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Position-Specific Circumstances of Concussions in the NFL: Toward the Development of Position-Specific Helmets

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Abstract—Consideration of position-specific features of the NFL concussion environment could enable improved risk mitigation through the design of position-specific helmets to improve self-protection as well as protection for the other player with whom the contact occurs. The purpose of this paper is to quantify position-specific features of scenarios resulting in concussions to NFL players, and the players they contact, by reviewing all game footage (broadcast and non-broadcast) over 4 seasons. Position-specific features were documented for 647 concussions in which a primary exposure could be visualized, including impact source, helmet impact location, activity, and the other player with whom the contact occurred. Findings include the over-representation of helmet-to-ground impacts to the rear of the quarterback's helmet, the high frequency of impacts to the side (upper) location of both concussed players and the players they contacted regardless of position, and distinct differences in the circumstances of concussions to cornerbacks and safeties. The study shows that some features of concussion scenarios are common to all positions, but several position-specific features exist and can inform the design of position-specific helmets for NFL players.

Keywords—Head injury, Biomechanics, Helmet design.

INTRODUCTION

Each of the 22 on-field players in an American football game performs a set of tasks that reflects the unique responsibilities of the player's position. Thus, players experience different impact environments and different injury risk and causation profiles depending on the positions they play (e.g., References[7,8,16]). The National Football League (NFL) has embarked on a multi-year effort to improve the understanding of the biomechanics of head injuries in professional football and to enable the development of improved protective equipment.[17] The development of position-specific helmets, optimized to mitigate concussion risk in each position's environment, represents an opportunity to further mitigate concussion risk. Such designs would consider

1. *Self-protection*, or how well a helmet protects the player wearing it. This would be facilitated, for example, by knowing position-specific distributions of head impact location, magnitude, and frequency for concussed players, as well as the different impact sources (the ground, another helmet, or another body region) encountered by each position, and
2. *protection for the player with whom they come into contact*, or how well a helmet manages forces associated with concussion in an opposing player during a helmet-to-helmet impact. This would be

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facilitated, for example, by knowing position-specific distributions of head impact location in positions that cause concussions when striking another player in a helmet-to-helmet impact, such as a running back striking a linebacker's helmet and causing a concussion to the linebacker.

Past studies have attempted to quantify some position-specific aspects of head impacts in American football, using sensors (e.g., References[3–5,9,12,15,19]) and video analysis (e.g., References[2,12,13]). None of these studies, however, describes the position-specific features of head impacts with sufficient accuracy, representativity, and detail to facilitate the design of position-specific helmets for the NFL, and none to our knowledge have quantified position-specific aspects of incompatibility (i.e., the degree to which a position puts another position at increased risk). Current sensor systems can be prone to error in resolving helmet impact location[1,6,11,12,20] and have not been widely used on-field in the NFL. Video-based analyses have either not focused on the NFL[12] or have not focused specifically on position-specific helmet impact location and the other player with whom a concussed player comes into contact.[2,13,18]

Lessley *et al.*[13] developed a method to document game concussions in the NFL using a detailed visual analysis of game video footage of concussions reported in the NFL's Electronic Medical Record (EMR) system. The results of that study revealed position-specific trends that suggested opportunities for position-specific interventions. The purpose of the current study is to employ that method on additional years of game video and expand the analysis of the combined dataset to inform the design of position-specific helmets with consideration of both the concussed player, and also the player with who they come into contact, in helmet-to-helmet impacts.

This video analysis does not consider non-concussive head impacts, for which there is growing research interest (e.g., [21]), nor does it allow for the quantification of impact severity, so this study is a necessary but insufficient component of a comprehensive ongoing effort to develop a knowledge base upon which to design position-specific helmets. Concurrent efforts are underway to document non-injurious impact exposures (any contact to the head) in the NFL and to quantify the magnitude and frequency of head impacts experienced by NFL players. The current study focuses on the impact location (the specific location on the helmet), impact source (e.g., the specific body region of a contacted player or the ground), the other player with whom the contact occurs, and the players' activities when a concussion was sustained in an NFL game.

MATERIALS AND METHODS

Concussions sustained by NFL players during games are diagnosed with the NFL Game Day Concussion Diagnosis and Management Protocol and recorded in the NFL's league-wide electronic medical record (EMR) system.[13] The NFL EMR was negotiated between the NFL and the NFL Players Association to serve, in part, as a workplace injury surveillance system. NFL players sign authorization forms for the data provided to this system to be used in furtherance of certain research approved by the league and the union. This study underwent that review and was approved by the parties.

The methodology of Lessley *et al.*[13] was used for the current study, including the same injury identification method, inclusion criteria, identification of injury play, video footage sources, multi-reviewer process, and video review definitions. The data reported here, combined with the data reported by Lessley *et al.*,[13] yield a dataset of all reported concussions sustained in an NFL preseason, regular season, or postseason game played during the 2014–2015, 2015–2016, 2016–2017, and 2017–2018 seasons. Each diagnosed concussion was reviewed to determine the injury play, primary exposure, primary helmet impact source, primary helmet impact location, and the activities of both the player and the player with whom they came into contact, for each player-position.

Player-position was described by one of ten generalized position categories: cornerback (CB), defensive line (DL), kicker (K), linebacker (LB), offensive line (OL), quarterback (QB), running back (RB), safety (S), tight end (TE), and wide receiver (WR). Each player was assigned to the most appropriate position category based on his listed roster position at the time of the game. While the roster position provides a consistent basis to assign player-position for this study, it is possible that a player may perform some activities in a position that is different from that listed on the roster, particularly on special teams plays. For that reason, analyses were performed on 1) the dataset of all identified primary exposures and 2) a subset that excluded special teams plays (viz., kickoffs, punts, and field goals). Finally, for the analyses that focused on incompatibility, a subset that included only helmet-to-helmet impacts was analyzed with specific focus on the player with whom the concussed player came into contact.

To discriminate between the concussed player (P1), and the player with whom they came into contact (P2), the following definitions were developed for comparison analysis:

P1 – the player that sustained a concussion

P2 – another player who contacted P1 during the impact that resulted in P1 sustaining a concussion

Additionally, P2 is not always a member of the opposing team and can be (in some circumstances) a member of the same team. In rare circumstances, P2 may also have been concussed (which can occur if two players sustain a concussion resulting from the same helmet-to-helmet impact). In cases where P1 was concussed from an impact with the ground rather than from contact with another player, the ground was designated as P2. This was necessary to ensure that each P1 had a corresponding P2, and to incorporate the apportioning of ground-sourced concussions in the overall distribution of P2.

Descriptive statistics were calculated for the following outcome measures stratified by position: helmet impact location, helmet impact source, P1 activity, play type, P2, and P2 activity. Impact characteristics related to both P1-protection and P2-protection were considered. These findings are then discussed in a narrative fashion highlighting priorities and specific traits of concussive events in each position category, with a focus on attributes that could inform the design of position-specific helmets. An *Incompatibility* metric is introduced for informing the relative significance of P1- and P2-protection for each position. In helmet-to-helmet impacts, the distributions of P1 and P2 are not uniform across positions. In other words, some positions have a higher concussion count ($\mathrm{P1count_{position}}$) in helmet-to-helmet impacts, and some positions are more frequently P2, the player that is contacted ($\mathrm{P2count_{position}}$). The helmet-to-helmet *Incompatibility* of a position is defined in those terms as

$$\mathrm{Incompatibility} = \mathrm{P2count_{position}}/\mathrm{P1count_{position}}$$

The *Incompatibility* of a position is simply the ratio of the number of times a player at that position was P2 (player that was contacted) in a helmet-to-helmet impact divided by the number of times a player at that position was P1 (player that was concussed) in a helmet-to-helmet impact with any other player.

RESULTS

Over the four NFL seasons analyzed, 851 concussions were sustained during game play by 685 unique players. The injury play could be identified in 735 (86.4%) cases, and of these the primary exposure could be identified in 647 (88.0%) (Fig. 1). In 88 (12.0%) cases in which the injury play was identified, the primary exposure could not be identified either due to obscured visualization of the injury event or the presence of multiple exposures of similar severity precluding the positive identification of a primary exposure. Of the 647 cases in which a primary exposure could be identified, 646 (99.8%) involved a direct impact to P1's helmet. The final dataset for detailed analysis comprised these 646 cases (Fig. 1). Consistent with Lessley *et al.*[13], no concussions were sourced to a mechanism other than a direct blow to the helmet or head.

Overall Distributions (n = 646 Concussed Players, Primary Exposure Identified)

Cornerbacks sustained the greatest proportion of concussions (21%) and kickers the lowest (1%) (Table 1). The side (upper) was the most common helmet impact location across all positions (39.3% of concussions) and was the most common location for each position except defensive linemen (32.9% to the facemask (central)) (Table 1). Across all positions, the most common impact source was another player's helmet (39.3% of concussions), but there was pronounced position specificity. The most common impact source for cornerbacks (39.1%) and safeties (48.5%) was the body of another player, and for quarterbacks it was the ground (51.5%). The most common P1 activity across all positions was tackling (39.9% of concussions) and this activity was associated with the majority of concussions sustained by all defensive positions, viz. cornerbacks (74.6%), safeties (83.3%), linebackers (65.1%), and defensive linemen (51.2%). On offense, wide receivers (62.4%), tight ends (52.5%), running backs (64.6%), and quarterbacks (93.9%) all sustained the majority of their concussions while being tackled. Offensive linemen were most frequently concussed while blocking (79.5%). Most concussions (52.9%) were sustained on passing plays, and concussions for quarterbacks were almost exclusively on pass plays (93.9%). Concussions to linebackers, offensive linemen, and defensive linemen were roughly evenly distributed between rushing and passing plays, whereas running backs sustained 41.7% of their concussions on rushing plays and 22.9% on passing plays. Across all P1 positions, the most common P2 was a linebacker (22.1% of concussions), followed by the ground (16.3%), a running back (15.9%), a safety (12.5%), and a defensive lineman (11.1%). The most common P2 for concussed cornerbacks (25.4%), linebackers (30.1%), and safeties (45.5%) was a running back, whereas the most common P2 for concussed offensive linemen (41.0%), tight ends (34.4%), and running backs (41.7%) was a linebacker. The leading P2 for concussed wide receivers were the ground and a safety (30.1% each). Concussed defensive linemen exhibited the most uniform distribution of P2. Surprisingly, their most common P2 was another defensive lineman (22.0%), and they were also frequently con-

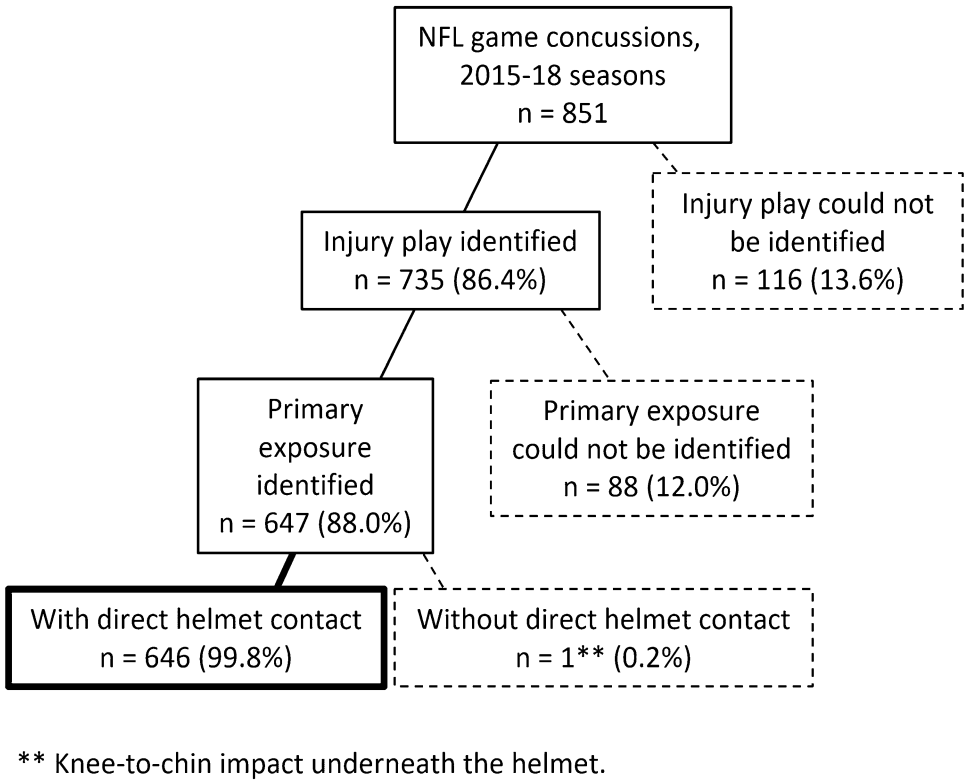

FIGURE 1. Breakdown of concussion cases during the 2015–2018 seasons. NFL, National Football League.

cussed by a linebacker (14.6%). Running backs (17.1%) and the ground (14.6%) were similarly represented as P2 for defensive line.

Non-Special Teams Plays (n = 513, Primary Exposure Identified)

When special teams plays were removed from the dataset, most of the trends described above persisted. The percent distribution of helmet impact location and impact source, for example, were virtually unchanged. Furthermore, the ranking of P1 activity, P2, and P2 activity were similar (Table 2). Tackling, for example, remained the most common P1 activity. Cornerbacks (84.3%), linebackers (78.2%), safeties (94.4%), and defensive linemen (58.8%) all sustained the majority of their concussions while tackling. Wide receivers (68.9%) and tight ends (65.3%) were most frequently concussed while being tackled, while quarterbacks (93.9%) and running backs (93.5%) were concussed almost exclusively during that activity. Offensive linemen were most frequently concussed while blocking (83.8%).

When only helmet-to-helmet impacts were considered ($n = 186$), the most frequent activities remained tackling (36.6% of concussions), being tackled (35.5%), and blocking (17.7%) (Table 3). Linebackers (28.0%) and safeties (21.5%) were the most common P2, followed by defensive linemen and running backs (12.9% each).

Incompatibility

Linebackers, safeties, and defensive linemen had the highest *Incompatibility* (Fig. 2). They were P2 more than twice as often as they were P1 in helmet-to-helmet impacts. Running backs also had an *Incompatibility* greater than 1.0. They were P2 50% more often than they were P1 in helmet-to-helmet impacts. All other offensive players had *Incompatibility* of 0.5 or lower, with quarterbacks having a value of 0.0 (they were never the helmet-to-helmet P2 over the seasons studied here). Cornerbacks were the only defensive position to have an *Incompatibility* less than 1.0, with the ratio of 0.4 reflecting the high frequency of concussions to cornerbacks and how infrequently they are P2 in helmet-to-helmet impacts.

Using this *Incompatibility* metric, positions can be grouped by the less incompatible (*Incompatibility* $<$ 1.0) and the more incompatible (*Incompatibility* $>$ 1.0). The impact locations of P1 in the more vulnerable category (i.e., priority locations for P1-protection) and of P2 in the more incompatible category (i.e., priority locations for P2-protection) are reported in Table 4.

TABLE 1. Counts of P1 Position by P1 Helmet Impact Location, P1 Helmet Impact Source, P1 Activity, Play Type, P2, and P2 Activity for All Cases (*n*=646).

		Counts by P1 Position (All Cases, *n* = 646)											
		CB	WR	LB	OL	S	TE	RB	DL	QB	K	Subtotal	%
P1 Helmet Impact Location	Top	11.0	4.5	6.5	5.0	3.5	4.0	2.5	1.0	1.0	0.0	**39.0**	**6.0**
	Front	9.0	5.3	9.0	11.0	5.0	6.0	10.0	2.8	0.5	0.0	**58.7**	**9.1**
	Side (upper)	60.0	37.2	33.2	29.0	29.0	24.0	20.0	10.0	10.3	1.5	**254.2**	**39.3**
	Side (lower)	11.5	7.8	2.3	4.5	8.3	7.5	4.2	1.8	1.0	1.0	**50.0**	**7.7**
	Rear (upper)	15.0	8.5	3.0	7.5	2.0	6.5	1.5	4.0	11.8	0.5	**60.3**	**9.3**
	Rear (lower)	0.5	0.0	0.0	1.5	0.0	1.0	0.0	1.0	1.5	0.0	**5.5**	**0.9**
	Facemask (central)	13.8	14.5	17.0	9.5	7.3	7.3	4.0	13.5	1.5	1.0	**89.5**	**13.9**
	Facemask (upper edge)	5.3	6.3	4.8	4.5	3.5	1.8	1.8	4.2	1.0	0.5	**33.8**	**5.2**
	Facemask (side edge)	11.8	8.8	7.2	5.5	7.3	2.8	4.0	2.7	4.3	0.5	**55.0**	**8.5**
	Subtotal	**138.0**	**93.0**	**83.0**	**78.0**	**66.0**	**61.0**	**48.0**	**41.0**	**33.0**	**5.0**	**646.0**	100.0
	%	**21.4**	**14.4**	**12.8**	**12.1**	**10.2**	**9.4**	**7.4**	**6.3**	**5.1**	**0.8**	100.0	
P1 Helmet Impact Source	Body*	54.0	9.0	28.0	17.0	32.0	14.0	8.0	11.0	5.0	1.0	**179.0**	**27.7**
	Ground	19.0	28.0	6.0	10.0	1.0	11.0	7.0	6.0	17.0	0.0	**105.0**	**16.3**
	Helmet	39.0	41.0	38.0	32.0	22.0	30.0	26.0	15.0	8.0	3.0	**254.0**	**39.3**
	Pure Shoulder	26.0	15.0	11.0	19.0	11.0	6.0	7.0	9.0	3.0	1.0	**108.0**	**16.7**
	Subtotal	**138.0**	**93.0**	**83.0**	**78.0**	**66.0**	**61.0**	**48.0**	**41.0**	**33.0**	**5.0**	**646.0**	100.0
	%	**21.4**	**14.4**	**12.8**	**12.1**	**10.2**	**9.4**	**7.4**	**6.3**	**5.1**	**0.8**	100.0	
P1 Activity	Blocked	17.0	9.0	22.0	8.0	4.0	5.0	3.0	10.0	0.0	0.0	**78.0**	**12.1**
	Blocking	2.0	2.0	5.0	62.0	5.0	17.0	10.0	5.0	0.0	0.0	**108.0**	**16.7**
	Tackled	3.0	58.0	0.0	1.0	1.0	32.0	31.0	0.0	31.0	1.0	**158.0**	**24.5**
	Tackling	103.0	9.0	54.0	4.0	55.0	5.0	3.0	21.0	0.0	4.0	**258.0**	**39.9**
	Diving/Leaping	8.0	15.0	0.0	0.0	0.0	2.0	1.0	1.0	0.0	0.0	**27.0**	**4.2**
	Other	5.0	0.0	2.0	3.0	1.0	0.0	0.0	4.0	2.0	0.0	**17.0**	**2.6**
	Subtotal	**138.0**	**93.0**	**83.0**	**78.0**	**66.0**	**61.0**	**48.0**	**41.0**	**33.0**	**5.0**	**646.0**	100.0
	%	**21.4**	**14.4**	**12.8**	**12.1**	**10.2**	**9.4**	**7.4**	**6.3**	**5.1**	**0.8**	100.0	
Play Type	Passing	80.0	71.0	28.0	34.0	30.0	40.0	11.0	17.0	31.0	0.0	**342.0**	**52.9**
	Rushing	35.0	3.0	27.0	34.0	24.0	9.0	20.0	17.0	2.0	0.0	**171.0**	**26.5**
	Kickoff	11.0	7.0	18.0	3.0	8.0	5.0	12.0	6.0	0.0	4.0	**74.0**	**11.5**
	Punt	11.0	12.0	10.0	4.0	4.0	7.0	5.0	0.0	0.0	1.0	**54.0**	**8.4**
	FG/ExP	1.0	0.0	0.0	3.0	0.0	0.0	0.0	1.0	0.0	0.0	**5.0**	**0.8**
	Subtotal	**138.0**	**93.0**	**83.0**	**78.0**	**66.0**	**61.0**	**48.0**	**41.0**	**33.0**	**5.0**	**646.0**	100.0
	%	**21.4**	**14.4**	**12.8**	**12.1**	**10.2**	**9.4**	**7.4**	**6.3**	**5.1**	**0.8**	100.0	
P2	LB	17.0	20.0	14.0	32.0	7.0	21.0	20.0	6.0	6.0	0.0	**143.0**	**22.1**
	Ground	19.0	28.0	6.0	10.0	1.0	11.0	7.0	6.0	17.0	0.0	**105.0**	**16.3**
	RB	35.0	0.0	25.0	1.0	30.0	2.0	1.0	7.0	0.0	2.0	**103.0**	**15.9**
	S	16.0	28.0	4.0	3.0	2.0	12.0	12.0	4.0	0.0	0.0	**81.0**	**12.5**
	DL	5.0	2.0	7.0	27.0	2.0	8.0	3.0	9.0	9.0	0.0	**72.0**	**11.1**
	WR	23.0	5.0	9.0	2.0	17.0	0.0	1.0	1.0	0.0	1.0	**59.0**	**9.1**
	TE	11.0	0.0	7.0	0.0	6.0	2.0	1.0	2.0	0.0	0.0	**29.0**	**4.5**
	CB	5.0	8.0	2.0	1.0	1.0	5.0	2.0	1.0	1.0	2.0	**28.0**	**4.3**
	OL	4.0	2.0	8.0	2.0	0.0	0.0	1.0	4.0	0.0	0.0	**21.0**	**3.3**
	QB	3.0	0.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	**5.0**	**0.8**
	K	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
	Subtotal	**138.0**	**93.0**	**83.0**	**78.0**	**66.0**	**61.0**	**48.0**	**41.0**	**33.0**	**5.0**	**646.0**	100.0
	%	**21.4**	**14.4**	**12.8**	**12.1**	**10.2**	**9.4**	**7.4**	**6.3**	**5.1**	**0.8**	100.0	
P2 Activity	Tackling	33.0	47.0	14.0	6.0	9.0	26.0	26.0	12.0	14.0	1.0	**188.0**	**29.1**
	Tackled	60.0	6.0	33.0	2.0	46.0	3.0	2.0	7.0	0.0	4.0	**163.0**	**25.2**
	NA†	19.0	28.0	6.0	10.0	1.0	11.0	7.0	6.0	17.0	0.0	**105.0**	**16.3**
	Blocked	5.0	2.0	7.0	49.0	4.0	18.0	9.0	9.0	0.0	0.0	**103.0**	**15.9**
	Blocking	16.0	9.0	22.0	8.0	5.0	3.0	4.0	5.0	0.0	0.0	**72.0**	**11.1**
	Other	5.0	1.0	1.0	3.0	1.0	0.0	0.0	2.0	2.0	0.0	**15.0**	**2.3**
	Subtotal	**138.0**	**93.0**	**83.0**	**78.0**	**66.0**	**61.0**	**48.0**	**41.0**	**33.0**	**5.0**	**646.0**	100.0
	%	**21.4**	**14.4**	**12.8**	**12.1**	**10.2**	**9.4**	**7.4**	**6.3**	**5.1**	**0.8**	100.0	

† - P2 is the ground.

TABLE 2. Counts of P1 Position by P1 Activity, P2, and P2 Activity for All Cases in Non-Special Teams Plays (n = 513).

		Counts by P1 Position (Non-ST plays, n = 513)										
		CB	WR	OL	LB	S	TE	DL	QB	RB	Subtotal	%
P1 Activity	Tackling	97.0	3.0	2.0	43.0	51.0	3.0	20.0	0.0	0.0	**219.0**	**42.7**
	Tackled	1.0	51.0	0.0	0.0	0.0	32.0	0.0	31.0	29.0	**144.0**	**28.1**
	Blocking	0.0	2.0	57.0	1.0	0.0	11.0	1.0	0.0	2.0	**74.0**	**14.4**
	Blocked	6.0	3.0	6.0	10.0	2.0	1.0	9.0	0.0	0.0	**37.0**	**7.2**
	Diving/Leaping	7.0	15.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	**24.0**	**4.7**
	Other	4.0	0.0	3.0	1.0	1.0	0.0	4.0	2.0	0.0	**15.0**	**2.9**
	Subtotal	**115.0**	**74.0**	**68.0**	**55.0**	**54.0**	**49.0**	**34.0**	**33.0**	**31.0**	**513.0**	100.0
	%	**22.4**	**14.4**	**13.3**	**10.7**	**10.5**	**9.6**	**6.6**	**6.4**	**6.0**	100.0	
P2	LB	11.0	14.0	27.0	5.0	3.0	16.0	4.0	6.0	12.0	**98.0**	**19.1**
	Ground	18.0	26.0	7.0	5.0	0.0	9.0	4.0	17.0	6.0	**92.0**	**17.9**
	RB	31.0	0.0	1.0	19.0	25.0	0.0	6.0	0.0	0.0	**82.0**	**16.0**
	DL	4.0	2.0	26.0	7.0	2.0	8.0	8.0	9.0	2.0	**68.0**	**13.3**
	S	13.0	24.0	3.0	3.0	1.0	11.0	4.0	0.0	9.0	**68.0**	**13.3**
	WR	19.0	0.0	1.0	3.0	17.0	0.0	1.0	0.0	0.0	**41.0**	**8.0**
	TE	11.0	0.0	0.0	6.0	6.0	0.0	1.0	0.0	0.0	**24.0**	**4.7**
	CB	1.0	8.0	1.0	1.0	0.0	5.0	1.0	1.0	2.0	**20.0**	**3.9**
	OL	4.0	0.0	2.0	5.0	0.0	0.0	4.0	0.0	0.0	**15.0**	**2.9**
	QB	3.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	**5.0**	**1.0**
	Subtotal	**115.0**	**74.0**	**68.0**	**55.0**	**54.0**	**49.0**	**34.0**	**33.0**	**31.0**	**513.0**	100.0
	%	**22.4**	**14.4**	**13.3**	**10.7**	**10.5**	**9.6**	**6.6**	**6.4**	**6.0**	100.0	
P2 Activity	Tackling	29.0	39.0	5.0	14.0	5.0	25.0	12.0	14.0	23.0	**166.0**	**32.4**
	Tackled	58.0	3.0	1.0	23.0	45.0	2.0	7.0	0.0	0.0	**139.0**	**27.1**
	NA†	18.0	26.0	7.0	5.0	0.0	9.0	4.0	17.0	6.0	**92.0**	**17.9**
	Blocked	1.0	2.0	46.0	2.0	0.0	12.0	5.0	0.0	2.0	**70.0**	**13.6**
	Blocking	6.0	3.0	6.0	10.0	3.0	1.0	4.0	0.0	0.0	**33.0**	**6.4**
	Other	3.0	1.0	3.0	1.0	1.0	0.0	2.0	2.0	0.0	**13.0**	**2.5**
	Subtotal	**115.0**	**74.0**	**68.0**	**55.0**	**54.0**	**49.0**	**34.0**	**33.0**	**31.0**	**513.0**	100.0
	%	**22.4**	**14.4**	**13.3**	**10.7**	**10.5**	**9.6**	**6.6**	**6.4**	**6.0**	100.0	

† - P2 is the ground.

Among the less incompatible positions, the side (upper) helmet impact location is the most common (37.2% of helmet-to-helmet concussions), followed by the facemask (central) (17.0%), facemask (side edge) (11.4%), and side (lower) and front (9.0% each). Interestingly, among the more incompatible positions, P2's helmet impact location was also most frequently the side (upper) (36.8%). In other words, the most common helmet impact location for players both sustaining an injurious helmet-to-helmet impact, and causing one, is the side (upper) location. The top (27.4%) and front (19.5%) helmet impact locations were also common among P2 in the more incompatible positions. There was some additional position sensitivity in that distribution, with defensive linemen most frequently delivering injurious impacts with the front and top, whereas linebackers, safeties, and running backs most frequently caused injurious impacts with the side (upper) location.

DISCUSSION

Overall Distributions and Dataset

This study expands on the Lessley *et al.*[13] paper, which was limited to two seasons of data, by adding two additional years of data and introducing a new metric to evaluate the relative incompatibility of each player position in helmet-to-helmet collisions. The overall distributions in the four seasons analyzed here were similar to those presented by Lessley *et al.*[13]. This similarity suggests that, despite variation in the number of concussions in each season, the circumstances of concussion events in the NFL have been reasonably stable over the four target seasons, and thus that this multi-year dataset provides a reasonable basis for understanding position-specific aspects of concussive events in contemporary NFL play.

Position Summary and Insights for Position-Specific Helmet Design

Ideally, position-specific designs would be optimized to the unique environment of each position. This in-

TABLE 3. Counts of P1 Position by P1 Activity, P2, and P2 Activity for Helmet-to-Helmet Cases in Non-Special Teams Plays (n = 186).

		Counts by P1 Position (Non-ST plays, H2H Only, n = 186)										
		WR	CB	OL	TE	LB	S	RB	DL	QB	subtotal	%
P1 Activity	Tackling	3.0	20.0	2.0	1.0	16.0	18.0	0.0	8.0	0.0	**68.0**	**36.6**
	Tackled	25.0	1.0	0.0	17.0	0.0	0.0	15.0	0.0	8.0	**66.0**	**35.5**
	Blocking	2.0	0.0	23.0	5.0	1.0	0.0	1.0	1.0	0.0	**33.0**	**17.7**
	Blocked	1.0	4.0	2.0	1.0	6.0	0.0	0.0	2.0	0.0	**16.0**	**8.6**
	Other	0.0	2.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	**3.0**	**1.6**
	Diving/Leaping	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
	Subtotal	**31.0**	**27.0**	**27.0**	**24.0**	**23.0**	**18.0**	**16.0**	**12.0**	**8.0**	**186.0**	100.0
	%	**16.7**	**14.5**	**14.5**	**12.9**	**12.4**	**9.7**	**8.6**	**6.5**	**4.3**	100.0	
P2	LB	8.0	3.0	13.0	10.0	2.0	2.0	7.0	3.0	4.0	**52.0**	**28.0**
	S	17.0	4.0	0.0	7.0	2.0	1.0	7.0	2.0	0.0	**40.0**	**21.5**
	DL	1.0	0.0	11.0	3.0	2.0	1.0	1.0	2.0	3.0	**24.0**	**12.9**
	RB	0.0	5.0	0.0	0.0	10.0	7.0	0.0	2.0	0.0	**24.0**	**12.9**
	WR	0.0	9.0	1.0	0.0	1.0	6.0	0.0	0.0	0.0	**17.0**	**9.1**
	CB	5.0	0.0	0.0	4.0	1.0	0.0	1.0	0.0	1.0	**12.0**	**6.5**
	OL	0.0	2.0	2.0	0.0	3.0	0.0	0.0	2.0	0.0	**9.0**	**4.8**
	TE	0.0	4.0	0.0	0.0	2.0	1.0	0.0	1.0	0.0	**8.0**	**4.3**
	QB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
	Subtotal	**31.0**	**27.0**	**27.0**	**24.0**	**23.0**	**18.0**	**16.0**	**12.0**	**8.0**	**186.0**	100.0
	%	**16.7**	**14.5**	**14.5**	**12.9**	**12.4**	**9.7**	**8.6**	**6.5**	**4.3**	100.0	
P2 Activity	Tackling	25.0	9.0	2.0	17.0	6.0	4.0	15.0	6.0	8.0	**92.0**	**49.5**
	Tackled	3.0	14.0	1.0	1.0	9.0	14.0	0.0	2.0	0.0	**44.0**	**23.7**
	Blocked	2.0	0.0	20.0	5.0	2.0	0.0	1.0	2.0	0.0	**32.0**	**17.2**
	Blocking	1.0	3.0	4.0	1.0	6.0	0.0	0.0	2.0	0.0	**17.0**	**9.1**
	Other	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.0**	**0.5**
	Subtotal	**31.0**	**27.0**	**27.0**	**24.0**	**23.0**	**18.0**	**16.0**	**12.0**	**8.0**	**186.0**	100.0
	%	**16.7**	**14.5**	**14.5**	**12.9**	**12.4**	**9.7**	**8.6**	**6.5**	**4.3**	100.0	

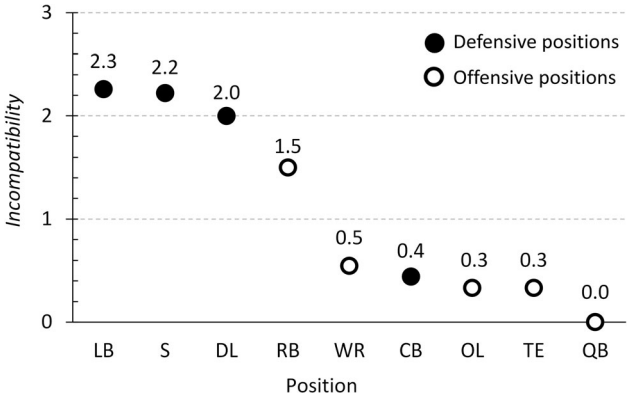

FIGURE 2. Distribution of P2/P1 ratio by position for all helmet-to-helmet cases during non-special teams plays (n = 186).

cludes consideration of P2, impact sources, helmet impact locations, and player activities when concussions occur. Furthermore, the balancing of P1-protection and P2-protection is position-specific, with positions having greater *Incompatibility* justifying greater focus on P2-protection. These aspects of each position are summarized below with a specific focus on findings that may guide the development of position-specific designs.

Position-Specific Concussion Scenarios for Cornerbacks

The most common helmet impact location for cornerbacks is the side (upper). Cornerbacks are the second-most commonly concussed position from helmet-to-ground impacts, with the side (upper) and rear (upper) being the most common impact locations in concussive impacts from the ground.

In non-special teams plays, cornerbacks are concussed most often while tackling, with helmet-to-body impacts being the most common source of concussion (only safeties experience a higher proportion of helmet-to-body concussions). Running backs, wide receivers, and the ground are concussed cornerbacks' most common P2. Cornerbacks are one of the least frequent P2 (i.e., they have low *Incompatibility*). Most often they are the concussed player when involved in a concussive interaction with another player.

TABLE 4. Counts of Helmet Impact Location for Select P1 and P2 Positions in Helmet-to-Helmet Cases in Non-Special Teams Plays.

		Counts by Position (Non-ST, H2H Only)										
		Less Incompatible					More Incompatible					
		WR	CB	OL	TE	QB	LB	S	DL	RB	Subtotal	%
P1	Top	2.0	1.5	2.0	1.5	1.0					**8.0**	**6.8**
	Front	1.5	1.0	5.5	2.5	0.0					**10.5**	**9.0**
	Side (upper)	11.0	9.0	11.5	10.0	2.0					**43.5**	**37.2**
	Side (lower)	3.0	3.0	0.0	3.5	1.0					**10.5**	**9.0**
	Rear (upper)	0.0	2.0	0.0	0.5	0.0					**2.5**	**2.1**
	Rear (lower)	0.0	0.5	0.0	0.5	1.0					**2.0**	**1.7**
	Facemask (central)	6.5	4.5	4.5	2.8	1.5					**19.8**	**17.0**
	Facemask (upper edge)	2.0	1.5	2.0	0.8	0.5					**6.8**	**5.8**
	Facemask (side edge)	5.0	4.0	1.5	1.8	1.0					**13.3**	**11.4**
	Subtotal	**31.0**	**27.0**	**27.0**	**24.0**	**8.0**					**117.0**	**100.0**
P2	Top						13.3	11.0	7.0	7.0	**38.3**	**27.4**
	Front						12.8	5.0	7.5	2.0	**27.3**	**19.5**
	Side (upper)						20.5	17.5	5.0	8.5	**51.5**	**36.8**
	Side (lower)						1.3	2.5	0.5	4.0	**8.3**	**6.0**
	Rear (upper)						0.0	1.0	1.0	1.0	**3.0**	**2.1**
	Rear (lower)						0.0	0.0	0.0	0.0	**0.0**	**0.0**
	Facemask (central)						0.5	1.0	0.5	0.0	**2.0**	**1.4**
	Facemask (upper edge)						1.8	1.0	2.0	1.5	**6.3**	**4.5**
	Facemask (side edge)						1.7	1.0	0.5	0.0	**3.2**	**2.3**
	Subtotal						**52.0**	**40.0**	**24.0**	**24.0**	**140.0**	**100.0**

Comparison of the Less Incompatible P1 Positions with the More Incompatible P2 Positions in Helmet-to-Helmet Impacts.

Position-Specific Concussion Scenarios for Wide Receivers

The helmet impact location for wide receivers trends closely with the average of all cases. The side (upper) location is the most common, but the rear (upper) is also common in helmet-to-ground impacts.

In non-special teams cases, helmet-to-helmet is the most common impact source followed by helmet-to-ground. For wide receivers, being tackled is the most common activity during concussion events. Diving/leaping is more common in wide receivers than in any other position and accounts for most of their helmet-to-ground concussions in non-special teams plays. Being tackled accounts for 81% of their helmet-to-helmet concussions. In non-special teams plays, the ground is the most common P2 (35.1%), though safeties and linebackers combined account for approximately half of wide receivers' concussions. Wide receivers are P2 half as often as they are P1 (i.e., they have low *Incompatibility*).

Position-Specific Concussion Scenarios for Linebackers

Helmet-to-helmet and helmet-to-body (or -shoulder) are the most common sources of concussions to linebackers. The proportion of helmet-to-ground impact source is lower than average. Passing and rushing plays have nearly equal apportioning. Linebackers are most often concussed by running backs. Helmet impact location for linebackers trends closely with the overall average, with a slightly higher prevalence of impacts to the facemask occurring predominantly in helmet-to-shoulder impacts. Tackling is the most common activity during linebacker concussions. Linebackers are the most commonly concussed position in special teams plays, which account for about a third of linebacker concussions.

Linebackers are the most common P2, accounting for about one-fifth of all concussions and are P2 over twice as often as they are P1 in helmet-to-helmet impacts (i.e., they have high *Incompatibility*). Thus, position-specific designs for linebackers should especially focus on both P1- and P2-protection. Linebackers most commonly are involved in impacts that concuss offensive linemen, tight ends, and wide receivers. When linebackers are P2 in helmet-to-helmet impacts, linebackers most frequently contact P1 with the side (upper) helmet impact location, followed by the top and the front in roughly equal proportion.

Position-Specific Concussion Scenarios for Offensive Linemen

The vast majority of concussions to offensive linemen occur while blocking. Passing and rushing plays are equally common. Compared to most other posi-

tions, offensive linemen are less frequently concussed on special teams plays.

In non-special teams plays, helmet-to-helmet and helmet-to-shoulder are the most common impact sources for offensive linemen. Linebackers and defensive linemen are P2 in most of those cases. Concussed offensive linemen experience the highest proportion of helmet-to-shoulder impacts of any position. Helmet impact location trends closely with the overall average. Offensive linemen are infrequently P2 (i.e., they have low *Incompatibility*).

Position-Specific Concussion Scenarios for Safeties

Concussions to safeties occur predominantly when tackling (83.3% of all cases, which is the highest of any position). Passing plays are the most common, followed by rushing plays. Safeties almost never sustain helmet-to-ground concussions, with only one occurrence of a concussive ground impact observed in four seasons. Helmet impact locations for safeties trend closely with the overall average. In non-special teams plays, safeties experience the highest proportion of helmet-to-body impact source of any position, with helmet-to-helmet also being substantial. Only safeties and cornerbacks experience the greatest proportion of their concussions from helmet-to-body impacts. Safeties are most often concussed by running backs and wide receivers.

Safeties have high *Incompatibility*, being P2, 2.2 times more often than they are P1 in helmet-to-helmet impacts. Safeties most often caused concussions when colliding with wide receivers and cornerbacks. In these four seasons, no safety was concussed by a cornerback, but there were 13 occurrences of a cornerback being concussed by a safety. When safeties are P2 in helmet-to-helmet concussions, they most frequently contact P1 with the side (upper) helmet location, followed by the top.

One of the key findings of this study is that the concussion environment of safeties is dramatically different from that of cornerbacks, despite them both playing in the defensive backfield. Safeties have among the highest *Incompatibility*, whereas cornerbacks have among the lowest, and cornerbacks are much more likely to sustain a concussion by falling to the ground. This may reflect a tendency of safeties to start farther back in the defensive secondary and to move forward more often relative to the developing play, whereas cornerbacks typically start closer to the line and more often are called upon to stay with their wide receiver, particularly in ''press'' coverage and more often move away from the developing play. As a result, cornerbacks may be less able to observe potential injurious situations developing. Their starting location often being more lateral on the field may also be a factor. Thus, from a position-specific helmet design perspective, the prioritization of visibility may also differ between safeties and cornerbacks, along with the priorities for P1- and P2-protection.

Position-Specific Concussion Scenarios for Tight Ends

Tight ends are most often concussed during passing plays. Helmet impact location trends closely with the overall average. In non-special teams plays, helmet-to-helmet is the most common impact source, while helmet-to-shoulder is the lowest proportion of any position other than quarterback. Tight ends are concussed most commonly when being tackled, which occurs much more often than when they are being blocked. Tight ends have low *Incompatibility* and are most often concussed by linebackers, safeties, and the ground. In helmet-to-helmet cases, linebackers and safeties account for most tight end concussions.

Position-Specific Concussion Scenarios for Running Backs

Running backs sustain a small proportion of player concussions. They are most commonly concussed in rushing plays, though special teams play accounts for about a third of running backs' concussions, which is the highest proportion of special teams concussions for all non-kicking positions. Running backs' impact locations generally trend with the average, though there is slightly increased involvement of the front of the helmet and slightly less of the facemask and rear of helmet.

In non-special teams plays, helmet-to-helmet is the most common impact source (as P1, running backs have the highest proportion of helmet-to-helmet of any position). Running backs are almost always concussed while being tackled, though occasionally from blocking. Running backs are most commonly concussed by linebackers, followed by safeties.

Running backs are one of the most common P2; only linebackers and the ground produce more concussions. Running backs thus have high *Incompatibility* and are the only offensive position with an *Incompatibility* over 1.0. As P2, running backs most commonly are involved in impacts that concuss cornerbacks and safeties. When restricted to helmet-to-helmet cases, running backs most commonly are involved in impacts that concuss linebackers and safeties. When running backs are P2 in helmet-to-helmet concussions, they most frequently strike the concussed player with the side (upper) helmet location, followed by the top, then the side (lower).

Position-Specific Concussion Scenarios for Defensive Linemen

Defensive linemen are among the least commonly concussed positions. Passing and rushing plays are equally represented. Defensive linemen are unique in the high proportion of concussive impacts to the facemask (central) location and the relatively lower (though still meaningful) proportion to the side (upper) location. Defensive linemen are not commonly concussed on special teams plays.

In non-special teams plays, helmet-to-helmet is the most common impact source, followed closely by helmet-to-body. Defensive linemen are most commonly concussed while tackling, followed by being blocked. Other defensive linemen are the most common P2, followed by running backs and linebackers. Defensive linemen are among the least often concussed in helmet-to-ground impacts.

Defensive linemen have high *Incompatibility*. They most commonly are involved in impacts that concuss offensive linemen, particularly so among helmet-to-helmet cases wherein offensive linemen account for almost half of concussions when P2 is a defensive lineman. When defensive linemen are P2 in helmet-to-helmet concussions, they most frequently contact P1 with the front and top helmet locations, followed by the side (upper).

Position-Specific Concussion Scenarios for Quarterbacks

Concussions to quarterbacks occur nearly exclusively from being tackled during a passing play. The helmet impact location for concussed quarterbacks is unique among positions in the high proportion of impacts that occur to the rear of the helmet. This is particularly pronounced in helmet-to-ground cases. The ground is also the most common impact source, accounting for more than half of all quarterback concussions, which is by far the highest proportion of this impact source for any position. The helmet-to-helmet impact source is also important. In helmet-to-helmet cases, the most common P2 are linebackers and defensive linemen. Quarterbacks are the least common P2 of the non-kicking positions and have an *Incompatibility* of 0. In other words, they were never P2 in a helmet-to-helmet concussion over the four seasons studied here.

The over-representation of helmet-to-ground impacts to the rear of the quarterback's helmet, coupled with the complete absence of *Incompatibility* at that position, suggests that designs focusing energy management to the rear of the helmet, and possibly tuned to the compliance of turf, may be particularly beneficial to quarterbacks. This may, in fact, include consideration of unique helmet shapes that provide additional stroke, and thus energy dissipation, for impacts to the back of a quarterback's helmet.

Position-Specific Concussion Scenarios for Kickers

Concussions to kickers occur infrequently. When these do occur, it is most often when kickers are tackling the returner on a kickoff. The paucity of data for this position precludes isolation of additional position-specific features of this position.

Implications, Limitations, and Future Work

This study is a first step toward a comprehensive description of position-specific injury environments in the NFL. The detailed video review provides insights into the mechanisms and circumstances of concussions in the NFL, and those data have been examined by positions in this paper with the intent of informing the design of position-specific helmets for NFL players. This study lays a foundation for future studies focused on quantifying the magnitudes and frequencies of impacts, both concussive and not, experienced by players in each position. Work in this area is ongoing, including video review of non-concussive impacts, on-field player tracking during games, and the development of head impact sensors to be deployed in the NFL. These studies will help address many of the key limitations of our work, including its inability to count non-injurious impacts, to quantify impact severity, to identify all injury plays, and to assign exposures to all cases.

The purpose of the current study is to quantify position-specific features of scenarios in which NFL players sustain concussions. While differences in exposure to non-injurious impacts likely also vary by position, they have not been considered in this study and, thus, no indication of injury risk or rates are possible with the current data set alone.

Despite the need for additional research, certain positional aspects identified in this study can be leveraged immediately to the design of position-specific helmets. For example, the identification of an *Incompatibility* metric for each position can inform the consideration of P1- and P2-protection (the marked differences between cornerbacks and safeties are particularly relevant in this context, as is the high *Incompatibility* of running backs, linebackers, and defensive linemen, and the low *Incompatibility* of quarterbacks). Balancing P1- and P2-protection in helmet-to-helmet impacts in football has parallels with the long-studied issue of vehicle compatibility in traffic crashes (see, e.g., References[10,14]) and the principles of mass compatibility, stiffness compatibility, and geo-

metric compatibility may apply to football helmet compatibility. In football, the mass compatibility in a helmet-to-helmet impact is strongly linked to player alignment and, thus, to helmet impact location for both P1 and P2. Importantly, opportunities for both P1- and P2-protection may involve increased impact mitigation for the side (upper) location. While variations among positions exist, as described in the Results section, this location is the most common helmet impact location for both P1 and P2. This likely reflects, among other things, the established directional sensitivity of brain injury tolerance (for P1) (e.g., Reference[22]) and the ability of a tackling player to align his torso and head along the closing velocity vector (for P2) (i.e., "lowering the head"). Beyond the side (upper) location, the distribution of helmet impact location differs considerably between P1 and P2 in helmet-to-helmet impacts (Fig. 3). Specifically, compared to the P1 distribution, the P2 distribution exhibits substantially greater proportions of the top and front of the helmet as well as a substantially lower proportion of the facemask. The greater proportion of the top and front may indicate the "lowering the head" impact posture for P2, wherein P2's head and helmet are more aligned with his spine, mass from his torso is incorporated into the impact, and his effective mass is therefore greater during the impact. This increase in the effective mass allows for a reduction in P2's (i.e., the striking player's, in this context) head acceleration for a given impact force and an increase in the head acceleration of the less-aligned P1 struck in the helmet (i.e., the player in a posture that does not incorporate significant torso mass into the impact). This alignment (and hence mass) incompatibility is reflected, for example, in the apportioning of facemask impacts. The facemask (central) location was struck in 17% of P1 studied here, but in less than 2% of P2 (Table 4). That impact location is one that does not facilitate alignment of the impact vector with the long axis of the torso and hence is an impact location having innately lower effective impacted mass compared to, for example, the top impact location. As expected, then, the top location exhibits the opposite P2-to-P1 trend. The top of the helmet was the impact location for only 7% of P1 but was the impact location for approximately a quarter of P2 (Table 4). The top of the helmet allows for maximum alignment and mass recruitment making it an especially incompatible impact location.

This study also identified the importance of helmet-to-body impacts reported previously by Lessley *et al.*[13], particularly for cornerbacks and safeties. The majority of concussions to those two positions are caused by impacts to an opposing players' body. Thus, improved tackling technique may provide an opportunity for risk reduction. Furthermore, the design of shoulder pads and other body padding should consider the risk of concussion to an opposing player. Future work should focus on the development of impact performance targets for body padding that consider both P1- and P2-protection.

This study considered only NFL games, and thus represents the athletes, rules, and other unique features of that league. The degree to which these findings can be translated to practice situations or other levels of

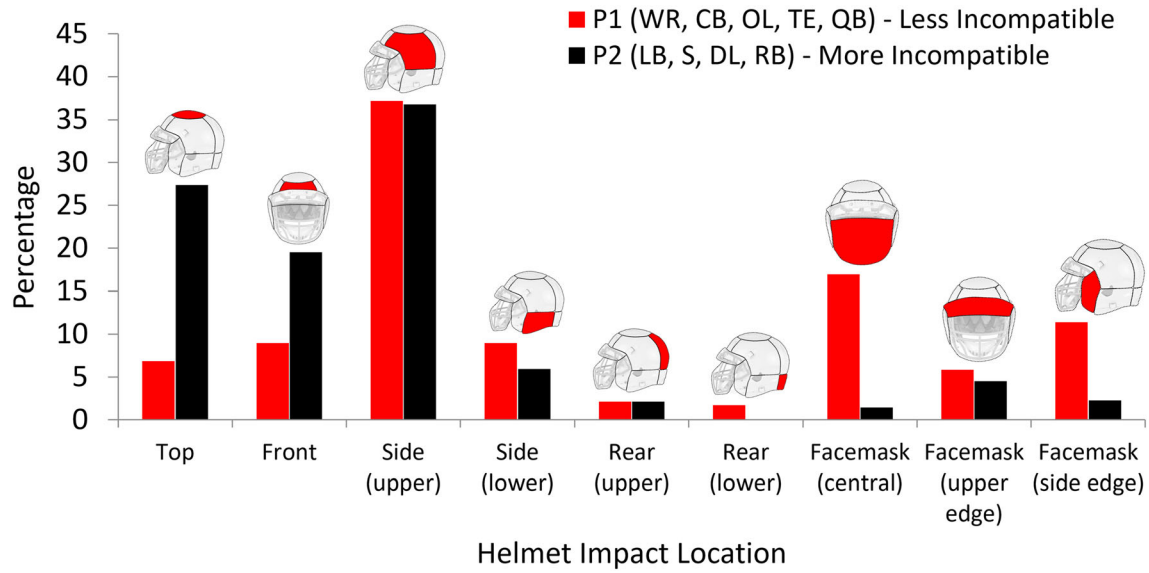

FIGURE 3. Helmet impact location in helmet-to-helmet cases in non-special teams plays. Comparison of the less incompatible P1 positions with the more incompatible P2 positions in helmet-to-helmet impacts.

play is unknown and no such translation should be attempted.

Consideration of position-specific features of P1- and P2-protection can facilitate improved concussion mitigation by NFL helmets. This study has documented position-specific features of helmet impact location (for P1 and P2), helmet impact source, and activity (for P1 and P2). The findings may be leveraged immediately to refine helmet designs for specific positions.

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