Kinematics of Facemask Impacts in Professional American Football

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Abstract Nearly a third of concussions in professional American football are due to impacts to the facemask, however facemask designs have remained mostly unchanged over the past decade. Head acceleration sensors in live sport provide data to potentially guide improvements in design. During the 2019-2022 seasons, 98 players from the NFL were equipped with instrumented mouthpieces that measured six degrees-of-freedom head kinematics. A total of 5104 head acceleration events (HAEs) were collected during 115 player-seasons. Datasets corresponding to the most severe HAEs were generated for the $\geq$90th percentile HARM, peak angular acceleration (PAA), and peak linear acceleration (PLA). Facemask impacts represent 59% of the $\geq$90th percentile HARM sample, with the proportion varying by position group: linemen (66%), hybrid (56%), speed (46%). Similar findings were observed for PLA and PAA. Facemask impacts were primarily due to contact with the helmet shell of the collision partner, with positional variance: linemen (49%), hybrid (43%), speed (33%). This decrease in the hybrid and speed groups was offset primarily by increased impacts to the shoulder of the impact partner. Given the high prevalence of facemask impacts in this sample, future work should be directed towards interventions that reduce the frequency and magnitude of these impacts, including improvement in facemask design and changes to player techniques and rules that mitigate facemask contact.

Keywords American football, facemask, head acceleration events, impact sensors, instrumented mouthguards.

I. INTRODUCTION

Broadly in sport, there has been a focus on reducing the number of concussions sustained by players through both clinical and engineering innovations. From an engineering perspective, prevention strategies in equipment design, technique improvement, and rule changes have been explored. In professional American football, this emphasis combined with enhanced clinical protocols and broad education has resulted in a reduction of 23% in average incidence of National Football League (NFL) game concussions from 2015–2017 to 2018–2019 [1]. The effort has been informed by a detailed review of concussion scenarios – overall and by position – to identify impact locations, impact source, football activity, play type, and collision partner [2-3]. From this review, nearly all (>99%) of concussions in the NFL from 2014–2018 [3] involve direct impact to the concussed player's helmet. The side of the helmet represents the most common impact location, comprising 47% of the concussions [3]. As a result, common football helmet testing programs (e.g., Virginia Tech STAR program, NFL/NFLPA helmet testing program) give high weights to shell impacts in their helmet scoring [4-5] and improvements in helmet test scores mostly derive from material and structural improvements to the helmet shell and liner. Importantly however, the second most frequent impact location is the facemask representing nearly a third of concussions in the NFL [3]. In contrast to helmet shells, facemask designs have remained mostly unchanged over the last decade [6] and potentially represent an opportunity for equipment improvement.

Implementing head acceleration sensors in sport provides an opportunity to understand the kinematics of facemask impacts and to direct improvements in design. For the last two decades, instrumented helmets have been used to collect head acceleration events (HAEs) in American football at the youth [7-8], high school [9-10] and collegiate [11-12] levels. However, laboratory validation studies have demonstrated limited accuracy of peak kinematics measured by instrumented helmets [13-15], particularly for impacts to the facemask, which was attributed to relative motion between the helmet and the head. Mouthguard sensors have been found to have

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increased accuracy compared to other HAE sensor systems due to superior sensor-skull coupling [16-17].

Recently, instrumented mouthpieces (IM) have been implemented with selected teams in the NFL during the 2019–2022 seasons to measure kinematics of HAEs. Players consented to wear the IM during both games and practices, and data was collected passively for later analysis. The quantitative kinematics from the IM were combined with detailed video review and player tracking data from global positioning system data to quantify the severity of HAEs and provide important qualitative contextual information about the scenarios of impact. Together, this combined dataset allows a deep dive into HAEs in professional football – fueling priorities for interventions that mitigate the scenarios that lead to concussion and high severity HAEs. In this manuscript, we utilise this dataset to identify the subset of HAEs with an impact location to the facemask. The contextual data for this subset was reviewed to identify characteristics of facemask impacts that can be used to drive improvements in equipment design.

II. METHODS

A total of 98 football players from the NFL were equipped with instrumented mouthpieces (IM) that measure six degrees-of-freedom head kinematics via triaxial linear (±400 g) and angular (±20 krad/s^2) accelerometers. The IM was validated in both laboratory and on-field studies to accurately quantify the count and severity of HAEs sustained in American football [18-19]. These players were recruited from 12 NFL clubs during the 2019–2022 seasons. All players on these teams were eligible to participate, though participation was optional and approved by the Institutional Review Board at Mount Sinai School of Medicine and the NFL and NFL Players Association, via the NFL-NFLPA Collective Bargaining Agreement.

The data were collected using IMs consisting of two different form factors: a mouthguard and a retainer. Both options consisted of a flexible electronics board (Diversified Technical Systems, Inc., Seal Beach, CA) embedded in thermoplastic materials; however, there was an additional 0.3 mm of thermoplastic material between the board and teeth in the mouthguard. Each participant could choose which form factor they preferred. Mouthpieces were manufactured for each player based on three-dimensional scans of the upper dentition (OPRO Ltd., Hemel Hempstead, UK).

During the study period, IMs were worn during practices and games. This analysis utilises only the game data, as contextual information from video needed to evaluate impact location was only standardised in games. Kinematic data were recorded when the magnitude of acceleration in any of the three cartesian axes of the linear accelerometer exceeded 10 g for more than 1.92 ms (i.e., event trigger). The kinematic data were time stamped to coordinated universal time (UTC) and sampled at a rate of 5.5 kHz for a duration of 70 ms (20 ms pre-trigger and 50 ms post-trigger). After the completion of a game, data were downloaded from the IMs and uploaded to a secure cloud database, where they underwent post-processing and storage for further analysis (Amazon Web Services, Inc., Seattle, WA).

The kinematic data were post-processed as follows: data were debiased using the mean of the pre-trigger signal and filtered using a zero-phase shift, four pole, digital IIR filter with a low pass frequency of 300 Hz (CFC 180). The acceleration data were numerically integrated using the trapezoidal method to calculate linear and angular velocities. The kinematics measured at the IM were transformed to a local head coordinate system through a rigid body transformation defined by the geometry of a medium-sized male headform [18-19-20]. An updated version of a previously developed machine learning (ML) model, described by Gabler *et al.,* 2020 [19] and developed from video verified HAEs from IMs worn by collegiate players during games, was used. Additionally, the IM in this study was equipped with an ambient light sensor (ALS); the ALS was used to determine whether an event occurred while the IM was worn by the player. An IM event was classified as a HAE when the probability output from the ML model exceeded a threshold for HAEs, and readings from the ALS fell below a threshold for ambient light. IM data were time windowed via synchronised video data and player tracking data obtained from a league-wide tracking system, Next Gen Stats (NGS), to determine active time periods for every player-play in every game (Zebra Technologies Corp., Lincolnshire, IL).

Various kinematic-based metrics were calculated from the IM data: resultant peak linear acceleration (PLA), resultant peak angular acceleration (PAA), and resultant peak angular velocity (PAV). Additionally, injury metrics used to evaluate helmet safety were computed for each HAE: Head Injury Criterion (HIC) [20], Diffuse Axonal Multi-Axis General Evaluation (DAMAGE) [21], and Head Acceleration Response Metric (HARM) [5]. (Equations 1-3)

$$HIC = max\left\{(t_2 - t_1)\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}\right\} \quad (1)$$

where a is the resultant linear acceleration and t_2-t_1 is the time duration.

$$DAMAGE = \beta \max_t \{ |\vec{\delta}(t)| \}, \text{where} \quad (2a)$$

$$\ddot{\vec{\delta}}(t) + [m]^{-1}[k]\left(b\dot{\vec{\delta}}(t) + \vec{\delta}(t)\right) = \ddot{\vec{u}}(t) \quad (2b)$$

and m, k, b, and β are parameters for a damped, 3DOF coupled second order system that is an analog for brain deformation response ($\ddot{\vec{\delta}}, \dot{\vec{\delta}}, \vec{\delta}$) to angular acceleration of the skull $\ddot{\vec{u}}$.

$$HARM = 0.0148 * HIC + 15.6 * DAMAGE \quad (3)$$

A multi-faceted approach, incorporating HAE classification (e.g. separating true positives from false positives) via ML and ALS, spatial/temporal windowing via NGS, and video review using time-synchronised video of high severity time histories, was utilised to distinguish HAEs with resultant peak linear acceleration of greater than 10 *g* from spurious events.

Three datasets were curated for analysis: one comprised of HAEs in the 90th percentile and above based on HARM, one comprised of HAEs in the 90th percentile and above for PAA, and one comprised of HAEs in the 90th percentile and above for PLA. Individual video review of each sensor-recorded event in the 90th percentile datasets was performed. For sensor-recorded events that were confirmed as head acceleration events (HAEs), contextual data was coded, including impact activity (i.e., blocking, blocked, tackling, tackled, fall/dive, other), impact location (i.e., facemask, top, front, side, rear) and collision partner impact source (i.e., helmet shell, helmet facemask, shoulder, body, ground). For helmet-to-helmet HAEs, the impact location on the helmet of the collision partner was also coded.

III. RESULTS

A total of 5104 head acceleration events (HAEs) were collected during 115 player-seasons, resulting in 511 HAEs in each $\geq$90th percentile sample (i.e., PLA, PAA, and HARM). The 90th percentile HARM was 3.39; the 90th percentile PAA was 2462 rad/s^2; and the 90th percentile PLA was 33.2 *g*. No concussions were observed in this dataset. The study sample, in terms of player-seasons and HAE count, by position group is provided in Table I. Impacts to the facemask represent 59% of the $\geq$90th percentile HARM sample, 56% of the $\geq$90th percentile PAA sample, and 55% of the $\geq$90th percentile PLA sample. This proportion varies by position group, with 66% of high severity HARM impacts to the facemask of the linemen positions (offensive and defensive linemen), 56% of the hybrid positions (tight end, running back, and linebacker), and 46% of the speed positions (wide receiver and defensive back) (Fig. 1). This importance of facemask impacts for linemen was further emphasised in the $\geq$90th percentile PAA sample. Facemask impacts for linemen represent 66% of this sample contrasted with 48% and 32% for hybrid and speed positions, respectively. The PLA sample showed similar patterns.

TABLE I
$\geq$90TH PERCENTILE STUDY SAMPLE OVERALL AND BY POSITION

Position group	Player-seasons	Number of HAEs		
		PLA	PAA	HARM
All	94	511	511	511
Linemen	48	240	288	239
Hybrid	24	203	160	201
Speed	22	68	63	71

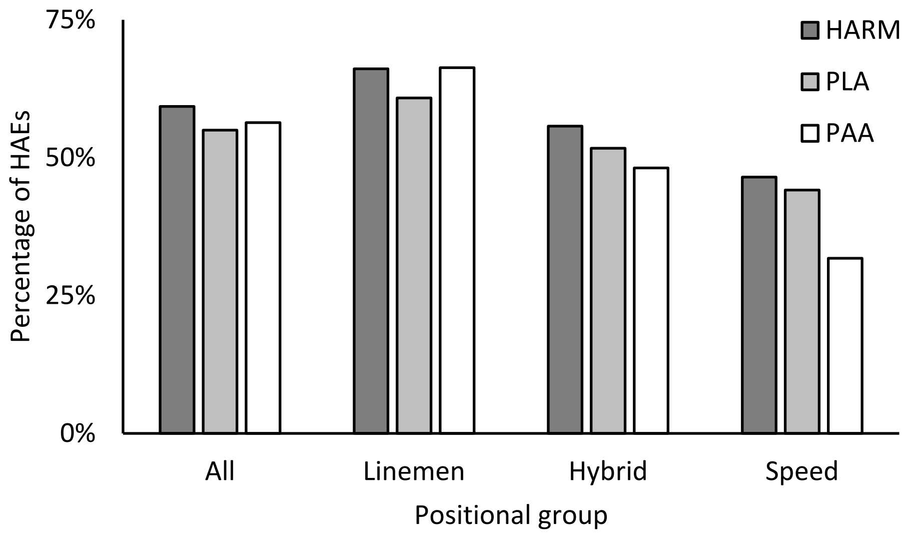

Fig. 1. Percentage of head acceleration events (HAEs) in the study sample that were to the facemask of the instrumented player by positional group. HARM: Head Acceleration Response Metric. PAA: peak angular acceleration. PLA: peak linear acceleration.

The most common player activities for the instrumented player during facemask impacts are described in Table II. For linemen, almost two-thirds of the facemask impacts occurred while they were blocking; for hybrid and speed players it was more evenly distributed across different player activities.

TABLE II
INSTRUMENTED PLAYER ACTIVITY DURING FACEMASK IMPACTS (BASED ON HARM MEASURES)

Activity	All Positions	Linemen	Hybrid	Speed
Blocked	27.9%	24.8%	35.1%	20.0%
Blocking	49.3%	63.7%	35.1%	28.0%
Tackled	2.8%	0	3.9%	12.0%
Tackling	18.1%	11.5%	23.4%	32.0%
Fall/Dive	0.9%	0	1.3%	4.0%
Other	0.9%	0	1.3%	4.0%

Impacts to the facemask of the instrumented player were primarily due to contact with the helmet shell and shoulder of the impact partner (Fig. 2). This however varied by positional group (Fig. 3); in particular, the predominance of the helmet shell of the impact partner decreased, based on HARM measures, from linemen (49%) to hybrid (43%) to speed (33%). This decrease was counteracted by increased impacts to the shoulder of the impact partner and, to a lesser degree, increased impacts to the body and ground (though both remained relatively rare) in the hybrid and speed groups.

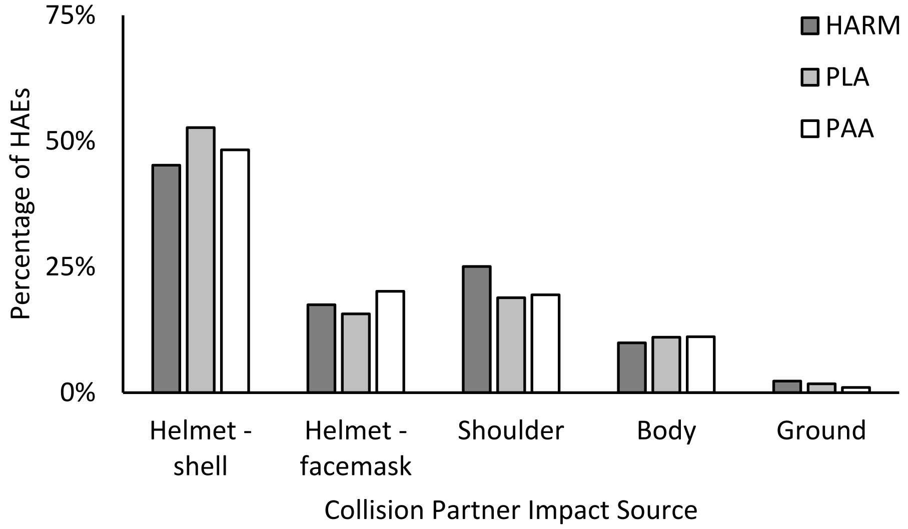

Fig. 2. Distribution of collision partner impact source for facemask head acceleration events (HAEs). HARM: Head Acceleration Response Metric. PLA: peak linear acceleration. PAA: peak angular acceleration.

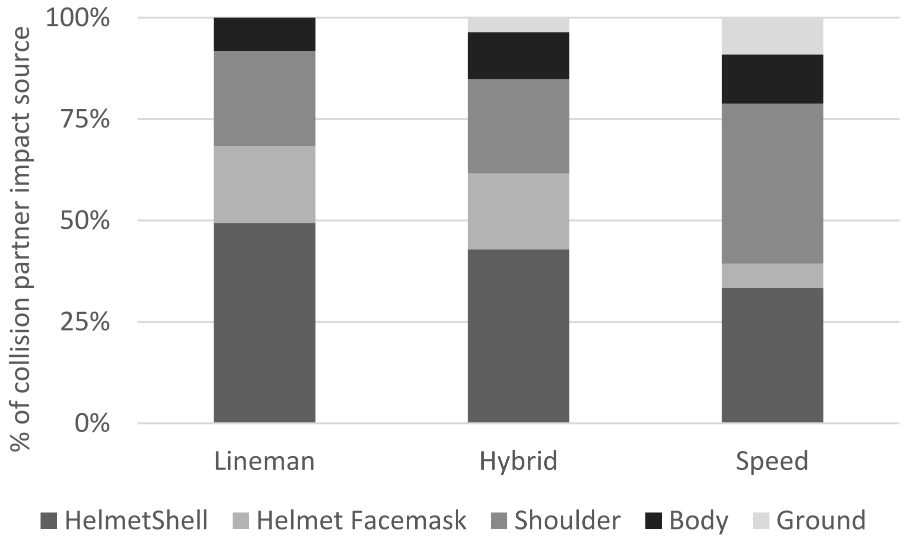

Fig. 3. Distribution of collision partner impact source for facemask head acceleration events (HAEs) stratified by positional group of the instrumented player. Data based on HARM measures.

IV. DISCUSSION

Advancements in technology permit the collection of rigorous HAE data during sports, providing the foundation to drive prevention strategies to potentially mitigate concussions and reduce overall head impact exposure. The analyses in this manuscript are derived from the only kinematic dataset of HAEs in contemporary professional American football, with over 5000 head acceleration events, enhanced with time-synced, multi-dimensional contextual data. Data were collected in the NFL via IMs which demonstrate superior coupling to the skull, improving accuracy, and methods follow recently outlined best practices for head acceleration measurement [22]. This rich dataset was probed to understand the frequency and scenarios of higher severity impacts to the facemask – a component of the helmet identified as stagnant from innovation and thus, an opportunity for improvement.

In the sample studied, representing HAEs in the $\geq 90^{th}$ percentile by severity for HARM, PAA and PLA, impacts to the facemask represent nearly 60% of the sample. This is of particular importance for linemen where 66% of this sample were impacts to the facemask, regardless of whether the metric is HARM or PAA. For hybrid (56% based on HARM sample) and speed position (48% based on HARM sample) groups, facemask impacts represented meaningful, though increasingly smaller proportions. Interesting position-specific patterns exist when examining what proportion of impacts are to the facemask – across the different outcome metrics. For linemen, the proportion of facemask impacts was similar for both the HARM and PAA samples, however facemask impacts for hybrid and speed players represented a smaller proportion when examining the PAA sample compared to the HARM sample. For example, the speed players' facemask impacts represented 46% of the HARM sample, compared to 32% of the PAA sample. HARM is a metric that weights the different rotational directions of impact – with a higher weight applied to axial motion – as opposed to resultant PAA calculation which treats each direction equally. Our findings suggest that hybrid and speed players are experiencing more impacts generating axial rotation compared to linemen, which reflect the interactions players from these positions have during a game. These directional loading differences may guide the development of position-specific facemask design, suggesting a slimmer design for hybrid and speed players to minimise the likelihood of high severity axial impacts.

Examining previously published concussion data from the NFL [3], facemask impacts represent the impact locations for approximately one-third of the concussions for linemen, reducing to approximately one-quarter for other positions. These data suggest that linemen are experiencing frequent and relatively high severity – and in particular high angular severity – facemask impacts that do not result in a concussion. Given the biomechanical basis of angular kinematics as the basis for injury [23-25], the potential cumulative effect of these repetitive impacts that cause no acute injury must be further studied.

When facemask impacts do occur, they are commonly impacting the shell and/or facemask of the collision partner – over two-thirds of the time. Current NFL/NFLPA helmet testing programs incorporate impacts to the facemask by the collision partner impact shell surrogate. Facemask impacts represent the third most heavily weighted impact direction and account for slightly over 20% of the helmet performance score in this testing scheme [5]. Recently, position-specific helmet evaluation methods were introduced and data from impacts to the facemask were upweighted to over 40% in the offensive linemen and defensive linemen test methods – owing to the importance of this loading condition to this position group [26-27]. As uptake of helmets which rate highly on these position-specific test methods increase, further monitoring of HAE kinematics will shed light on the effectiveness of new helmet designs on mitigating energy when the impact is to the facemask. To our knowledge however, there are no specific design modifications that have primarily focused on impact attenuation characteristics of the facemask. These could include structural and material changes to the facemask itself or alterations in how it is attached to the helmet (e.g. attachment location, joint type and flexibility of the attachment). In addition, it is likely that the chin strap plays a role in how the energy of facemask impacts are transmitted to the head and thus, reimagination of this retention system represents an additional opportunity for improvement.

The collision partner impact source data also demonstrates position group variance. Speed players in particular experience facemask impacts to the shoulder of the collision partner – and while still rare, the importance of ground impacts begins to be relevant. The role of shoulder pads in causing injury to those that strike them has been relatively understudied. A recent study demonstrated the capability of a relatively small increase in padding of the shoulder pad to reduce kinematics of a striking head surrogate [28]. This study, however, focused on head impacts to the side of the helmet. Understanding the balance of self-protection and partner protection for shoulder pad design is an area of future equipment design development. Helmet-to-ground impacts have also been relatively understudied with the limited work identifying key kinematic differences between these impacts and traditionally studied helmet-to-helmet impacts [29]. Again, this analysis focuses mainly on helmet shell impacts to the ground; the geometry of the facemask impacting the ground would only amplify the importance of the obliqueness of the impact velocity vector and the interface with the ground surface (natural grass or synthetic turf).

It is important to highlight the need for video review to assess impact location. The vector for resultant head motion generated by the acceleration data is not equivalent to impact location, and therefore the ability to access contextual data in enough detail to review the impact is critical for these types of research questions.

This study has several limitations. While all players on the selected teams were offered the chance to participate, participation was voluntary. As a result, HAEs experienced by the players wearing IMs may not fully represent the player population. The voluntary nature of the study led to unequal participation across positions, with more linemen and less speed and hybrid players. The results herein only evaluate HAE severity in games, and the conclusions cannot be extended to the practice environment. While the $\geq 90^{th}$ percentile HAEs were all confirmed on video, the majority of HAEs below this severity level were not. As a result, some of the impacts below the 90^{th} percentile severity may be false positives; however, the ML model used to classify head impacts had precision greater than 95%. Furthermore, the HAE classifier and trigger configuration used may not have captured all HAEs at the low end of the severity distribution. The classifier defines a HAE as an event where there is clear contact with the player's helmet, resulting in a visible change in the trajectory of the helmet [19]. This definition addresses direct head contact, as described in a recent consensus study [30]. While it is possible that indirect or inertial head accelerations were included in the severity distributions, these events are typically of lower magnitude and are unlikely to have a significant effect on the overall distribution of HAEs exceeding 10 g [31].

V. CONCLUSION

Similar to their high prevalence among concussions, facemask impacts comprise a majority of high severity impacts in American professional football, based on IM data. This is particularly important for positions of offensive and defensive linemen. Due to helmet design, impacts to this location have a larger effective moment arm and generate higher angular kinematics than impacts to other helmet locations. It is important to direct future work towards interventions that reduce the frequency and magnitude of these impacts. These interventions should encompass improvements in facemask design, as well as changes to rules and enforcement of those rules to mitigate facemask contact.

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