 (7.0-7.8)[e]	383	7.3 (6.9-7.7)[e]	214	8.1 (7.6-8.6)[g]
Lower extremity—muscle								
Gluteals	5	0.1 (0.0-0.2)	7	0.1 (0.1-0.3)	3	0.1 (0.0-0.2)	3	0.1 (0.0-0.3)
Quadriceps	38	0.7 (0.5-1.0)	51	1.0 (0.8-1.3)	59	1.1 (0.9-1.4)	34	1.3 (0.9-1.8)
Hamstrings	21	0.4 (0.3-0.6)	26	0.5 (0.3-0.7)	22	0.4 (0.3-0.6)	14	0.5 (0.3-0.9)
Adductors	7	0.1 (0.1-0.3)	10	0.2 (0.1-0.4)	8	0.2 (0.1-0.3)	1	0.0 (0.0-0.2)
Lower leg flexors	16	0.3 (0.2-0.5)[b,d]	40	0.8 (0.6-1.0)[c]	26	0.5 (0.3-0.7)[b]	28	1.1 (0.7-1.5)[e]
Lower leg extensors	18	0.3 (0.2-0.5)[b,h]	31	0.6 (0.4-0.8)[b]	40	0.8 (0.6-1.0)[c]	37	1.4 (1.0-1.9)[i]
Gastrocnemius/soleus/plantaris	42	0.8 (0.6-1.1)[d]	30	0.6 (0.4-0.8)[d]	93	1.8 (1.5-2.1)[e]	22	0.8 (0.6-1.2)[d]
Muscles of the foot	17	0.3 (0.2-0.5)	27	0.5 (0.4-0.7)	32	0.6 (0.4-0.8)	13	0.5 (0.3-0.8)
Lower leg combined	93	1.8 (1.5-2.1)[f]	128	2.5 (2.1-2.8)[f]	191	3.6 (3.2-4.1)[g]	100	3.8 (3.2-4.4)[g]
Lower extremity—muscle combined	164	3.1 (2.7-3.5)[d,f]	222	4.3 (3.8-4.7)[e]	283	5.4 (5.0-5.8)[g]	152	5.8 (5.2-6.4)[g]

[a]Wilks λ lower extremity—joint ($F_{15,4636} = 1.783$; $P = .001$); lower extremity—muscle ($F_{7,4644} = 3.013$; $P = .0001$). IIR, injury incidence rate (calculated as [*number of injuries/number of team games*] × 10).

Statistically significant at [b,c]$P < .05$, [d,e]$P < .01$, [f,g]$P < .001$, [h,i]$P < .0001$.

TABLE A4
Frequency and Rate of Game-Related High School Football Injuries Between Artificial Turf Infill Systems by Cleat Design, Environmental Factors, and Turf Age[a]

	Infill Weight							
	≥9.0 lb/ft^2 (n = 528)		6.0-8.9 lb/ft^2 (n = 521)		3.0-5.9 lb/ft^2 (n = 525)		0.0-2.9 lb/ft^2 (n = 263)	
Variable	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)	n	IIR (95% CI)
Cleat design								
7-studded removable cleats	129	2.4 (2.1-2.8)[b]	185	3.6 (3.2-4.0)[c]	174	3.3 (2.9-3.7)[c]	75	2.9 (2.3-3.4)[b]
12-studded removable cleats	185	3.5 (3.1-3.9)[d]	219	4.2 (3.8-4.6)[d]	329	6.3 (5.8-6.7)[e]	56	2.1 (1.7-2.7)[d]
Edge/blade-style cleats	106	2.0 (1.7-2.4)[b,f]	107	2.1 (1.7-2.4)[b]	146	2.8 (2.4-3.2)[b]	104	4.0 (3.4-4.6)[c,g]
Molded/hybrid cleats	423	8.0 (7.7-8.3)[d,f,h]	572	11.0 (10.7-11.3)[b,e]	797	15.2 (14.7-15.6)[c,g]	511	19.4 (19.0-19.7)[c,i]
Turf/elastomeric short rubber	74	1.4 (1.1-1.7)[f,h]	241	4.6 (4.2-5.1)[i]	144	2.7 (2.4-3.1)[g]	78	3.0 (2.4-3.5)[g]
Field conditions								
No precipitation/dry field	777	14.7 (14.2-15.1)[d,f]	1083	20.8 (20.4-21.1)[b,e]	1395	26.6 (26.0-27.0)[c,g]	726	27.6 (26.9-28.1)[c,g]
Rain/snow/sleet	72	1.4 (1.1-1.7)[d]	157	3.0 (2.6-3.4)[b,e]	78	1.5 (1.2-1.8)[d]	54	2.1 (1.6-2.6)[c,d]
No precipitation/wet field	68	1.3 (1.0-1.6)[d]	84	1.6 (1.3-2.0)[d]	117	2.2 (1.9-2.6)[e]	44	1.7 (1.3-2.2)[d]
Adverse conditions combined	140	2.7 (2.3-3.0)[d,f]	241	4.6 (4.2-5.1)[g]	195	3.7 (3.3-4.1)[e]	98	3.7 (3.2-4.3)[e]
Temperature								
Cold days (≤59°F)	116	2.2 (1.9-2.6)[b,d,h]	255	4.9 (4.4-5.3)[e]	320	6.1 (5.7-6.5)[i]	147	5.6 (5.0-6.2)[c]
Moderate days (60-79°F)	532	10.1 (9.9-10.2)[f,h]	560	10.7 (10.4-10.9)[d,g]	742	14.1 (13.6-14.6)[e,i]	354	13.5 (12.8-14.1)[e,i]
Hot days (≥80°F)	269	5.1 (4.7-5.5)[h]	509	9.7 (9.5-9.8)[i]	528	10.1 (9.9-10.2)[b,i]	323	12.3 (11.7-12.8)[c,i]
Turf age								
New	91	1.7 (1.4-2.1)[b,d]	136	2.6 (2.3-3.0)[c]	168	3.2 (2.8-3.6)[e]	96	3.7 (3.1-4.2)[e]
1-3 y	390	7.4 (7.0-7.7)[d,h]	481	9.2 (9.0-9.4)[e]	476	9.1 (8.8-9.3)[i]	389	14.8 (14.1-15.4)[i]
4-7 y	379	7.2 (6.8-7.50[f,h]	648	12.4 (12.0-12.8)[i]	691	13.2 (12.7-13.6)[i]	229	8.7 (8.2-9.1)[g]
≥8 y	57	1.1 (0.8-1.4)[h]	59	1.1 (0.9-1.4)[h]	255	4.9 (4.4-5.3)[i]	110	4.2 (3.6-4.8)[i]

[a]Wilks λ cleat design ($F_{4,4646} = 15.570$; $P = .0001$); field conditions ($F_{4,4646} = 6.184$; $P = .0001$); temperature ($F_{2,4649} = 7.520$; $P = .0001$); turf age ($F_{3,4649} = 21.621$; $P = .0001$). IIR, injury incidence rate (calculated as [*number of injuries/number of team games*] × 10).

Statistically significant at [b,c]$P < .05$, [d,e]$P < .01$, [f,g]$P < .001$, [h,i]$P < .0001$.