Identifying Injury Characteristics for Three Player Positions in American Football Using Physical and Finite Element Modeling Reconstructions

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Abstract Sport-related concussion has been implicated in long-term neural degeneration and cognitive impairment. Thus, research efforts directed at elucidating as many risk factors as possible is valuable. Epidemiological studies have identified particular playing positions in American football that are at a heightened risk of sustaining concussions. The purpose of this study was to examine dynamic response and brain tissue deformation metrics from head injury reconstructions representing head impacts for football players in the linebacker, wide receiver and lineman positions. These events were reconstructed using pendulum and linear impactor apparatus and a Hybrid III headform. The University College Dublin Brain Trauma Model was used to measure the resulting brain tissue deformations as maximum principal strain (MPS). Peak linear acceleration, peak rotational acceleration and MPS all varied according to playing position. The injury reconstruction for the linebacker position reported the highest values for all measures, followed by head impacts for the wide receiver and the lineman. A relatively high probability of concussion for the linebacker head impact event was observed. In contrast, the associated concussion risk for the impact to the lineman was low, despite a high impact mass. These results show an important distinction in mechanisms and nature of trauma sustained as a result of American football head injuries based on the injury reconstructions for each player position.

Keywords American football, concussion, injury reconstruction, impact biomechanics

I. INTRODUCTION

Mild traumatic brain injury (mTBI) has emerged as a significant public health concern; 3 million cases occur in the United States per year as a result of sport alone [1]. Although traumatic injuries to the head have decreased substantially, concussions remain common even when players wear protective headgear in both leisure and professional sports [2]. Of all concussions that occur in sport, American football is responsible for the largest incidence [3]. This has become a cause for concern, as recently published studies have suggested that multiple concussive impacts over the course of a player's career in sports such as American football and boxing may result in permanent brain degeneration [4-5]. Significant research has been undertaken to better understand the biomechanical characteristics of this injury and its effects on neural tissue.

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Peak linear and rotational acceleration have been shown to correlate with traumatic brain injury (TBI); however, each contributes to distinct injury outcomes. Linear acceleration has been linked primarily to focal brain lesions such as closed skull fracture [6] while rotational acceleration has been shown to be associated with injuries involving axonal tracts such as concussion [7].

Epidemiological studies involving concussion in football report a head injury risk that is associated with the position played: linebacker, wide receiver and defensive back are among the highest risk for concussion [8]. However, while these risks have been observed, links to biomechanical responses describing head injuries commonly seen in these positions have not been elucidated. Pellman and colleagues [9] using National Football League collision reconstructions reported that the offensive team is most vulnerable with respect to injury frequency. They reported that specific types of plays which most commonly result in concussion include passing plays, rushing plays, kickoffs and punts. An analysis of the players' activities at the time of head injury revealed that the highest injury frequency occurred for players who were either tackling or being tackled [9].

The purpose of this study is to describe specific mechanisms of concussion reflective of specific American football playing positions. Using the biomechanical measures described, a better understanding of the degree and character of the risk of brain injury for American football positions can be used to develop preventive strategies specific to both this sport and individual playing positions within the game.

II. METHODS

Physical Reconstructions

Three different head injury events associated with three specific playing positions were reconstructed at the Neurotrauma Impact Science Laboratory. Injuries sustained by a linebacker, wide receiver and lineman were obtained from video footage, which was viewed and analyzed using video analysis software (Kinovea 0.8.15). The lines and markings visible in the plane of the camera view were used to draw a perspective grid and used as a scaling reference to convert pixels to metres. The video footage of elite games follows the National Television System Committee (NTSC) encoding, which consists of 29.97 frames per second. Thus, time between each frame was established as 0.03337 seconds and from this, impact velocity was calculated.

The criteria used for selection of cases were that video recordings were of the best resolution quality for ease of identifying impact parameters for reconstruction. For each playing position, the chosen impacts were either head-to-head, head-to-shoulder or arm, or head-to-ground such as occurs in falls. Only hits for which the associated injury was due to multiple hits rather than a single known event, the lines and markings of the field were not visible (to facilitate velocity calculation), or those for which a close-up view of the impact location on the helmet was not available were excluded. The football players in this study ranged from high school (linebacker impact) to professional (lineman impact). No specific impact locations or velocities were excluded as long as these could be accurately reconstructed by the limits of the laboratory equipment. A video of a high mass hit to the front of the head was selected to represent the lineman position, as these players experience a large number of impacts with the full weight of their bodies behind them starting from rest. A high velocity impact to the side of the head was reconstructed to represent one possible linebacker hit, as this position requires a great amount of speed and tackling. Lastly, a moderate velocity hit to the front boss region of the head was chosen as an example of a wide receiver impact because this position’s role is to catch passes from the quarterback. Thus, wide receivers may get hit in the head while attempting to catch the ball in such plays.

Location, velocity and mass were obtained from the video recordings, while compliance was selected to match the impacting surfaces during the event. A vinyl nitrile impactor was used to mimic a football helmet on the striking player in the head-to-head collisions. Vinyl nitrile is the most common material used in sport helmet shells, as this material absorbs energy effectively and thus enhances performance of helmets designed for multiple-impact sports. As all three impacts occurred via a helmet-to-helmet mechanism, this compliance was chosen to represent the compliance of such impacts [10]. The rationale of selecting particular velocities and effective masses was based on previous literature. Pellman et al.’s NFL reconstruction research reports an average velocity of 9.3 m/s for concussed players and uses a striking player effective mass of 25 kg [11]. A guided linear impactor, similar to the linear impactor used by the National Operating Committee on Standards for Athletic Equipment [12], was used with a Hybrid III headform to reconstruct the impacts representing the linebacker and wide receiver head injuries. As the linear impactor had a minimum inbound velocity of approximately 5.0 m/s, the lineman impact reconstruction employed a pendulum system to recreate the low velocity. A standard American football helmet containing a vinyl nitrile liner was impacted in each of the reconstructions (Fig. 1).

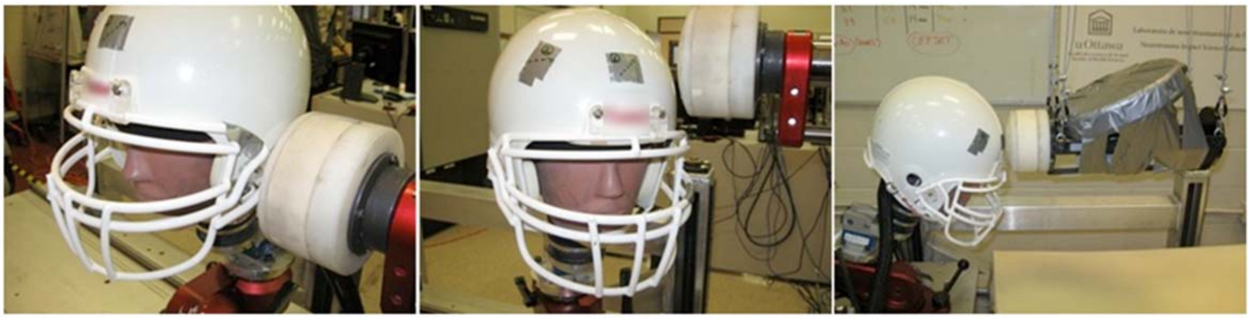

Figure 1. Reconstruction set-up for linebacker (left), wide receiver (middle) and lineman (right).

The 50^{th} percentile adult male Hybrid III headform was outfitted with a 3-2-2-2 accelerometer array for measurement of dynamic response in three dimensions [13]. The accelerometers were Endevco (Capistrano, CA) 7264C-2KTZ-2-300 which were sampled at 0 kHz and filtered with a 1650 Hz 2^{nd} order lowpass Butterworth filter using Diversified Technical Systems TDAS Pro lab module software. Table 1 shows the impact velocities, masses, kinetic energies and locations of each impact used in the injury reconstructions.

Table 1. Impact parameters for head injury reconstructions

Position	Velocity (m/s)	Mass (kg)	Kinetic Energy (J)	Impact location
Linebacker	11	13.1	792.55	Left ear/facemask
Wide Receiver	7	13.1	320.95	Left front boss
Lineman	3.28	28	150.61	High centre forehead

Three impacts were performed for each injury event reconstruction. The peak linear and rotational accelerations were recorded for each reconstruction. The resulting dynamic responses were used as input for the University College Dublin Brain Trauma Model for measurement of the resulting brain tissue deformations. Past reconstruction research has indicated that maximum principal strain (MPS) is a predictive variable for concussion and as a result was used as the brain deformation metric [14-15]. This study reports the peak MPS value in the cerebrum, excluding the auditory association area due to modeling restrictions in the elements in this region between the tentorium and adjacent brain tissue. This functional region results in inaccurate strain values and has been excluded from analysis by researchers [16] in order to report the most accurate peak cerebral MPS. Validation of the UCDBTM was successfully performed when these elements were excluded.

Computational Modeling

The University College Dublin Brain Trauma Model (UCDBTM) [17-18] was used for this research. The model is not representative of a 50th percentile adult male as medical imaging was used to obtain the geometry of a male cadaver. The cadaver head was that of a 38-year old male. The CT, MRI and sliced colour photographs were obtained from the Visible Human Project [19]. These male CT data were chosen by Horgan and Gilchrist [18] due to their availability and high recording resolution. The size of this head was 130.90 mm wide at its widest point, 173.64 mm long along the anterior-posterior axis at its longest point, and 140.42 mm high from the base of the brainstem to the vertex of the brain. The distinction between grey matter, white matter and the ventricles of the brain was made by modifying the baseline finite element mesh so that elements were assigned material properties appropriate to the corresponding cerebral tissue types. Specifically, a purpose-written MATLAB program registered MRI head scans with cerebral elements in space, then a global followed by a local search was performed by each element to locate the nearby MRI voxels that were contained within its volume. By means of appropriate choice of threshold values of voxel intensities, the element was assigned the material properties of grey, white or ventricular matter.

This version of the model is comprised of the dura, cerebrospinal fluid (CSF), pia, falx, tentorium, grey and white matter, cerebellum and brainstem. The UCDBTM has approximately 26,000 elements and was validated against Nahum et al.’s [20] and Hardy et al.’s [21] cadaver impact research. Further validation of the model was done through real life reconstructions, which were found to be in good agreement with lesions on CT scans for TBI incidents [22].

The material properties of the model are presented in Tables 2 and 3. The brain characteristics were derived from Zhang et al. [23]. A linear viscoelastic material model was used to model the brain tissue [14-15, 24-25]. The compressive behaviour of the brain was considered elastic, and the shear characteristics of the brain were defined as:

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$$

where G_∞ is the long term shear modulus, G_0 is the short term shear modulus and β is the decay factor [17]. The brain-skull interaction was accomplished by modeling the CSF as solid elements with a high bulk modulus and low shear modulus; the contact definitions allowed for no separation and used a friction coefficient of 0.2 [26]. The peak MPS in each brain region was obtained from a single element.

Table 2. Material characteristics of the UCDBTM

Material	**Poisson's Ratio**	**Density (kg/m^3)**	**Young's Modulus (MPa)**
Dura	0.45	1130	31.5
Pia	0.45	1130	11.5
Falx	0.45	1140	31.5
Tentorium	0.45	1140	31.5
CSF	0.5	1000	-
Grey Matter	0.49	1060	Hyperelastic
White Matter	0.49	1060	Hyperelastic

Table 3. Material characteristics of the brain tissue used for the UCDBTM

	Shear Modulus (kPa)			
Material	**G_0**	**G_∞**	**Decay Constant (GPa)**	**Bulk Modulus (s^{-1})**
White Matter	12.5	2.5	80	2.19
Grey Matter	10	2	80	2.19
Brain Stem	22.5	4.5	80	2.19
Cerebellum	10	2	80	2.19

Data Analysis

Three one-way independent sample ANOVAs with the independent variable of American football playing position (3 levels: linebacker, wide receiver, lineman) were used to analyze each of the three dependent variables (3 levels: linear acceleration, rotational acceleration, MPS). When significance was found, post-hoc analyses were performed as Bonferroni corrections. The probability of making a type I error for all comparisons was set at $p < 0.05$. All data analyses were performed using the statistical software package SPSS 16.0 for Windows.

III. RESULTS

As reported in Table 4, the reconstruction of the impact representing the linebacker position showed significantly higher levels of peak linear and peak rotational acceleration than the reconstructed impacts sustained by the wide receiver and lineman positions ($p < 0.05$). The mean peak linear acceleration for this impact was 159.7(SD 25.6) *g*. In contrast, the wide receiver and lineman impact reconstructions demonstrated lower average peak linear accelerations of 54.9(2.4) *g* and 31.6(7.03) *g* respectively. The wide receiver also showed lower linear acceleration than the lineman but was only significantly different than linear acceleration results of the linebacker (p <0.05) but not from that of the lineman ($p = 0.34$). The average peak rotational acceleration results showed a similar trend among the three playing positions: 10,361.7(445.4) rad/s^2, 5,570(423) rad/s^2 and approximately 1,951(929) rad/s^2 for the linebacker, the wide receiver and the lineman impacts respectively. After post-hoc analysis, rotational acceleration remained significantly different across all playing positions (p <0.05).

Table 4. Peak values of linear acceleration and rotational acceleration (**Resultant**; peaks in all three axes in brackets)

Player position	Peak resultant linear acceleration (*g*)	Peak resultant rotational acceleration (rad/s^2)
Linebacker	**131.2** (22.7,-129.7,-40.9)	**10,528** (6100,2900,-10400)
	167.1 (-20.0,-166.2,-51.4)	**9,857** (8300,3800,-9800)
	180.7 (12.9,-179.5,-46.6)	**10,700** (8200,3900,-10600)
Wide Receiver	**57.6** (-37.2,-49.9,14.6)	**5,982** (4700,-2800,-3100)
	53.1 (-33.2,-43.8,11.6)	**5,136** (3900,-2400,2600)
	53.9 (35.2,-45.9,11.9)	**5,592** (4200,-2800,-2800)
Lineman	**25.0** (-24.9,-1.60,4.60)	**1,136** (410.1,-1030.3,718.5)
	30.8 (-30.7,3.8,6.1)	**1,755** (-337.1,-1732.7,762.3)
	39.0 (32.0,3.60,-22.2)	**2,962** (-611.1,2893.7,841.3)

Table 5. Peak Cerebral Maximum Principal Strain

Player position	Peak MPS in cerebrum
Linebacker	0.670
	0.608
	0.570
Wide Receiver	0.214
	0.218
	0.208
Lineman	0.074

	0.084
	0.179

Brain deformation, measured by maximum principal strain, was highest for the linebacker impact, followed by that of the wide receiver, and the lowest peak value was recorded for the lineman (Table 5). Mean peak MPS values for each position reconstruction were 0.616 (0.050), 0.213 (0.005) and 0.112 (0.058) for the linebacker, wide receiver and lineman impacts respectively. After post-hoc analysis, the linebacker impact was significantly greater than the other two positions (p <0.05), but the wide receiver and lineman impacts were not statistically significant from one another (p = 0.096). Thus, all three dependent variables showed a similar trend of the highest outcome measures resulting from the linebacker position and the lowest for the lineman.

IV. DISCUSSION

Impacts to the head sustained by American football players in three playing positions were reconstructed and brain tissue deformation was ascertained via finite element modeling. Significant differences were observed in the dynamic response between the linebacker, wide receiver and lineman impacts. A similar trend was noted among the three positions with respect to maximum principal strain. MPS was chosen as the brain tissue deformation metric as past reconstruction research has identified it as a good predictor for concussion [14-15, 27]. The UCDBTM is able, however, to discern deformation variance by brain region using other measures such as von Mises stress, strain rate and shear strain. The present study's dynamic response results are lower but comparable to those reported by Pellman et al. [11] in their research on concussion in National Football League players. These researchers reported a peak linear acceleration in concussed players of 98 ± 28g, whereas struck but clinically uninjured players sustained impacts of statistically significantly lower translational acceleration (60 ± 24g). Thus, the degree of trauma, when quantified by linear acceleration, sustained by the linebacker in the present study is in keeping with Pellman and colleagues' observations of concussive impacts in football. Conversely, the results from the wide receiver and lineman impacts fall below the threshold of what these researchers observed to result in concussive injury. Rowson and colleagues [28] reported separate concussion risk curves based on impacts recorded from football players by means of two in-helmet accelerometer arrays. These authors report an under-predicting injury curve, in comparison to that of Pellman et al.: the average concussive impact had a rotational acceleration of 5022 rad/s^2, and a head rotational acceleration of 6383 rad/s^2 represented a 50% risk of concussion. When the present study's results are compared to these findings, all of the linebacker and wide receiver impacts exceed the average rotational acceleration of a concussed player. It is recognized, however, that using reconstructions from either in-helmet accelerometers or video analysis has inherent limitations and inaccuracies which is an advantage of using finite element-established thresholds [29-30].

As discussed, the levels of brain trauma sustained by the three football players in this study are associated with widely varying risks of concussion. Zhang and colleagues [14] proposed a series of thresholds of probability of mild traumatic brain injury, based on various biomechanical metrics. These authors report linear accelerations of 66, 82 and 106g, and rotational accelerations of 4600, 5900 and 7900 rad/s^2 to represent a 25%, 50% and 80% risk of concussion respectively. The linebacker in the present research thus represents a notably high risk of concussion for both linear and rotational acceleration. Kleiven [15] proposed similar distinctions for proportion of injury risk based on maximum principal strain. He proposed that a MPS level of 0.26 in the grey matter of the brain is representative of a 50% probability of concussion. According to these thresholds, both the impacts for the linebacker and wide receiver demonstrate a concussion risk at or above 50%, with the wide receiver falling just below this proposed 50% probability threshold (table 5). *In vivo* tissue models have also been used as a means of determining a strain threshold criterion. Bain and Meaney's [31] delivery of functional injury to an animal model reflected an average strain of 0.181 (± 0.02) to be the threshold for electrophysiological impairment in a nerve. Although mechanical injury in humans may not occur at such lower strain levels, functional impairment is probable in an *in vivo* context. When this threshold is applied to the impacts experienced in the three playing positions, the linebacker and wide receiver results are well above the strain threshold criterion and the strain of impact representing the lineman is very close (0.101) to this threshold value.

The parameters of the three impacts also have influence on the results. In the game of American football, wide receiver and linebacker are considered high-risk positions due to the often high-velocity nature of the impacts, which results in high accelerations. In contrast, linemen may be at risk of neurological damage over time despite the lower velocities and shorter distances of impacts commonly sustained by players in this position. The frequency at which impacts of this type are encountered by offensive and defensive linemen is higher than any other position [32]. Additionally, both the linebacker and wide receiver impacts occurred to the side of the head. Impacts to the side of the head specifically have been shown to result in higher dynamic response than impacts to other locations, which may be in part due to the higher rotational component at this location [33]. The high mass that was present in the lineman reconstruction (28 kg) yet absent from the others may have had less of an influence on the player's outcome in terms of injury severity than other impact characteristics such as location and velocity. An inbound mass greater than approximately 10 kg has been shown to have comparatively less influence on the dynamic response and brain tissue deformation [34].

There is a considerable standard deviation among dynamic response results of the same playing position. This variation among trials is likely a result of progressive changes of the material of the helmet over the course of each condition's three trials. The standard deviation of the wide receiver impacts was relatively low (2.4 g for peak linear acceleration); however, the high standard deviation for the linebacker impacts was likely a result of the high velocity nature of this condition (11 m/s), as this high velocity causes progressive degradation of the helmet's material and is beyond the range of a football helmet's ideal performance conditions. Via a similar mechanism, high standard deviation among trials of the lineman reconstruction can be attributed to this condition's high mass (28 kg) [35].

The kinetic energies of the three impact conditions also differ from one another (Table 1). However, the purpose of this study was to establish the dynamic response of the head and subsequent tissue deformation in the brain following football position-associated impacts. Thus, the aim of this research was not to compare the response of the head to similar impacts. A sample of the various possible types of hits in football was presented on the premise that each impact mechanism and conditions are distinct and result in distinct dynamic response measures of the head. The considerably higher mass used for the lineman reconstruction was chosen to account for the mechanism of head collision that linemen in football experience. These players experience a high number of lower magnitude hits with increased body mass involved in such impacts. Thus, 28 kg was chosen to account for the mass of the body in these head impacts as reported in previous reconstruction literature [11].

Importantly, the findings of this research are limited to the specific players analyzed for each position. As such, they cannot be applied in a general manner to all players in these three positions. Further, the results of this research warrant closer examination of differences among additional playing positions, both in the context of the game of football and in other sports.

V. CONCLUSIONS

The results of this research revealed significant differences between impacts to the head in three American football player positions. These differences were consistent across both dynamic response of the impact and brain deformation. Establishing profiles based on the degree of trauma sustained during sport events, such as football, enhances understanding of the mechanism of concussion. Profiles of brain trauma could also be stratified according to players' experience, skill level and other factors to correlate particular characteristics with certain patterns of trauma.

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