Published in final edited form as:

Proc Inst Mech Eng P J Sport Eng Technol. 2021 March 01; 235(1): 62–69. doi:10.1177/1754337120949061.

Relating on-field youth football head impacts to pneumatic ram laboratory testing procedures

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Abstract

A youth-specific football helmet testing standard has been proposed to address the physical and biomechanical differences between adult and youth football players. This study sought to relate the proposed youth standard-defined laboratory impacts to on-field head impacts collected from youth football players. Head impact data from 112 youth football players (ages 9–14) were collected through the use of helmet-mounted accelerometer arrays. These head impacts were filtered to only include those that resided in corridors near prescribed National Operating Committee on Standards for Athletic Equipment (NOCSAE) impact locations. Peak linear head acceleration and peak rotational head acceleration magnitudes collected from pneumatic ram impactor tests as specified by the proposed NOCSAE youth standard were compared to the distribution of on-field head impacts. All laboratory impact tests were among the top 10% in terms of magnitude for Severity Index and peak rotational acceleration of matched location head impacts experienced by youth football players. As concussive head impacts are among the most severe impacts experienced on the field, a safety standard geared toward mitigating concussion should assess the most severe on-field head impacts. This proposed testing standard may be refined as more becomes known regarding the biomechanics of concussion among youth athletes.

Keywords

Head acceleration; helmet standards; impact testing

Introduction

Sports-related concussions have received considerable attention as research has shown the potential for long-term, deleterious effects associated with these injuries.[1] Football has a high incidence of brain injury and has been linked to conditions like chronic traumatic encephalopathy (CTE).[1–3] Recently, researchers have related not only a history of concussions, but repeated head impacts in general, that may lead to these lasting effects.[4] Head impact exposure can be mitigated through proper teaching, rule modification, and better equipment.[5–8] Proper teaching and rule modification would predominately focus on

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Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

limiting an athlete's frequency of impact. Better equipment would serve to provide greater protection for head impacts that remain after other methods have been implemented.[5]

Currently, all football helmets are certified by the National Operating Committee on Standards for Athletic Equipment (NOCSAE).[9] This standard was developed to limit catastrophic head injury, like skull fracture, and has succeeded in this regard.[10] The standard currently consists of linear drop tests at a variety of impact speeds with biomechanical thresholds in place that a helmet cannot exceed to be NOCSAE-certified. It has been observed that the NOCSAE testing standard assesses only the most severe impacts that players may experience on the field, and youth and adult football helmets do not differ in terms of performance.[11] In today's game, the most severe head impacts experienced on the field for varsity athletes are associated with concussion, rather than more serious brain injuries or skull fracture. This same information is not yet known for youth athletes. Youth football players are a unique population, differing from adults both in terms of overall head impact exposure and the biomechanics of concussion.[6,12–20] While youth players may experience impacts as severe as adult players, such impacts occur less frequently. On average, impacts at the youth level are associated with lower acceleration levels. As such, the proposed youth testing standard should be evaluated based on conditions more typical of on-field head impacts and the biomechanics of youth concussion.

On-field head impacts from football have been previously paired with laboratory testing for the development of the Virginia Tech STAR Ratings.[21,22] NOCSAE recently proposed a youth-specific testing protocol that considers both linear and rotational head acceleration by using a pneumatic ram impactor, which allows for both linear and rotational head motion, instead of a linear drop tower currently used as the test apparatus.[23,24] Helmets are subjected to a series of impacts at a single impact speed (5.2 m/s) at several impact locations around the helmet, and biomechanical limits (Severity Index < 1200 and peak rotational acceleration < 6000 rad/s^2) must be met in order to be certified under the standard. For comparison, the NOCSAE varsity football helmet standard protocol subjects helmets to pneumatic ram impacts at a velocity of 6 m/s with the same biomechanical limits. More detailed information regarding the standard is presented in the Methods section of this manuscript. The objective of this study was to relate the proposed NOCSAE youth standard to on-field head impacts. The testing protocol should be representative, in that head accelerations measured during standards impact testing should be consistent with the severity of on-field head impacts. Data from this study provide real world context to results from laboratory testing. As the intended goal of the youth testing standard is to mitigate concussions in youth football, relating laboratory impact data to on-field concussion biomechanics is crucial.

Methods

On-field head impact data were collected from youth football players over four seasons between 2015 and 2018 in this study approved by the Virginia Tech Institutional Review Board. A total of 112 youth football players provided verbal assent to participate in this study while their guardians provided written consent. Each athlete wore either Riddell Speed (Speed) or Riddell SpeedFlex (SpeedFlex) youth football helmets, both of which are currently commercially-available. Player ages ranged from 9 to 13 for athletes wearing the Speed helmet and 12 to 14 for athletes wearing the SpeedFlex helmet.

All helmets were instrumented with an accelerometer array associated with the Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH USA). The array consists of six accelerometers mounted on an elastic base to maintain contact between the array and the head throughout impact. This ensures that head acceleration is measured. Previous work has shown that head acceleration represents a small percentage (< 10%) of helmet acceleration.[25] Players wore these instrumented helmets for every game and practice. Any resultant acceleration reading below 10 g was automatically filtered out of the dataset to eliminate acceleration levels associated with running or jumping, rather than head impacts. Linear and rotational head accelerations for valid impacts were computed.[26,27]

These on-field head impact data were filtered to include only those impacts which matched testing locations for the proposed youth standard.[23,24] On-field head impacts within ±15° of azimuth and elevation of a test location were considered representative of standard testing conditions. Each impact recorded by the HIT System is also defined by measures of azimuth and elevation angles to characterize impact location. The standards test locations consider all regions of the helmet, as well as centric and non-centric head impact configurations (Table 1, Figure 1). The azimuth and elevation angles of these impact locations were identified by determining the specific coordinates relative to the center of gravity of the medium-sized NOCSAE headform. An unhelmeted, medium-sized NOCSAE headform was positioned according to the standards test locations (Table 1), and then the distances from the center of the impact location to the coronal, transverse, and sagittal planes of the medium-sized NOCSAE headform were measured. The center of gravity of the medium-sized NOCSAE headform is located 0.223 inches posteriorly to the coronal plane and 1.044 inches superiorly to the basic plane. Angles of azimuth for each location were determined by calculating the inverse tangent between the sagittal and coronal measurements. Angles of elevation were determined by calculating the inverse tangent between the transverse measurement and the hypotenuse that would complete the triangle formed by the sagittal and coronal measurements in the transverse plane (Table 1).

Measurements of y and z-position are relative to the basic plane of the NOCSAE headform. Positive rotation in the y-direction is tilting toward the ram, while positive rotation in the z-direction is clockwise. Positive displacement in the y-direction is represented by motion anterior to the coronal plane, while positive displacement in the z-direction consists of motion superior to the basic plane. The proposed NOCSAE standard also stipulates testing at a non-centric rear boss location and a random location on the helmet, neither of which could reasonably be reconciled to the on-field data.[24]

The NOCSAE testing protocol utilizes a pneumatic ram to impart energy to a head-neck-torso assembly, which is free to move upon impact. The youth-specific testing on the pneumatic ram is conducted at a velocity of 5.2 m/s (±3%) for all test locations, compared to 6.0 m/s for the varsity helmet testing protocol. For a helmet to pass the standard, the Severity Index (SI) value must not exceed 1200 and the peak rotational acceleration must not exceed 6000 rad/s^2. The SI is a correlate of energy transfer to the head during an impact and is defined by acceleration (a) and time (t) as shown in equation (1). At present, the proposed youth standard does not differ from the adult standard in terms of testing equipment.[24]

$$\mathrm{SI} = \int a(t)^{2.5} dt \tag{1}$$

A pneumatic ram linear impactor was used that is in accordance with NOCSAE testing standards (Figure 2). The impactor head weighs 2.3 kg and has a convex face with a radius of 127 mm.[23] A medium NOCSAE headform (57.6 cm circumference) was mounted to a Hybrid III 50th percentile neck as stipulated by the NOCSAE standard. This head and neck assembly, weighing 15.75 kg, was then mounted to a linear slide table (Biokinetics, Ottawa, Canada). The slide table had five degrees of freedom, which allowed for adjustment and consistent orientation of the head and neck for each test. The NOCSAE headform was instrumented with three single-axis accelerometers (Endevco 7264B-2000, Meggitt Sensing Systems, Irvine, CA), as well as a tri-axial angular rate sensor (ARS3 PRO-18K, DTS, Seal Beach, CA). All instrumentation was mounted at the headform center of gravity to allow for linear and rotational head kinematics to be computed with six degrees of freedom. All data were sampled at 20,000 Hz. Linear acceleration data was filtered according to SAE J211 standards (CFC 1000), while angular rate data was filtered at a frequency of 255 Hz.[28] For each test, peak linear resultant head acceleration, peak rotational resultant head acceleration, and SI were computed. It should be noted that the NOCSAE standard does stipulate the use of a nine accelerometer array to compute linear and rotational impact kinematics with all data filtered at a frequency of 300 Hz (CFC 180).

Two models of the Speed and SpeedFlex helmets were tested at four impact locations prescribed by the proposed youth standard that could be matched to on-field data (Table 1). Each helmet-location combination was repeated three times, resulting in 48 total tests. Data from repeated trials were averaged for each helmet and location. For each impact location, a bivariate cumulative distribution function (CDF) that considered SI and peak rotational head acceleration was determined from the on-field head impact data. The averaged values from laboratory impact testing at each location were then mapped to these on-field CDFs to relate the test conditions to on-field biomechanical percentiles.

ANOVA was used to investigate the effect of helmet and impact location on peak rotational acceleration and SI values for the laboratory impact testing data. Tukey's Honest Significant Difference test was used post-hoc to determine which factor levels differed from each other. A significance level of 0.05 was used in this study and the difference in means (Δ) and effect size using Cohen's d (*d*) were reported.

Results

A total of 18,572 head impacts were recorded for the youth players in this study, with 10,099 occurring in the Speed helmet and 8473 in the SpeedFlex helmet. For players wearing the Speed helmet, the median and 95th percentile peak linear head acceleration values were 18.3 g (95% confidence interval (95% CI): 18.0–18.5 g) and 49.5 g (95% CI: 48.4–50.8 g), respectively. The median and 95th percentile peak rotational head acceleration values were 905 rad/s^2 (95% CI: 894–917 rad/s^2) and 2485 rad/s^2 (95% CI: 2425–2544 rad/s^2), respectively. The median and 95th percentile SI values were 4.5 (95% CI: 4.4–4.6) and 50.9 (95% CI: 48.2–54), respectively. Those athletes wearing the SpeedFlex helmet had median and 95th percentile peak linear head acceleration values of 19.9 g (95% CI: 19.7–20.2 g) and 44.3 g (95% CI: 42.9–45.2 g), respectively, and median and 95th percentile peak rotational head acceleration values of 1042 rad/s^2 (95% CI: 1028–1054 rad/s^2) and 2448 rad/s^2 (95% CI: 2397–2513 rad/s^2), respectively. The median and 95th percentile SI values were 8.8 (95% CI: 8.5–9) and 65.3 (95% CI: 61.3–70.8), respectively.

After filtering the on-field head impact data to only include those head impacts which fell within the prescribed impact locations tested, 900 head impacts remained for the Speed (8.9%) and 1218 head impacts remained for the SpeedFlex (14.4%). On-field head impacts for athletes wearing the SpeedFlex were associated with higher magnitudes for the rear ($\Delta = 15$), rear boss ($\Delta = 12$), and front boss ($\Delta = 12$) impact locations for SI relative to impacts for those athletes wearing the Speed, with similar peak rotational head accelerations observed for the two helmet models (Figure 3). There were no observed differences in either SI or peak rotational head acceleration between locations for the Speed. For the SpeedFlex, similar SI values were observed for each impact location. The rear impact location was associated with higher peak rotational acceleration values than the front boss ($\Delta = 339$ rad/s^2) and side ($\Delta = 331$ rad/s^2) impact locations, while the rear boss impact location was associated with higher peak rotational acceleration values than the front boss ($\Delta = 200$ rad/s^2) impact location for the SpeedFlex.

Pneumatic ram impact tests resulted in peak resultant linear acceleration values that ranged from 52.1 to 83.1 g, peak resultant rotational accelerations values that ranged from 2907 to 5871 rad/s^2, and SI values that ranged from 101 to 248. The most severe impact kinematics were observed for the Speed helmet at the front boss impact location. All of the impact tests conducted in this study resulted in impact kinematics that were within the top 10% of on-field head impacts measured for youth players for both helmets (Table 2, Figure 4).

Differences in SI values for pneumatic ram impact tests between the Speed and SpeedFlex helmets were observed for the front boss ($P < 0.0001$, $\Delta = 66$, $d = 6.82$) and rear boss locations ($P = 0.003$, $\Delta = 29$, $d = 2.32$), but not for the rear or side locations ($P > 0.798$, $\Delta < 11$, $d < 1.16$). Differences in peak rotational acceleration were observed for the front boss location ($P = 0.038$, $\Delta = 563$ rad/s^2, $d = 1.52$). For the SpeedFlex helmet, the rear impact location resulted in higher SI values than all other locations ($P < 0.001$, $\Delta > 31$, $d > 7.23$), while the rear boss impact location resulted in lower SI values than all other locations ($P < 0.0001$, $\Delta > 55$, $d > 4.32$). Peak rotational acceleration was observed to be lowest at the rear impact location ($P < 0.002$, $\Delta > 749$ rad/s^2, $d > 2.53$) and highest at the side impact location ($P < 0.0001$, $\Delta > 1320$ rad/s^2, $d > 4.19$). For the Speed helmet, the front boss impact location resulted in higher SI values than all other locations ($P < 0.0001$, $\Delta > 31$, $d > 2.73$) and the rear boss impact location was associated with the lowest SI values among all impact locations ($P < 0.0001$, $\Delta > 44$, $d > 3.91$). Peak rotational acceleration was lowest at the rear impact location ($P < 0.0001$, $\Delta > 1208$ rad/s^2, $d > 4.37$).

Discussion

This study sought to investigate the proposed NOCSAE youth football helmet testing standard on the pneumatic ram as it related to on-field head impact kinematics.[24] SI values and peak rotational head acceleration values for laboratory impacts were observed to be among the hardest head impacts youth football players would experience on the field for both helmets considered in this analysis.

On-field head impacts collected from youth football players over four seasons of play served as the point of comparison for the laboratory results in this study. The median and 95th percentile peak linear head acceleration and peak rotational head accelerations reported here are consistent with previous research with this population.[6,14,29,30] Differences between the on-field distributions of the two helmets were observed. It should be noted that the players in the SpeedFlex helmets were from an older population and only a subset of all head impacts were included in the analysis. This may explain why the acceleration and SI values are greater for the athletes wearing the SpeedFlex helmet.

A helmet testing standard should assess the hardest head impacts that a player may experience on the field. All pneumatic ram impact tests in this study were among the top 10% of head impacts from the on-field data set for both helmets. With the exception of the rear impacts, the impact kinematics produced in lab were in the 97th percentile or greater of the on-field head impacts, though all laboratory impacts were among the 10% of on-field head impacts when considering both SI and peak rotational acceleration (Table 2). The SI values in this study were much lower than the proposed threshold of 1200, and the peak rotational head acceleration values for impacts in this study did not exceed the proposed threshold of 6000 rad/s^2. There is no prescribed rotational acceleration threshold for the other-sized NOCSAE headforms, but it is possible that different kinematic responses may result. All pneumatic ram impact tests were conducted at 5.2 m/s, as prescribed by the proposed NOCSAE youth football helmet testing standard. This velocity is on the upper end of head impact velocities that have been previously reported for youth football.[31]

The proposed youth football helmet testing standard is aimed at mitigating concussion in youth football. The biomechanical limits should then be relevant to youth concussion, and not based on data from older populations for more serious brain and head injuries. Concussions in youth football have been reported for mean peak linear head accelerations of 62.4 ± 29.7 g (range: 26.9–118.4 g), mean peak rotational head accelerations of 2609 ± 1591 rad/s^2 (range: 578–6955 rad/s^2), and mean SI values of 103 ± 88 (range: 12–293).[32] These average youth concussion biomechanics correspond to the 96th percentile of on-field head impacts when considering both linear and rotational head acceleration. The laboratory impacts measured in this study were generally more severe than these average concussion values, though these data suggest that it may be appropriate to have more stringent biomechanical limits for SI and peak rotational head acceleration for helmets to be certified under NOCSAE's youth helmet testing standard in order to mitigate concussions in youth football.

Several limitations of this study should be noted. Firstly, only two football helmets were considered in this analysis, and performance may differ with other helmet models. The two helmets (Riddell Speed and Riddell SpeedFlex) were used as they were the models worn by participants during the on-field data collection. Secondly, only the medium-sized NOCSAE headform and youth large helmets were used for impact testing. Differences in impact performance between headforms or helmet sizes were not assessed. Lastly, the helmet-mounted accelerometers used in the on-field portion of this study have known measurement errors for individual measurements, though this error is minimized when investigating distributions of the head impact data.[33]

Conclusion

The development of a youth-specific testing protocol represents a key step forward by NOCSAE. At present, the proposed standard results in impact kinematics that are consistent with the highest severity head impacts a youth player may experience. This testing standard represents a crucial first step toward considering the differences between youth and adult football players. Impact test results were more severe than the average biomechanics associated with youth concussion from on-field data. In addition, the on-field data was generally much less severe than the biomechanical thresholds stipulated by the NOCSAE youth testing standard. Further knowledge regarding the biomechanics of concussion in youth collected using on-field data will be crucial in refining this proposed youth standard.

Acknowledgements

The content is solely the responsibility of the authors and does not necessarily reflect the official views of the National Institutes of Health. Lastly, the authors appreciate the support of the Institute for Critical Technology and Applied Science at Virginia Tech.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the the National Operating Committee on Standards for Athletic Equipment under Award 1-SAC-2017. Research reported in this publication was supported by the National Institute of Neurological Disorders and Stroke of the National Institutes of Health under Award Number R01NS094410.

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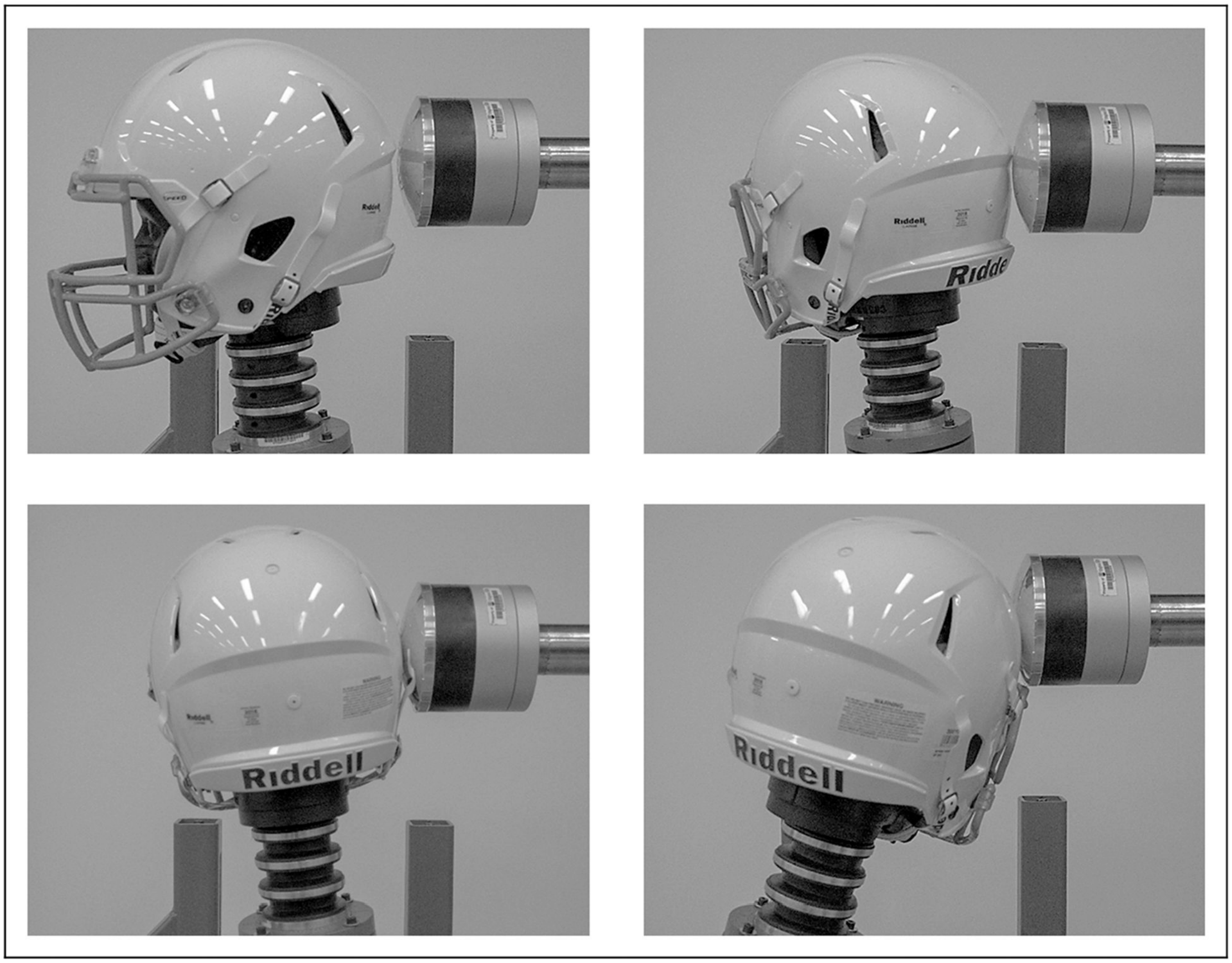

Figure 1.

Pneumatic ram impact test locations. Clockwise from top left: rear, rear boss, front boss, and side. All impacts were conducted with a medium-sized NOCSAE headform and a large youth football helmet.

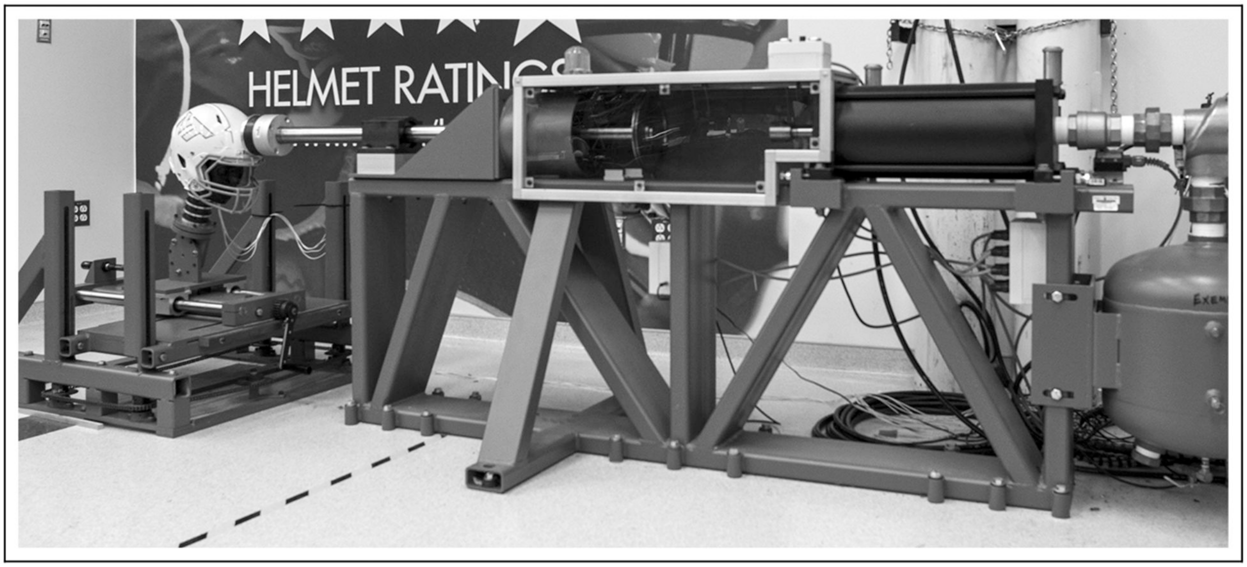

Figure 2.

Pneumatic ram linear impactor. A helmeted headform and neck assembly are mounted on the linear slide table. This system has the capacity to test speeds up to 11 m/s.

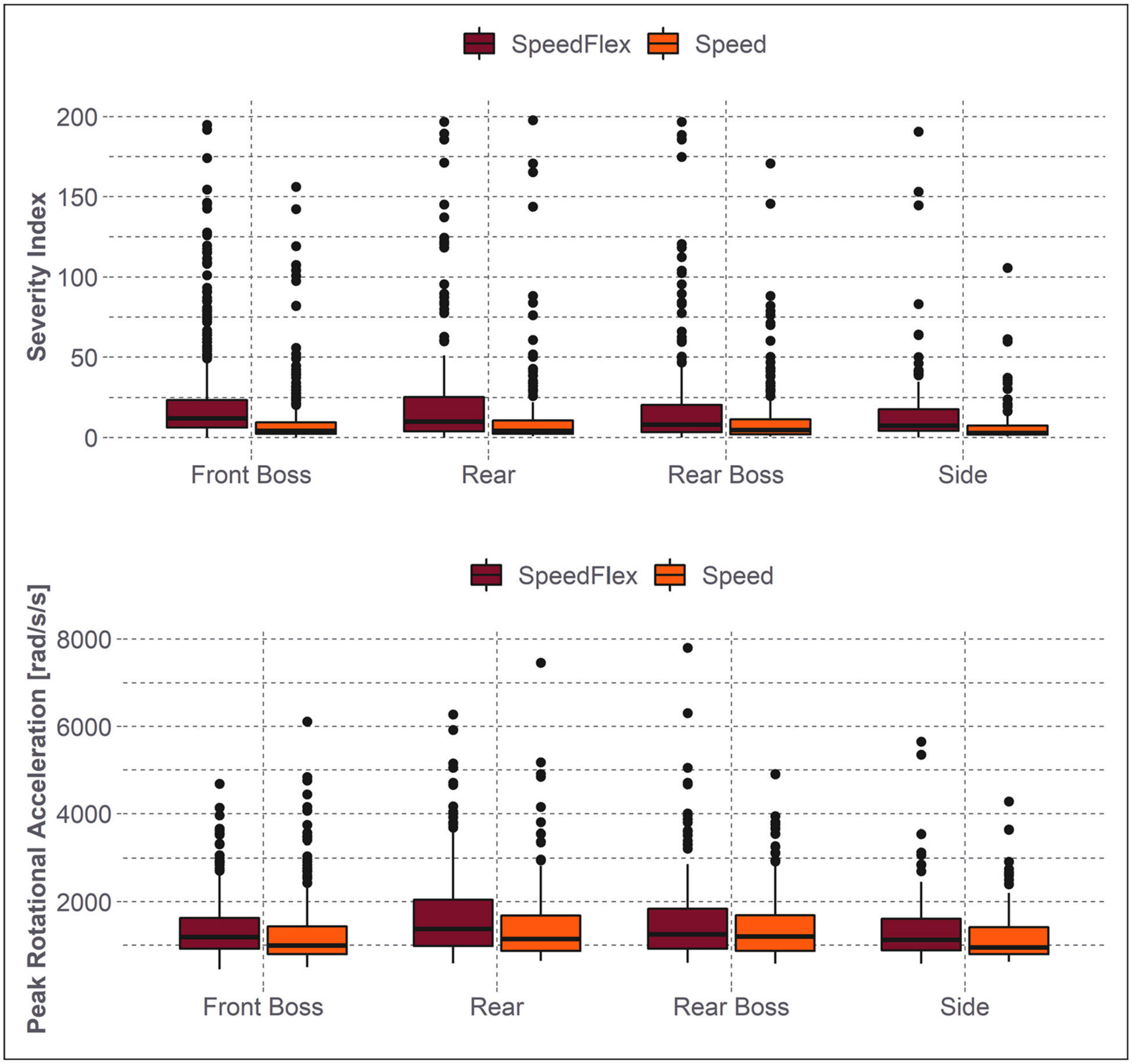

Figure 3.

Summary of on-field data by impact location. Impacts at the rear location for athletes wearing the SpeedFlex helmet were associated with higher peak rotational head acceleration values than the side or front boss impact locations. Differences in on-field head impact distributions between the two helmets may be attributed to differences in player age and helmet impact performance.

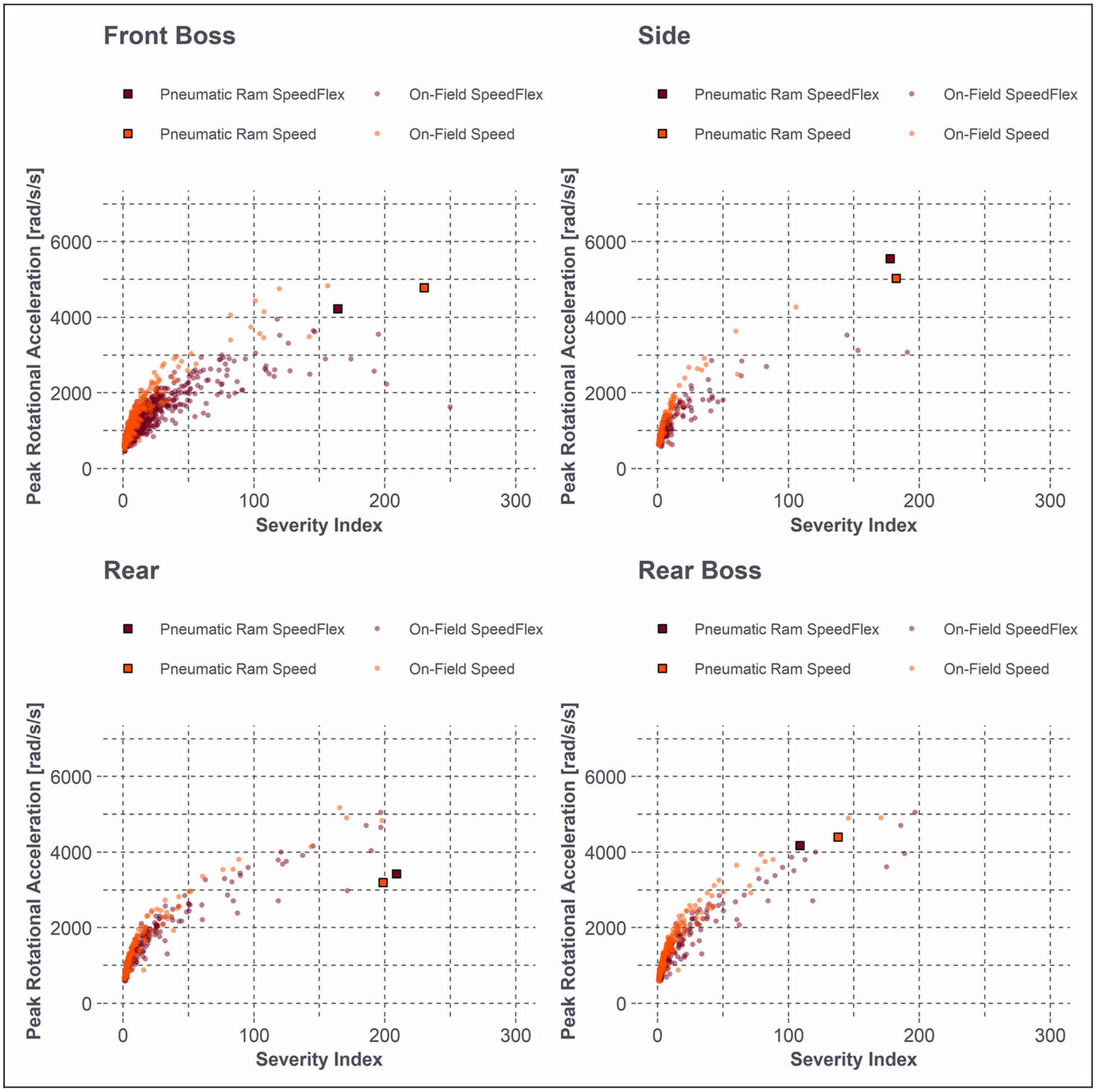

Figure 4.

Relating laboratory impact testing to on-field data by helmet and impact location. On-field data are shown as smaller points, while the average laboratory impact test results are shown as larger squares. The laboratory impacts resulted in biomechanical values that would have been among the highest in the on-field dataset. A small number of on-field head impacts (< 1% of the total dataset) were associated with SI values exceeding 300 or peak rotational acceleration values exceeding 7000 rad/s^2 and are not shown in the figure.

Table 1.

Pneumatic ram impact test locations.

Impact location	Y rotation (deg)	Z rotation (deg)	Y position (mm)	Z position (mm)
Side	7	−90	0	60
Rear Boss (Center of Gravity)	7	−135	−81	60
Rear	7	−180	0	60
Front Boss	15	−60	56	73

Table 2.

Summary of laboratory impact tests mapped to on-field data.

	Location	**SI**	**PRA (rad/s^2)**	**Percentile**
Speed	Front Boss	230 ± 11	4790 ± 334	98.9
	Rear	199 ± 10	3195 ± 191	95.5
	Rear Boss	138 ± 10	4403 ± 302	99.1
	Side	182 ± 11	5030 ± 318	100
SpeedFlex	Front Boss	164 ± 5	4227 ± 340	100
	Rear	209 ± 13	3425 ± 229	91.1
	Rear Boss	109 ± 6	4174 ± 149	97.6
	Side	178 ± 16	5547 ± 224	98.5

Nearly all of the impact configurations were among the top 3% of head impacts experienced by youth football players. SI: Severity Index; PRA: Peak Rotational Acceleration.