Video Analysis of Reported Concussion Events in the National Football League During the 2015-2016 and 2016-2017 Seasons

David J. Lessley,*† PhD, PE, Richard W. Kent,† PhD, James R. Funk,† PhD, PE, Christopher P. Sherwood,† MS, Joseph M. Cormier,† PhD, PE, Jeff R. Crandall,† PhD, Kristy B. Arbogast,‡ PhD, and Barry S. Myers,§ MD, PhD, MBA

Investigation performed at Biomechanics Consulting and Research (BioCore), LLC, Charlottesville, Virginia, USA

Background: Concussions in American football remain a high priority of sports injury prevention programs. Detailed video review provides important information on causation, the outcomes of rule changes, and guidance on future injury prevention strategies.

Purpose: Documentation of concussions sustained in National Football League games played during the 2015-2016 and 2016-2017 seasons, including consideration of video views unavailable to the public.

Study Design: Descriptive epidemiology study.

Methods: All reported concussions were reviewed with all available video footage. Standardized terminology and associated definitions were developed to describe and categorize the details of each concussion.

Results: Cornerbacks sustained the most concussions, followed by wide receivers, then linebackers and offensive linemen. Half (50%) of concussions occurred during a passing play, 28% during a rushing play, and 21% on a punt or kickoff. Tackling was found to be the most common activity of concussed players, with the side of the helmet the most common helmet impact location. The distribution of helmet impact source—the object that contacted the concussed player's helmet—differed from studies of earlier seasons, with a higher proportion of helmet-to-body impacts (particularly shoulder) and helmet-to-ground impacts and with a lower proportion of helmet-to-helmet impacts. Helmet-to-ground concussive impacts were notable for the high prevalence of impacts to the back of the helmet and their frequency during passing plays.

Conclusion: Concussion causation scenarios in the National Football League have changed over time.

Clinical Relevance: The results of this study suggest the need for expanded evaluation of concussion countermeasures beyond solely helmet-to-helmet test systems, including consideration of impacts with the ground and with the body of the opposing player. It also suggests the possibility of position-specific countermeasures as part of an ongoing effort to improve safety.

Keywords: head injuries/concussion; general sports trauma; medical aspects of sports; American football; biomechanics; general; epidemiology

American football has been the sport perhaps most thoroughly studied with regard to the incidence, diagnosis, biomechanical mechanisms, prevention, and long-term consequences of sports-related concussion (eg, Pellman and Viano,[26] Rowson et al,[31] Rowson and Duma,[32] Crisco et al,[7] Kerr et al[16,17]). These studies motivated substantive changes in diagnostic and return-to-play protocols, injury prevention strategies, and the rules of the game at all levels. For example, the National Football League (NFL) has made 47 rule changes since 2002 with the intent of reducing the risk of injuries, particularly concussion,[13] and it has supported the refinement of test methods (eg, Viano et al[36]) and improved helmet designs based on those test methods.[12] Despite these efforts, the concussion incidence in the NFL remains a concern, recently estimated to be >0.6 concussions per game.[5,19]

NFL games are documented extremely well, clinically and visually. Multiple camera views of every play are available, and injury-causing events are frequently well visualized and documented. This level of documentation has been used to quantify and describe the mechanisms and circumstances of severe head impacts and concussions

The American Journal of Sports Medicine
2018;46(14):3502–3510
DOI: 10.1177/0363546518804498

in the NFL. Pellman et al[27] reviewed NFL game video of 182 helmet impacts that occurred during the 1996-2001 seasons. They categorized initial impact locations using distinct regions of the struck helmet and identified impact sources with the intent of defining the circumstances that should be prioritized in helmet designs. One of the key findings of that study was the high prevalence of helmet-to-helmet impacts over the period evaluated. The importance of helmet-to-helmet impacts was confirmed in a follow-up study with a larger set of injury epidemiology data,[25] which concluded that 67.7% of NFL concussions between 1996 and 2001 involved impact by another player's helmet.

Many of the rule changes subsequently implemented by the NFL have focused on reducing the number and severity of helmet-to-helmet impacts. On the basis of video reviews of a subset of game concussions in the NFL during the 2010-2014 seasons, Clark et al[5] concluded that helmet-to-helmet impacts represented only approximately one-third of concussive impacts. Ongoing efforts since the 2014 season to reduce concussion risk via modifications to rules, equipment, and style of play indicate the need for assessment of the mechanisms and circumstances of concussions in the NFL and their documentation with as much detail and the most contemporary data set possible. The purpose of the current study was (1) to perform a comprehensive analysis of every available video view of the entire population of concussions reported as occurring during NFL games over the 2015-2016 and 2016-2017 seasons, (2) to develop a comprehensive database documenting the results of that analysis, and (3) to interpret the results within the context of contemporary NFL game play.

METHODS

Inclusion Criteria and Identification of Injury Play

Concussions sustained by NFL players during games are diagnosed with the NFL Game Day Concussion Diagnosis and Management Protocol[23] and recorded in the NFL's league-wide electronic medical record (EMR) system. The NFL EMR was collectively bargained between the NFL and the National Football League Players Association to serve, in part, as a workplace injury recording 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.

A complete list of reported concussions from the NFL's EMR system was provided by the league. All reported concussions sustained in an NFL preseason, regular season, or postseason game played during the 2 target seasons were included in this study. The list identified each concussed player and details about the game in which the concussion occurred.

An "injury play" was defined for each reported concussion as the single play during which the concussion was determined to have been sustained. The authors collaborated with personnel from the NFL Health and Safety Initiatives Department and NFL Films to identify the injury play. Multiple systems and data sources were used, including the NFL Game Statistics & Information System and NFL Injury Video Review System, injury reports from the NFL's certified athletic trainers (ATC Spotter) and unaffiliated neurotrauma consultants, and visual evidence from game video footage (ie, a head impact, injury behavior, and/or signs of impaired neurologic functioning postimpact[8]). Injuries that occurred outside the field of video coverage or lacked immediate injury behavior, the presence of multiple possible injurious impacts, or combinations of these factors sometimes precluded positive identification of the injury play. A specific documentation protocol was established to identify and categorize such cases (see Video Review Definitions section).

Video Footage

For each injury play, NFL Films provided all available video footage from 4 distinct video sources in the highest-quality formats available from each source: (1) "all 22" footage shot by the hosting team, which included the wide-angle end zone and sideline views typically used by coaches and teams for game review purposes; (2) network broadcast footage with replays, which included all footage aired during the televised network broadcast of the game; (3) NFL Films footage, which is untelevised footage frequently shot for the purposes of NFL documentaries; and (4) network melt reel footage, which is footage shot by the network but not included in the televised video feed of the game.

Each concussion event was reviewed with all available video footage. Video-editing software (Adobe Premiere Pro; Adobe Systems Incorporated) was used to pan, zoom, and view the video at various speeds. These edited video clips were saved for use by all reviewers.

*Address correspondence to David J. Lessley, PhD, PE, Biomechanics Consulting and Research (BioCore), LLC, 1621 Quail Run, Charlottesville, VA 22911, USA (email: dlessley@biocorellc.com).

†Biomechanics Consulting and Research (BioCore), LLC, Charlottesville, Virginia, USA.

‡Center for Injury Research and Prevention, The Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA.

§Duke University, Biomedical Engineering, Durham, North Carolina, USA.

The views expressed are solely those of the authors and do not represent those of Football Research Inc or any of its affiliates or funding sources.

One or more of the authors has declared the following potential conflict of interest or source of funding: This study was sponsored by Football Research Inc, with support from the National Football League. R.W.K. and J.R.C. have an ownership interest in a company (Biomechanics Consulting and Research LLC) that receives consulting fees from the National Football League, including for the conduct of the current study. D.J.L. and J.R.F. have received consulting fees from Biomechanics Consulting and Research LLC, and C.P.S. and J.M.C. are employees of the firm. K.B.A. and B.S.M. have received consulting fees from the National Football League Players Association. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

TABLE 1
Reported Video Review Parameters

Category: Parameter	Description
Injury play: play type	Field goal/extra point, kickoff, passing, punt, rushing
Video: view count	Number of views from which the concussion event was visible
Concussed player and primary exposure	
Position[a]	Cornerback, defensive line, kicker, linebacker, offensive line, quarterback, running back, safety, tight end, and wide receiver
Activity	Blocked, blocking, tackled, tackling, diving/leaping, other
Total number of exposures	Exposure count
Primary exposure type	Direct helmet contact or without direct helmet contact
Primary helmet impact location	See Figure 1
Primary helmet impact source	Helmet, ground, shoulder, thigh, knee, etc

[a]Player position is nominal and does not indicate that the player was necessarily performing tasks typically associated with that position. For example, a cornerback or lineman may play on special teams.

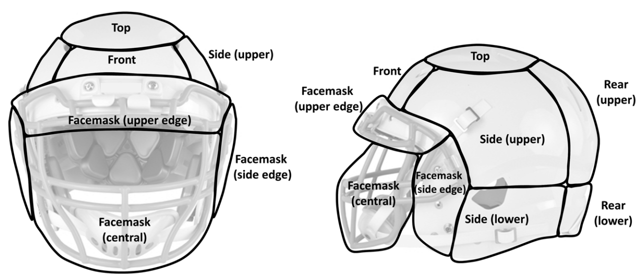

Figure 1. Helmet impact locations.

Video Review Definitions

Standardized terminology and associated definitions (Appendix A, available in the online version of this article) were developed to describe and categorize the details of each concussion. Once the injury play was identified, every event during the play that could reasonably be expected to be related to the concussion was defined as an "exposure" and documented. The helmet impact source and location were recorded for each exposure. "Helmet impact source" describes the object that contacted the helmet of the concussed player during each exposure. "Helmet impact location" was selected from the 9 helmet areas illustrated in Figure 1. Because the exact helmet impact location is always obscured by the impact partner at the time of contact, it could not be identified with great precision. Therefore, these 9 areas were chosen nominally to separate structurally distinct areas of the helmet and facemask. If an impact occurred at the boundary of 2 or 3 areas, then each area was assigned a proportionate fractional weighting for that exposure.

Concussion plays involving only 1 exposure were defined as "single-exposure" cases (eg, a single helmet-to-helmet impact), whereas plays involving >1 exposure were defined as "multiexposure" cases (eg, a helmet-to-helmet impact followed by a helmet-to-ground impact). In multiexposure cases, the "primary exposure" was the exposure that appeared to the video review team to be more severe than any other. When an injury play involved multiple exposures of similar severity, in which identification of a primary exposure was not possible, the primary exposure was defined to be "unclear." The exposure data reported in this article are the sum of the single-exposure cases and the primary exposures from the multiexposure cases.

A case was defined to be "determinate" when visualization of the concussed player was sufficient from available videos to enable documentation of exposures, impact types, helmet impact sources, and helmet impact locations. When visualization was not sufficient to make those observations, the case was defined to be "indeterminate."

Video Review Parameters

During the review of each concussion case, parameters were collected to describe details of the game, playing surface, injury play, and all exposures for the concussed player, as well as details regarding the collision partner and his interactions with the concussed player during the primary exposure (Table 1). The complete database for the 2 seasons analyzed contains approximately 50,000 individual data elements.

Video Review Procedure and Data Collection

Video reviews were first performed by 2 experienced biomechanical engineers, who independently documented the parameters in Table 1. The results were then compared, and the 2 reviewers deliberated to resolve any discordance. If differences remained, a committee of 4 experienced biomechanical engineers reached a consensus decision. Video footage from a subset of 60 well-visualized cases was provided to 4 additional reviewers who conducted independent and blinded reviews for comparison on a matched-case basis.

RESULTS

Over the 2 NFL seasons analyzed, 458 concussions were sustained during game play by 401 unique players. The injury play could be identified in 382 (83%) cases, and the occurrence of injury could be visualized in 367 (96%)

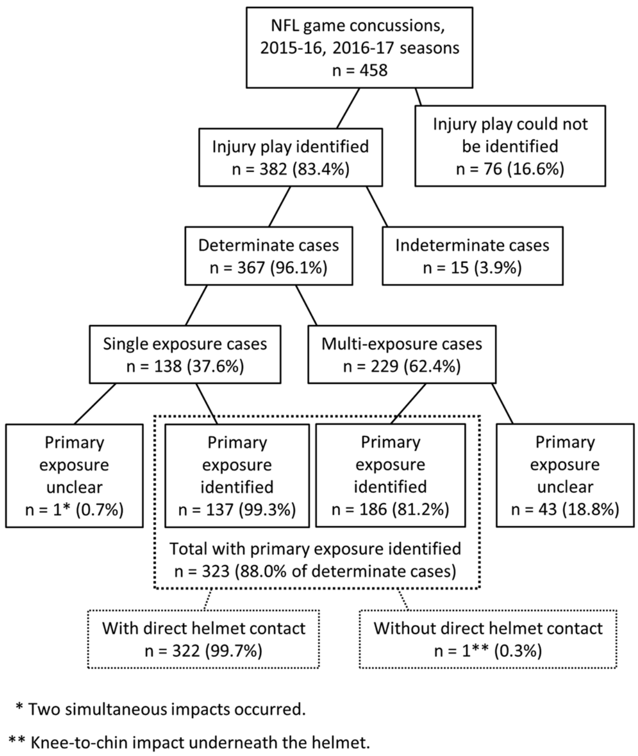

Figure 2. Breakdown of concussion cases. NFL, National Football League.

of those 382 cases. A complete breakdown of the cases is illustrated in Figure 2. The number of video views depicting the injury event in the determinate cases ranged from 1 to 14, with a mean ± SD 4.8 ± 2.1 views per concussion. A tabulated data summary is reported in Appendix B, available online.

Of the 367 determinate cases, 138 (38%) were single-exposure cases, whereas 229 (62%) were multiexposure cases. A primary exposure could be identified in 186 (81%) multiexposure cases. In 43 (19%) multiexposure cases, the primary exposure was unclear. In 1 (0.7%) single-exposure case, the exposure was from 2 simultaneous substantial impacts, so a single primary exposure could not be identified. Of the 323 cases in which a primary exposure could be identified, 322 (99.7%) involved a direct impact to the concussed player's helmet. The final data set for detailed analysis comprised these 322 cases (Figure 2). The 1 (0.3%) outlier involved a knee-to-chin impact underneath the helmet. In other words, no concussions could be sourced to a mechanism other than a direct blow to the helmet or head.

Overall Distributions

Of the 322 primary exposures identified, passing was the most common play type (50%); tackling was the most common activity of the concussed player (41%); and cornerbacks sustained the greatest proportion of concussions (23%) (Figure 3). Helmet-to-body impacts were the source of the concussion in nearly half (46%) of the cases.

Helmet Impact Source, Activity, and Player Position

Of the 322 primary exposures identified, 4 categories of helmet impact source were defined: helmet to helmet (n = 115), helmet to body (n = 92), helmet to ground (n = 59), and helmet to shoulder (n = 56). Helmet-to-shoulder impacts involved only the shoulder as the helmet impact source, with no concurrent loading from another body region (ie, "pure shoulder"). Helmet to helmet involved only the helmet as the helmet impact source. Helmet to ground involved the ground as the helmet impact source. The remaining category, helmet to body, included impacts from any other region of the body, including impacts that involved concurrent loading of the shoulder with another body part (ie, not pure shoulder). Over all player positions, 36% of concussions were caused by a helmet-to-helmet impact, 18% by a helmet-to-ground impact, and 22% by a helmet-to-shoulder impact (pure shoulder or shoulder/body) (Figure 4). The remaining 24% were caused by a blow from a region of the body other than the helmet, pure shoulder, or shoulder/body—with helmet to knee (5%), helmet to thigh (4%), helmet to hip/pelvis (4%), helmet to torso (4%), and helmet to arm (3%) being the most common of those.

Cornerbacks sustained the most (22.7%) concussions, followed by wide receivers, linebackers, and offensive linemen (Figure 5). The most common helmet impact source for cornerbacks was helmet to body. Wide receivers were infrequently concussed by a helmet-to-body impact source; instead, they most frequently sustained a concussion via helmet-to-ground or helmet-to-helmet impacts. Quarterbacks sustained the fewest concussions of the nonkicking positions and were unique in the high percentage of their concussions that were caused by a helmet-to-ground impact.

Overall, 41% of concussions were sustained while tackling, 23% while being tackled, and 29% while blocking or being blocked (Figure 6). All defensive positions were concussed most frequently when tackling. Ball carriers on offense (wide receivers, tight ends, running backs, and quarterbacks) were concussed most frequently while being tackled. Quarterbacks were concussed almost exclusively while being tackled and not at all while blocking. Offensive linemen were concussed most frequently while blocking. The diving/leaping category involved a high proportion of helmet-to-ground impacts (Figure 7) and was most frequently associated with wide receivers and cornerbacks (Figure 6), often while making an attempt for the ball. The most common combination of activity and helmet impact source was a helmet-to-body impact (no pure shoulder) while tackling (65 of 322 cases, 20%) (Figure 7). The combination of a helmet-to-helmet impact while being tackled occurred in only 33 of 322 cases (10%).

Helmet Impact Location

Of the 322 primary exposures identified, the side (upper) location was impacted in approximately 40% of all cases

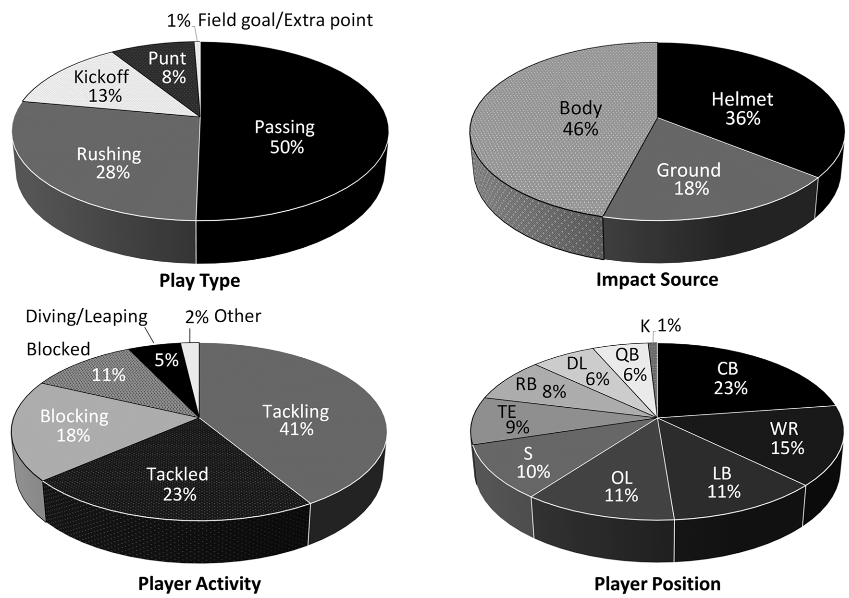

Figure 3. Distribution of cases (n = 322, primary identified) by play type, helmet impact source, concussed player activity, and concussed player position. CB, cornerback; DL, defensive line; K, kicker; LB, linebacker; OL, offensive line; QB, quarterback; RB, running back; S, safety; TE, tight end; WR, wide receiver.

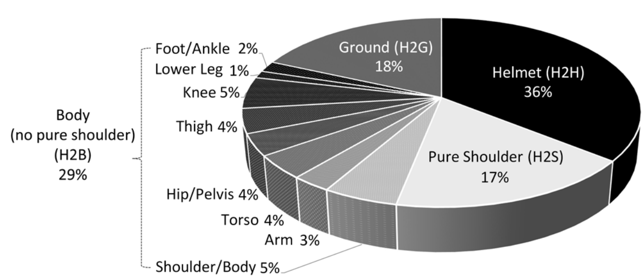

Figure 4. Distribution of helmet impact source (n = 322, primary identified). H2B, helmet to body; H2G, helmet to ground; H2H, helmet to helmet; H2S, helmet to shoulder.

and was the most common helmet impact location regardless of helmet impact source (Figure 8). The distribution of helmet impact location was generally consistent across helmet impact sources, except that the rear (upper) location was overrepresented in helmet-to-ground impacts (37% of those cases).

Play Type

Of 322 concussions, 162 (50%) occurred in passing plays and 89 (28%) in rushing plays (Figure 9). The distribution of helmet impact source was similar for all play types, except that the proportion of helmet-to-ground impacts was markedly greater in passing plays.

Blinded Matched-Case Comparisons

Blinded matched-case comparisons (n = 60) revealed that a majority of the 4 external reviewers agreed with the study authors on the helmet impact source in 93% of the cases and on the helmet impact location in 88% of the cases.

DISCUSSION

A rigorous method was developed to document the circumstances of all concussions that occurred in games over 2 seasons in the NFL (2015-2016 and 2016-2017) based on a visual analysis of all available game video footage. Helmet-to-helmet impacts remain a concern but now represent roughly a third of the concussive impacts in the NFL (cf Clark et al[5]). Concussions sustained via a helmet-to-helmet blow while a player is being tackled or blocked, which have been the subject of rule changes, represent only 15.5% of the total reported concussions.

The reduction in the proportion of concussive impacts that are helmet to helmet suggests prioritization of new research and broader development of concussion prevention countermeasures, particularly with regard to impacts from the ground (18%) and shoulder (17%). A helmet impact to the ground involves fundamentally different mechanics than a helmet-to-helmet impact in that the impact is to a compliant body (earth) of effectively infinite mass and different interface contact properties than another helmet. Helmet-to-ground impacts also frequently occur after a fall during which whole body kinematics generate an oblique helmet-to-ground impact vector and angular velocity of the head before impact. Whole body kinematics and preimpact angular motion of the head were shown to have a substantial influence on brain deformation and associated injury risk in a range of head impact scenarios (eg, Beusenberg et al,[3] Kerrigan et al,[18] Takhounts et al,[34] Smith et al,[33] Gabler et al[11]). No current or proposed football

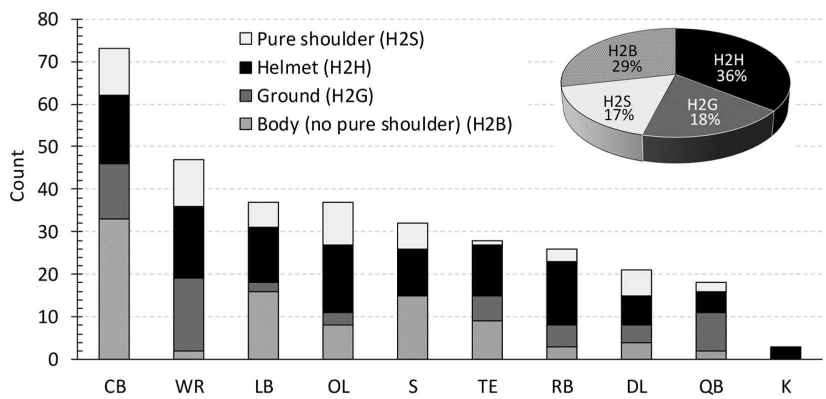

Figure 5. Distribution of helmet impact source stratified by concussed player position (n = 322, primary identified). CB, cornerback; DL, defensive line; H2B, helmet to body; H2G, helmet to ground; H2H, helmet to helmet; H2S, helmet to shoulder; K, kicker; LB, linebacker; OL, offensive line; QB, quarterback; RB, running back; S, safety; TE, tight end; WR, wide receiver.

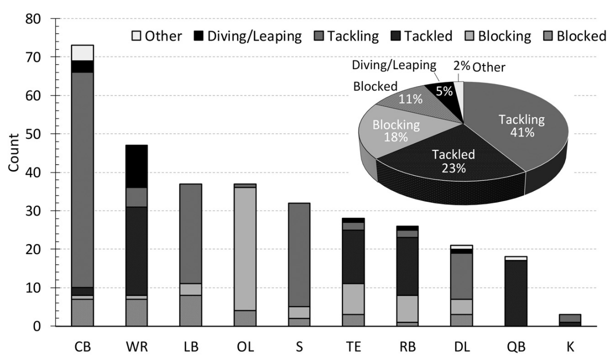

Figure 6. Distribution of concussed player activity stratified by concussed player position (n = 322, primary identified). CB, cornerback; DL, defensive lineman; K, kicker; LB, linebacker; OL, offensive lineman; QB, quarterback; RB, running back; S, safety; TE, tight end; WR, wide receiver.

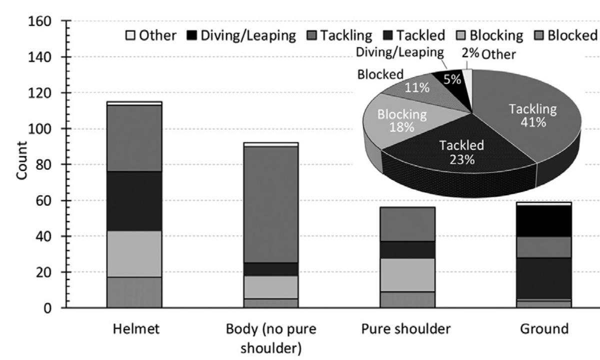

Figure 7. Distribution of concussed player activity stratified by helmet impact source (n = 322, primary identified).

helmet assessment methodology considers preimpact angular velocity of the head or oblique impacts with surfaces having groundlike compliance and friction.[20,21,32,36] Future research should evaluate these unique aspects of helmet-to-ground impacts and determine whether existing assessment methods sufficiently reflect them.

Likewise, mitigating concussion risk in a helmet-to-shoulder impact potentially involves different considerations than in a helmet-to-helmet impact. In particular, the shoulder pad should be further explored as a potential concussion countermeasure. Current body-padding impact attenuation testing methods (eg, ASTM International,[2] British Standards Institution[4]) do not directly address the case of football shoulder pads and have not been validated for their efficacy in assessing a shoulder pad's capacity to mitigate concussion risk to a collision partner. Tuning the effective stiffness and energy-mitigating capacity of shoulder pads with a biofidelic human shoulder model and modifying the surface contact characteristics to redirect helmets during an impact may thus impart less momentum to the head and may reduce the risk of concussion in helmet-to-shoulder impacts. Similar pad-related aspects of partner protection may reduce concussion risk during blows from other regions of the body (thigh, arm, etc), which collectively represent 29% of the concussive impacts documented in this study.

This study also identified an interaction between impact partner and the location on the helmet of an injurious impact. The most common impact location was the upper side of the helmet, regardless of impact partner. Blows to the back of the helmet were dramatically overrepresented in helmet-to-ground impacts (37% of total). This reflects the common scenario of a player, often a quarterback, being tackled and/or diving/falling backward and striking the back of his helmet on the ground.

The method currently used for ranking the impact performance of NFL helmets involves striking a helmeted dummy head, neck, and torso mass at 8 impact sites with a 14.3-kg impactor traveling at 3 impact speeds (5.5 m/s, 7.4 m/s, and 9.3 m/s).[9,14,36] These test conditions were based on NFL game impacts in the 1996-2001 seasons.[27,28] The current review identified blows to the upper side of the helmet to be the predominant impact location of concussions

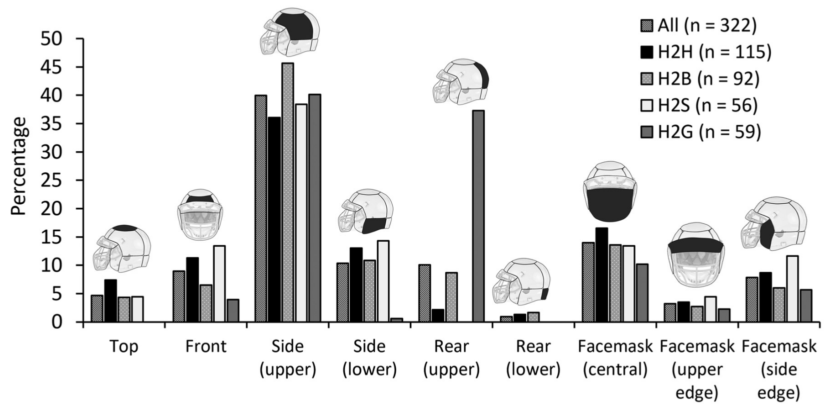

Figure 8. Helmet impact location for all helmet impact sources (n = 322, primary identified) and 4 subsets. H2B, helmet to body; H2G, helmet to ground; H2H, helmet to helmet; H2S, helmet to shoulder.

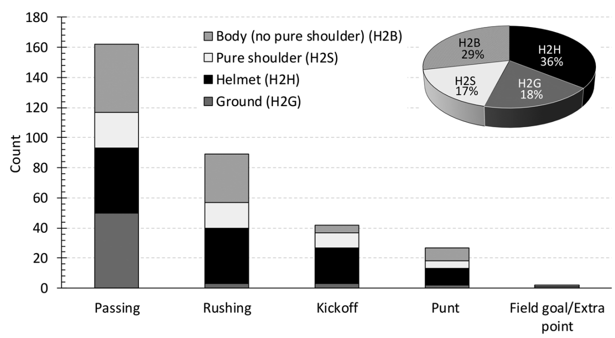

Figure 9. Distribution of helmet impact source stratified by play type (n = 322, primary identified). H2B, helmet to body; H2G, helmet to ground; H2H, helmet to helmet; H2S, helmet to shoulder.

(40% of total observable concussions). It is not known whether this finding reflects an increased exposure to blows in that location, a greater severity of blows that occur in that location, the innate difference in head injury tolerance by impact direction, or a combination of those factors. Future research should describe characteristics of nonconcussive blows in the NFL, particularly their location on the helmet to more fully characterize exposure and risk.

Multiple impacts in a single injury play resulting in concussion were highly prevalent in this sample. Of the 367 determinate cases studied here, 229 (62%) involved multiple exposures. Clark et al[5] also found that a substantial proportion of NFL concussions involved multiple impacts (168 of 429 injuries were categorized as not single impact). Of the 186 multiexposure cases for which the primary exposure could be identified in our study, the first exposure was the primary exposure in most cases (n = 114, 61%). The second exposure was the primary exposure in 33%, and the third exposure was the primary exposure in 5%. There were 43 multievent cases where the primary exposure could not be identified, all of which involved substantial impacts that occurred after the first impact. Brain tissue is viscoelastic and highly deformable, especially in shear (eg, Prange et al,[30] Takhounts et al[35]), and can remain in a deformed state for a substantial fraction of a second before returning to equilibrium (eg, Nicolle et al,[24] Alshareef et al[1]). In many of the multiple-exposure concussions studied here, sequential impacts occurred in very rapid succession, suggesting that the brain may have been in a prestressed condition during the second impact.[37] For example, there were several cases in which a player's helmet struck the side of another player's helmet and was rapidly redirected into the other player's shoulder, and vice versa. The findings of this study suggest the need for research to quantify the injury consequences of multiple sequential and concurrent impacts to the head. They also suggest that new helmet designs include rapid recovery such that the second exposure is to an intact helmet with its full energy-absorbing capacity available.

Video review of National Hockey League concussions classified 7 concussions (<5% of the total) as not involving a direct blow to the head,[15] and a recent video review of 429 NFL concussions[5] described 13 "injurious impacts" that did not involve contact with the injured player's helmet (2.4% of the 547 impacts counted). The current study did not identify a single concussion that occurred in the absence of a direct blow to the head or helmet. Thus, countermeasures targeting NFL concussions should prioritize injury scenarios associated with a blow to the head.

In-helmet sensors have shown different patterns, exposure, and severities of impacts by position in collegiate football (eg, Crisco et al,[6] Crisco et al,[7] Funk et al[10]). The analysis presented here found meaningful differences among positions in the helmet impact location, the concussed player's activity, and the impact partner. For example, half of the quarterback concussions observed in this study were associated with an impact to the ground, and a common impact location was to the back of the quarterback's helmet; all but 1 occurred while the quarterback was being tackled. Running backs were also most frequently injured while being tackled (58%), although their most common helmet impact source was a helmet (58%) and they were most often struck at the upper side location on the helmet. Cornerbacks also experienced a distinct set of scenarios when concussed. Their most common helmet impact source was the body; they were most frequently struck on the side of the helmet; and 77% of their concussions occurred while tackling. Cornerbacks also sustained a notably greater overall number of concussions than any other position category (73 of the 322 identified in this study). The most common concussion scenario observed in this study was a cornerback experiencing a helmet-to-body impact while tackling. Concussions to wide receivers were roughly equally distributed by helmet impact source among helmet, ground, and body, and only about half occurred while being tackled (blocking, blocked, and diving/leaping made up the other half). Linebackers and safeties were most commonly injured by a blow from the body while tackling, and the blow was most often to the upper side of the helmet. Offensive and defensive linemen were most often injured by a helmet-to-helmet blow. Defensive linemen experienced roughly equal proportions of impacts to the upper side and face mask locations, whereas offensive linemen were most frequently injured by a blow to the upper side.

Interestingly, almost twice as many concussions occurred while tackling as opposed to being tackled, and most concussions sustained while tackling were caused by a blow with the body of the tackled player. This finding may indicate potential for continued refinement and teaching of tackling techniques that minimize helmet impacts for the tackler.

This study has limitations. First, it relied exclusively on visual observation of game videos and did not quantify the severity of the concussive impacts. Past researchers used video analysis and laboratory reconstruction methods to quantify estimates of helmet and head kinematics and used inverse dynamics to estimate contact forces and other aspects of the concussive impacts.[22,28,29,36] The notable differences between the concussion-causing scenarios observed in this study and in these prior video and epidemiologic studies suggest that additional attention should be given to quantifying the exposure in helmet-to-ground and helmet-to-shoulder impacts by in-depth examination with quantitative videogrammetry and laboratory reconstruction techniques. Second, video reviews are limited by the quality and quantity of the footage available for review and the subjective nature of some of the determinations that the observers were asked to make. These limitations were addressed in several ways, including procurement of melt reels and all-22 footage, blinded matched-case comparisons by external reviewers, and independent analysis and collaborative reconciliation by multiple experienced biomechanical engineers. Third, the inability to identify all injury plays and events may create biases for events that are more difficult to observe or less frequently filmed. For example, the injury play could be identified in only 382 (83%) cases, and the occurrence of injury could be visualized in only 367 (80%). The random or systemic nature of this bias cannot be readily determined in this study and makes a case for the use of on-field sensing. By contrast, by using strict inclusion criteria, we increase confidence in the fidelity of the data reported herein. Another challenge is the accounting for exposure (eg, there are more cornerback exposures than quarterback exposures). Without accounting for actual play time, relative incidence data should be considered in this context. Finally, this study reflects the observations of only the professional game. College or other levels of play may well have different exposures.

Future research should consider alternative or supplemental methods for reducing data loss (eg, on-field or in-helmet sensors). One of the lessons learned in this study is that the availability of nonbroadcast footage, such as the melt reels and all-22 video, was important for visualizing and confidently documenting the level of detail reported here. Similarly, the highest-resolution video should be analyzed. Visualization is dramatically worse in compressed video, such as that typically available publicly on the internet. A unique aspect of this study was our ability to obtain game footage that is not publicly available.

CONCLUSION

The distribution of impact source among concussed NFL players has shifted toward a higher proportion of helmet-to-body impacts (particularly shoulder) and helmet-to-ground impacts and toward a lower proportion of helmet-to-helmet impacts. Tackling is the most common activity of concussed players, and the side of the helmet is the most common impact location. Cornerbacks sustained the most concussions, followed by wide receivers, then linebackers and offensive linemen. Half (50%) of concussions occurred during a passing play, 28% during a rushing play, and 21% on a punt or kickoff. Position-specific trends were particularly strong in helmet impact source and activity distributions, suggesting an opportunity for position-specific interventions. Helmet-to-ground concussive impacts were notable for the high prevalence of impacts to the back of the helmet and their frequency during passing plays. The majority (62%) of concussions occurred during plays that involved multiple impacts to the injured player's helmet; these impacts were often in rapid succession, suggesting the possibility that subsequent impacts could involve the brain being loaded while in a deformed state. The results of this study indicate the need for expanded consideration of concussion countermeasures beyond the typical helmet-to-helmet standardized test methods available today, including consideration of impacts with the ground, with the body of the opposing player, and from sequential impacts.

REFERENCES

1. Alshareef A, Giudice J, Forman J, Panzer M. Evaluating the biofidelity of human brain finite element models using sonomicrometry data. In: Proceedings of the 2017 International IRCOBI Conference on the Biomechanics of Impact; September 13-15, 2017; Antwerp, Belgium. Available at: http://www.ircobi.org/wordpress/downloads/irc17/pdf-files/96.pdf. Accessed April 11, 2018.
2. ASTM International. Standard test method for impact attenuation of player surface systems and materials. ASTM F355-10. Available at: http://www.astm.org/cgi-bin/resolver.cgi?F355-10. Published 2010. Accessed April 11, 2018.
3. Beusenberg M, Shewchenko NL, Newman J, de Lange R, Cappon H. Head, neck, and body coupling in reconstructions of helmeted head impacts. In: Proceedings of the 2001 International IRCOBI Conference on the Biomechanics of Impact; October 10-12, 2001; Isle of

Man, UK. Available at: http://www.ircobi.org/wordpress/downloads/irc0111/2001/Session5/5.3.pdf. Accessed April 11, 2018.
4. British Standards Institution. Motorcyclists' protective clothing against mechanical impact. Motorcyclists back protectors. Requirements and test methods. BS EN 1621-2:2003. Available at: https://shop.bsigroup.com/ProductDetail/?pid=000000000030109684. Published September 2003. Accessed October 1, 2004.
5. Clark M, Asken B, Marshall S, Guskiewicz K. Descriptive characteristics of concussions in National Football League games, 2010-2011 to 2013-2014. *Am J Sports Med*. 2017;45(4):929-936.
6. Crisco J, Fiore R, Beckwith J, et al. Frequency and location of head impact exposures in individual collegiate football players. *J Athl Train*. 2010;45(6):549-559.
7. Crisco J, Wilcox B, Beckwith J, et al. Head impact exposure in collegiate football players. *J Biomech*. 2011;44:2673-2678.
8. Davis G, Makdissi M. Use of video to facilitate sideline concussion diagnosis and management decision-making. *J Sci Med Sport*. 2016;19:898-902.
9. Funk J, Crandall J, Wonnacott M, Withnall C; Biomechanics Consulting Research. NFL linear impactor helmet test protocol. Available at: http://biocorellc.com/wp-content/uploads/2018/01/NFL-linear-impact-helmet-test-pro tocol.pdf. Published February 1, 2017. Accessed April 11, 2018.
10. Funk JR, Rowson S, Daniel RW, Duma SM. Validation of concussion risk curves for collegiate football players derived from HITS data. *Ann Biomed Eng*. 2012;40(1):79-89.
11. Gabler L, Crandall J, Panzer M. Assessment of kinematic brain injury metrics for predicting strain responses in diverse automotive impact conditions. *Ann Biomed Eng*. 2016;44(12):3705-3718.
12. HeadHealthTECH Challenge V. NFL Play Smart, Play Safe website. Available at: https://www.playsmartplaysafe.com/headhealthtech. Accessed April 11, 2018.
13. Health and safety-related changes for the 2017 season. NFL Play Smart, Play Safe website. Available at: https://www.playsmartplaysafe.com/focus-on-safety/protecting-players/health-safety-related-changes-2017-season. Published April 5, 2017. Updated August 31, 2017. Accessed April 11, 2018.
14. Helmet laboratory testing performance results. NFL Play Smart, Play Safe website. Available at: https://www.playsmartplaysafe.com/resource/helmet-laboratory-testing-performance-results/. Accessed April 11, 2018.
15. Hutchison M. *Concussions in the National Hockey League (NHL): The Video Analysis Project* [dissertation]. Toronto, Canada: University of Toronto; 2011.
16. Kerr ZY, Collins CL, Mihalik JP, Marshall SW, Guskiewicz KM, Comstock RD. Impact locations and concussion outcomes in high school football player-to-player collisions. *Pediatrics*. 2014;134(3):489-496.
17. Kerr ZY, Roos KG, Djoko A, et al. Epidemiologic measures for quantifying the incidence of concussion in National Collegiate Athletic Association sports. *J Athl Train*. 2017;52(3):167-174.
18. Kerrigan J, Crandall J, Deng B. A comparative analysis of the pedestrian injury risk predicted by mechanical impactors and post mortem human surrogates. *Stapp Car Crash J*. 2008;52:527-567.
19. Nathanson JT, Connolly JG, Yuk F, et al. Concussion incidence in professional football: position-specific analysis with use of a novel metric. *Orthop J Sports Med*. 2016;4(1):2325967115622621.
20. National Operating Committee on Standards for Athletic Equipment. Standard performance specification for newly manufactured football helmets. NOCSAE DOC (ND)002-13m15. Available at: http://nocsae.org/wp-content/files_mf/1436291444ND00213m15MfrdFBHelmetsStandardPerformance.pdf. Modified June 2015. Effective October 31, 2015. Accessed April 11, 2018.
21. National Operating Committee on Standards for Athletic Equipment. Standard performance specification for newly manufactured football helmets. NOCSAE DOC (ND)002-17m17a. Available at: http://nocsae.org/wp-content/files_mf/1501096770ND00217m17aMfrdFBHelmetsStandardPerformance.pdf. Revised January 2017. Modified July 2017. Effective November 1, 2018. Accessed April 11, 2018.
22. Newman JA, Beusenberg MC, Shewchenko N, Withnall C, Fournier E. Verification of biomechanical methods employed in a comprehensive study of mild traumatic brain injury and the effectiveness of American football helmets. *J Biomech*. 2005;38(7):1469-1481.
23. NFL Head, Neck and Spine Committee's Concussion Diagnosis Management Protocol. NFL Play Smart, Play Safe website. Available at: https://www.playsmartplaysafe.com/focus-on-safety/protecting-players/nfl-head-neck-spine-committees-protocols-regarding-diagnosis-management-concussion. Published June 20, 2017. Accessed April 11, 2018.
24. Nicolle S, Lounis M, Willinger R. Shear properties of brain tissue over a range relevant for automotive impact situations: new experimental results. *Stapp Car Crash J*. 2004;48:239-258.
25. Pellman E, Powell J, Viano D, et al. Concussion in professional football: epidemiological features of game injuries and review of the literature—part 3. *Neurosurgery*. 2004;54(1):81-96.
26. Pellman E, Viano D. Concussion in professional football: summary of the research conducted by the National Football League's Committee on Mild Traumatic Brain Injury. *Neurosurg Focus*. 2006;21(4):e12.
27. Pellman E, Viano D, Tucker A, Casson I. Concussion in professional football: location and direction of helmet impacts—part 2. *Neurosurgery*. 2003;53(6):1328-1341.
28. Pellman E, Viano D, Tucker A, Casson I, Waeckerle J. Concussion in professional football: reconstruction of game impacts and injuries. *Neurosurgery*. 2003;53(4):799-814.
29. Pellman E, Viano D, Withnall C, Shewchenko N, Bir C. Concussion in professional football: helmet testing to assess impact performance—part 11. *Neurosurgery*. 2006;58(1):78-95.
30. Prange M, Meaney D, Margulies S. Defining brain mechanical properties: effects of region, direction and species. *Stapp Car Crash J*. 2000;44:205-213.
31. Rowson S, Brolinson G, Goforth M, Dietter D, Duma S. Linear and angular head acceleration measurements in collegiate football. *J Biomech Eng*. 2009;131(6):061016-1-061016-7.
32. Rowson S, Duma S. Development of the STAR evaluation system for football helmets: integrating player head impact exposure and risk of concussion. *Ann Biomed Eng*. 2011;39(8):2130-2140.
33. Smith T, Halstead P, McCalley E, Kebschull S, Halstead S, Killeffer J. Angular head motion with and without head contact: implications for brain injury. *Sports Eng*. 2015;18(3):165-175.
34. Takhounts E, Craig M, Moorhouse K, McFadden J, Hasija V. Development of brain injury criteria (BrIC). *Stapp Car Crash J*. 2013;57:243-266.
35. Takhounts E, Crandall J, Darvish K. On the importance of nonlinearity of brain tissue under large deformations. *Stapp Car Crash J*. 2003;47:79-92.
36. Viano D, Withnall C, Halstead D. Impact performance of modern football helmets. *Ann Biomed Eng*. 2012;40(1):160-174.
37. Yoganandan N, Li J, Zhang J, Pintar F, Gennarilli T. Influence of angular acceleration-deceleration pulse shapes on regional brain strains. *J Biomech*. 2008;41(10):2253-2262.