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The Biomechanical Properties of Concussions in High School Football

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Abstract

INTRODUCTION—Sport concussion represents the majority of brain injuries occurring in the United States with 1.6 to 3.8 million cases annually. Understanding the biomechanical properties of this injury will support the development of better diagnostics and preventative techniques.

METHODS—We monitored all football related head impacts in 78 high school athletes (mean age 16.7 years) from 2005 through 2008 in order to better understand the biomechanical characteristics of concussive impacts.

RESULTS—Using the Head Impact Telemetry System (HITS), a total of 54,247 impacts were recorded and 13 concussive episodes captured for analysis. A classification and regression tree (CART) analysis of impacts indicated that rotational acceleration ($>5582.3 \text{ rad/s}^2$), linear acceleration ($>96.1 \text{ g}$), and impact location (front, top, back) yielded the highest predictive value of concussion.

CONCLUSIONS—These threshold values are nearly identical to those reported at the collegiate and professional level. If the HITS were implemented for medical use, sideline personnel can expect to diagnose one of every five athletes with a concussion when the impact exceeds these tolerance levels. Why all athletes did not sustain a concussion when the impacts generated variables in excess of our threshold criteria is not entirely clear, although individual differences between participants may play a role. A similar threshold to concussion in adolescent athletes compared to their collegiate and professional counterparts suggests an equal concussion risk at all levels of play.

Keywords

mild traumatic brain injury; head acceleration; sport injury; classification and regression tree (CART) analysis

INTRODUCTION

Concussion is an acceleration/deceleration injury resulting from biomechanical forces transmitted to the cerebral tissues from impacts to the head or torso (3). Several investigators have employed biomechanical analyses to impacts in an effort to identify a threshold for injury, with the ultimate aims of both improving protective equipment and developing a diagnostic tool. To date however, no single or cluster of variables has been identified to accurately predict injury risk.

Although no set of variables yet provided ideal sensitivity to concussive injuries, *in vivo* examinations of head kinematics of injury tolerance have yielded progressively more sophisticated findings with a progression from a single variable to a multi-variable analysis. Early work by Pellman et al (30) reported on data collected through Hybrid III crash dummy reconstruction of open field impacts in a small subset of concussed and non-concussed elite athletes. The findings indicated linear acceleration to be most directly related to concussion with a mean threshold for injury to be 98g and an impact generating a minimum 70–75g necessary to cause injury. These impact levels corresponded to a 75% and 50% injury risk, respectfully. Application of these thresholds to other levels of play however, has fallen short in accurately predicting concussions. In fact, in a dataset generated from high school level football athletes 271 impacts exceeded the 70g threshold and 78 impacts exceeded the 98g magnitude with only five reported concussive injuries(7).

Guskiewicz (14) later reported on data collected in collegiate level football players equipped with the Head Impact Telemetry System (HITS). This instrumentation permits the tracking of all impacts (concussive and not) in all athletes equipped with the device. The authors reported the mean linear acceleration of the 13 concussions recorded to be 102.8 g with a rotational acceleration of 5311.6 rad/s². The value for linear acceleration appears similar to that of professional athletes, although injury tolerance levels were not estimated. Notably, when the athletes were evaluated following a diagnosed concussion there appeared to be no relationship between the magnitude of impact and injury severity as measured by decrements to postural control, neurocognitive functioning, and increased symptom reports. This finding was counter to the commonly held belief that larger magnitude impacts would result in more severe injuries as indicated by worse performance on clinical tests.

Similarly, Greenwald and colleagues (12) calculated the risk for concussion from HITS biomechanical data collected in a large sample of collegiate and high school level football. Using a weighted principal component analysis from 17 concussive impacts, the investigators reported a combination of variables that included linear acceleration, rotational acceleration, Head Impact Criteria (HIC) (27), and impact location provided the highest sensitivity to concussive injuries. The analysis indicated that athletes exceeding the calculated principle component value of 63 were at 75% risk for injury. This multi-variable equation extends the work of previously published findings, but the ability to consistently and accurately predict concussion based on biomechanical data remains elusive.

Others have tried to improve upon injury diagnostics by predicting the relationship between cranial kinematics and brain tissue mechanics from impacts associated with injury. Zang (34) applied the National Football League study data to a finite element (FE) model of a human skull and brain in an attempt to predict both injury occurrence and severity. The authors reported the greatest level of shear stress was located in the brainstem and provided the highest predictive value of concussive injury. The predictive value of shear stress was surpassed by only the combined use of both the resultant linear and angular acceleration values. Concussion risk levels were also calculated and deviated little from previous reports, whereby a 106g and 79000 rad/s² impact resulted in an 80% injury risk. Implementing a more extensively validated

FE model, Kleiven (20) later evaluated the relationship between head kinematics and the simulated cerebral tissue response in 58 impacts (25 concussions and 33 non-concussive impacts) recorded from professional football. This analysis suggested that brain stem shear stress did not provide the highest predictive values to injury, but rather a combination of HIC and rotational velocity correlated with maximal brain strain and thusly provided the highest injury prediction values. A separate evaluation of simulated brain motion predicted from HITS recorded impact kinematics (without concussions) in collegiate level football demonstrated that measures of cerebral motion (eg maximal tissue strain) were most highly correlated to angular acceleration and velocity, but not with linear acceleration(32). Collectively, these findings suggest that rotational motion of the head following impact may be the best predictor of cerebral tissue strain and subsequent injury.

In combination these investigations provide an initial biomechanical explanation of cerebral concussions occurring in football. Yet, it is unknown if these same variables will offer a similar or improved sensitivity in high school athletes. Indeed, investigations have shown adolescent football athletes experience greater linear and rotational head accelerations during play (7) and have a theoretically higher threshold to concussive injury (26). Therefore, the purpose of this investigation is to elucidate the biomechanical threshold for concussive injuries sustained during high school football.

METHODS

As part of an ongoing investigation evaluating the biomechanical properties of sport concussion and its neurocognitive consequences, during the 2005, 2006, 2007 and 2008 competitive seasons, football athletes from two high schools were fitted with Riddell Revolution helmets equipped with the Head Impact Telemetry System [(HITS) Simbex, Lebanon, NH]. Impact data were collected across the entirety of all seasons including preseason practices, regular season practices and games, and post-season practices and games. This accounted for 166 total sessions of data collection. Data were screened on a daily basis to ensure that errant impacts (eg dropped helmet) were removed from the dataset. Prior to data collection, the Institutional Review Board reviewed and approved the study protocol and participant assent and parental consent was obtained following the appropriate procedures.

The HITS is a novel telemetry system designed to identify the location and magnitude of head impacts in real time. The HITS is capable of monitoring and recording the location and magnitude of impacts to the head that occur during sport. The system consists of two components: an encoder that is retrofitted into the football helmet and a sideline computer for data recording and storage. The encoder consists of six thimble sized single-axis accelerometers recording at 1000Hz, a telemetry unit and data storage device, and an onboard battery pack. The memory device can record and store up to 100 impacts when out of range of the sideline computer. The components are sealed in waterproof plastic and inserted between the internal padding of any standard Riddell football helmet (Figure 1). Helmets equipped with the HIT System look and function identically to other helmets and continue to meet National Operating Committee on Standards for Athletic Equipment (NOCSAE) standards for safety.

A sideline computer receives impact data continuously from up to 100 players simultaneously at ranges up to 137m. Consistent communication between the helmet and the sideline receiver is achieved through a continually changing, Federal Communications Commission approved radio frequency range. The sideline computer is housed in a waterproof plastic case and cooled with an internal fan. Within the case, the computer is padded with foam to lessen the effects of any ancillary impacts. The system has been successfully used in stadiums of more than 100,000 fans, with TV, radio, and other 2-way communication systems all simultaneously functioning.

In order for an impact to be recorded, a minimum threshold of 15g must be exceeded on at least one accelerometer. Following impact a total of 40ms worth of data are recorded as representative of the impact. This consists of the 12ms prior to impact and the 28ms following. Importantly, those athletes who are involved with the majority of plays (i.e. linemen), but whose impacts are obscured from video capture, can be monitored. A novel algorithm that determines the location and magnitude of each impact to the head (9) was validated against Hybrid III crash dummies fitted with a 3-2-2-2 accelerometer array (28). The correlation between the HITS and Hybrid III dummies was high ($r=0.98$) with a 4% absolute error rate when estimating both linear and angular accelerations (10). Likewise, impact location accuracy was validated using the National Operating Committee on Standards for Athletic Equipment (NOCSAE) testing protocol, whereby the HITS accurately identified impact location within $\pm 0.41\text{cm}$ (10).

For the purposes of this study the definition of concussion was taken from the American Academy of Neurology which states: “Concussion is a trauma-induced alteration in mental status that may or may not involve loss of consciousness” (1). All diagnoses were made by a certified athletic trainer and/or physician and the same physician determined return to play following injury. Injuries were not graded because of the lack of support from medical organizations for the use of grading scales (13) and emerging evidence that current grading scales are not accurately representative of severity (22).

Statistical Analysis

Descriptive statistics of means and standard deviations were calculated for participant demographics and helmet impacts. Demographic information was not available for data collected during the 2005 and 2006 seasons. To achieve our aim of using biomechanical variables as a predictor of concussion, we first employed classification and regression tree [(CART) Salford Systems, San Diego, CA](5), which is well suited for identifying important predictors in the classification of concussions. . This novel analytical approach permits the use of both continuous (eg linear acceleration) and categorical (eg impact location) independent variables to help predict our dependent outcome variable (ie concussion). CART analysis offers the advantage over other techniques, such as generalized linear modeling, by offering both simplicity of results interpretation, the flexibility of handling highly nonlinear relationships, and the ability to handle non-normally distributed data. With this flexibility the initial analysis can include a myriad of potentially valuable variables and reveal the most important relationships. Restraint in using all variables is warranted however, as the final classification tree should provide the highest level of prediction accuracy using the fewest number of variables, while maintaining a low misclassification rate. Tree stability was verified with a randomly selected subset of data (80% of the total sample) and a confirmatory analysis was completed using a generalized linear mixed model.

A number of variables were included in our analysis including linear acceleration, rotational acceleration, and impact location (eg front, side, back, and top), which were calculated by software provided by the manufacturer. We also calculated the number of preceding impacts, time between impacts, impact duration (ms), cumulative linear and rotational acceleration prior to a given impact, estimated impact force (7), impact impulse, BMI, head mass (33), and neck volume with a customized MatLab (version 6.5.1; MathWorks, Inc, Natick, MA) program. Each of these has been suggested to play a roll in determining concussion tolerance (7). The Head Injury Criterion was intentionally excluded from the analysis because it contains estimates of both linear acceleration and impact duration, making it redundant with other variables.

RESULTS

A total of 78 high school athletes participated in this investigation. Information collected prior to the start of the 2007 and 2008 seasons indicated mean (standard deviation) demographics of: 16.7(0.8) years, 86.7(17.6) kg, 181.0(6.7) cm, and 0.25(0.61) previous concussions. Detailed demographic information for the 2007 and 2008 season participants is presented in Table 1.

The 166 data collection sessions were spread across 128 practices and 38 games and accounted for 54247 recorded impacts. Table 2 presents mean biomechanical data for practice and game sessions throughout the investigation. Across the duration of the investigation, mean linear acceleration was 25.1(15.4) g from all sessions with 24.2(14.3) g impacts occurring during practices and 26.1(16.6) g impacts games. Rotational acceleration during all sessions was 1627.1(1182.9) rad/s², 1554.3(1082.8) rad/s² in practices, and 1711.2(1284.0) rad/s² in games. Impact duration was longest during practices at 10.2(3.6) ms, shortest in games at 10.1(3.7) ms, with an average of 10.2(3.7) ms from all sessions. Across the four year investigation 13 concussions were diagnosed with specific demographic and biomechanical information about each injury presented in Table 3.

To explore the relationships between “concussion” and biomechanical variables, we fit a classification tree to the data. The *R* package “tree” was used and the addition of nodes was stopped when no less than five observations were present. Using the complete dataset, the tree suggests that the best predictors for the risk of concussion are: resultant rotational acceleration, resultant linear acceleration, and impact location (Figure 2). The accuracy of injury prediction improves with the addition of each variable, indicating that impacts resulting in a rotational acceleration in excess of 5582.3 rad/s² (n=684) will be associated with 1.9% chance of injury for impacts above this level. When resultant linear acceleration in excess of 96.1 g (n=159) is included in the decision making process the chance rises to 6.9%. Further inclusion of impact location to the front, side, or top of helmet (n=82) elevates the chance to 13.4%. If we further examine the risk set for impacts that exceed 5582.3 rad/s², but fall below 8445 rad/s² (n=47), the risk of injury increases to 21.3%. Impacts exceeding 8445 rad/s² are associated with a lower injury risk, with concussions occurring once out of 35 impacts or 2.9% of impacts meeting these criteria. Further evaluation of resultant linear acceleration exceeding 96.1 g, but less than 102.6 g (n=9), increases the risk of injury to 55.6%. Impacts exceeding 102.6 g are associated with a lower injury risk with concussions occurring five out of 38 times or 13.2% of impacts meeting these criteria. Because the number of impacts meeting the criteria at the lower end of the tree (Figure 2) represents a small percent of all impacts, the risk calculations there are less reliable than those at the higher end of the tree.

To check the stability of the fitted classification tree, we repeatedly sampled 80% of the data randomly from the complete dataset and constructed the tree for each random sub-sample. After examining ten sub-samples, we found that the basic structure of the risk set from those trees remained stable.

To perform a confirmatory analysis of our predictive model, we defined the risk set as any impact with the following biomechanical measurements: rotational acceleration in excess of 5582.3 rad/s², linear acceleration greater than 96.1 g, and the location of impact to the front, side or top of the helmet (identified as 1 in the dataset and 0 otherwise). We fit a generalized linear mixed model (21) on the occurrence of concussion as the response variable, with the risk set indicator, the location indicator, and their interaction as fixed effects and the athlete as a random effect. Only the interaction effect is found to be significant ($p < 10e-15$). This confirms a highly significant association between concussion and the predictive factors identified in the classification tree.

DISCUSSION

This investigation implemented a telemetry based acceleration monitoring system in adolescent football athletes in an attempt to identify the biomechanical threshold for concussive injuries. An analysis of the 13 concussive episodes captured by the Head Impact Telemetry System indicated that measures of rotational acceleration, linear acceleration, and impact location appear to be the most important variables in establishing injury prediction criteria. More specifically, our injuries occurred at levels (ie 5582.3 rad/s², 96.1 g, and front, side, or top impacts) that are consistent with previous reports from data collected at other levels of play (12;17;30).

Our analysis demonstrates that rotational accelerations in excess of 5582.3 rad/s² may be the bottom threshold in increasing the probability of concussion in the high school athlete. This value and our range of values (5582 to 9515 rad/s²; Table 3) that resulted in concussion is similar to findings generated from adult athletes (17;30). Indeed, biomechanical data collected with the Head Impact Telemetry System on concussed collegiate athletes identified the mean rotational acceleration at 5311.6 rad/s² (17). Likewise, video reconstruction of concussed professional athletes found the mean rotational acceleration to be only slightly higher at 6432 rad/s² (30). It is unknown if these differences are clinically meaningful, but they all exceed previously proposed concussions thresholds (26).

The evaluation of linear acceleration values collected in this investigation indicated that impacts generating acceleration in excess of 96.1 g increased the sensitivity of our decision making tree. This value is nearly identical to the mean linear acceleration of 98g reported in professional athletes (30) and similar to 102.8 g mean reported in collegiate athletes (17). The range of linear accelerations (77.8 to 146.0 g; Table 3) also fell within the range of previous reports.

A complex interrelationship exists between impact location, linear and rotational acceleration and concussion. Temporal impacts, particularly when the athlete is unaware of the impending blow, are thought to generate the greatest concussion risk (16). This may be in part to the higher rotational component seen here (Table 3) and elsewhere (17) that result from lateral forces and its effect on brain stem integrity and subsequent loss of consciousness (25). Anatomically, brain stem fibers have an increased susceptibility to rotational loads due to their linear alignment (2) and computer simulation models indicate higher brain shearing with temporal impacts (34). Further, an analysis of Australian rules football athletes revealed the majority concussions (61 of 97) resulted from temporal region impacts that generated a high rotational component (24). Others have reported that linear acceleration is the single best predictor of concussion (30) and more tightly linked with severe injuries such as cerebral contusion and hemorrhaging (16). Our data do not support the use of linear acceleration as the prime variable of interest as rotational acceleration was the chief predictor within our classification tree.

The combined interpretation of rotational acceleration, linear acceleration, and impact location significantly improved the sensitivity of biomechanical variables in making injury diagnoses over previous estimates. In particular, when the single variable concussion threshold proposed by the Pellman and colleagues (30) was applied to our dataset, 259 impacts exceeded the 98g level, nine of which resulted in concussions, providing a 3.5% sensitivity. An alternative multivariable threshold estimate implementing linear acceleration, rotational acceleration, HIC, and impact location in excess of 63(12) also identified nine concussive episodes, but with only 150 false positive results (6.0% sensitivity). Our CART analysis however, accurately identified ten concussions among the 47 impacts exceeding our injury tolerance level (21.3% sensitivity). The improved sensitivity may have resulted from a more sophisticated data analysis technique and/or the development of an injury profile specific to the high school

athlete. Importantly, the analysis supports a multi-variable approach in determining the biomechanical components of the concussion mechanism.

An additional concern related to injury diagnostics is the tolerance athletes have in sustaining blows that do not result in concussion. That is, individual variability results in not all impacts exceeding the injury predictor levels to result in concussion. Thus, there is utility in determining the percent risk for injury given a pre-determined set of head acceleration criteria. As such, evaluation of concussion data collected in the NFL suggests that a 98g acceleration places the athlete at 75% injury risk (34). These same data were later re-evaluated on the premise of exposure bias during the original data collection period (11). The authors' statistical evaluation suggested that similar impact values (ie 107g, 6619 rad/s², and HIC of 191) lowered the injury risk in the professional athletes to 1%. Further evaluation of collegiate level impacts indicated that a similar set of acceleration criteria (ie 109g, 6714rad/s², and HIC of 232) resulted in the same 1% injury risk level (11). Application of these estimates to our high school dataset revealed 71 impacts exceeded the 1% risk estimate for the professional athlete, three of which were concussive impacts (4.3%). Where as application of the 1% risk estimates generated for collegiate athlete athletes generated 60 impacts exceeding the threshold with one reported concussion (1.7%). These findings suggest that the tolerance level in the high school football athlete is slightly lower than that of the collegiate and professional athlete, placing him at an increased risk for injury compared to his older counterparts given equivalent head kinematics following impact.

The clarification of concussion biomechanics and injury tolerance levels will ultimately yield better injury prevention equipment. American football helmets that were initially designed to reduce the risk of skull to skull contact resulting in fracture are now engineered to reduce concussion incidence. The Riddell (Elyria, OH) Revolution uses thickened padding in the temporal region that protects the athlete from lateral blows (8). Revolution helmets were solely employed in this investigation and we found only 2 of 13 concussions resulted from side impacts. It may therefore be reasonable to believe that this innovation has been successful at reducing concussion incidence resulting from blows to the lateral helmet, but other impact areas should be evaluated more closely. For example, consistent with impact descriptives from high school football (7), concussions resulting from top of head impacts were the result of the highest magnitude linear acceleration values (108.8 g; Table 3), but the majority of concussions resulted from front and back impacts (9 of 13).

Further, not all athletic endeavors require or allow the use of protective headgear, necessitating the exploration of alternative prevention methods. Neck strengthening protocols are one suggested, but unproven, concussion deterrent intervention. The underlying justification for this type of training is to tighten the neck musculature at the time of impact to create a single rigid unit of both the head and body to increase effective mass and decrease the resulting post-impact head acceleration. Animal based research highlights this principle when the impacted head is and is not secured by external means. Identical force application generating a concussion when the head is allowed to rotate freely did not yield injury when the head was externally secured (25). Others have shown the same effect by using electrical stimulation to generate neck musculature contractions forceful enough to prevent head motion and consequently concussion (19). Studies of soccer heading yield similar findings with sternocleidomastoid activation just prior to impact to stabilize the head against the ball (4). In combination these investigations support the idea that tensing the neck musculature in an effort to increase effective mass at the moment of impact and lessen head acceleration following impact may be an effective concussion prevention strategy.

This investigation provides a biomechanical assessment of concussions sustained in high school football athletes. While our statistical approach differs from previous accounts in both

collegiate and professional athletes, the variables of rotational acceleration, linear acceleration, and impact location all appear to play a similarly important role in injury prediction. In fact, the variables and values estimated here appear to be nearly indistinguishable to previous biomechanical studies generated from collegiate and professional athletes. The high school athlete's tolerance to impacts, given a standardized set of acceleration parameters, appears to be slightly lower than older players, placing them at a slightly elevated risk for injury. Despite this, epidemiological studies support the notion that overall concussion incidence rates are virtually identical across all levels of play: high school (3.6 to 5.6%)(18;31), collegiate (4.8 to 6.3%)(15;18), and professional (7.7%)(29). Although the slower and less physical high school game results in lower impact forces, injury incidence similarity may be a consequence of an immature musculoskeletal system and the subsequent diminished ability to control and thusly slow head acceleration following impacts (7). Additionally, equipment age, quality, and fit are known to be compromised at the high school level and may influence injury rates.

CONCLUSIONS

The interest among the scientific community to define the biomechanical properties of concussive injuries has increased in recent years with a number of investigations conducted at the collegiate and professional levels. Our findings add to this on going research by developing a concussion injury profile specific to the high school athlete. This analysis improved upon existing reports by generating a clinically useful pathway that was 21.3% accurate; a 3.6 fold improvement over the most recent estimates. Ultimately, the analysis fell short in identifying a single variable or set of variables that predicted concussion in high school football athletes on a level that can used for diagnostic purposes. The use, therefore, of the Head Impact Telemetry System as an acceptable diagnostic tool is not warranted at this time. The HITS can, and does, provide a clear indication of which individuals necessitate further evaluation following an impact.

While an accurate biomechanical diagnostic pathway continues to evade researchers, the clinical examination remains the gold standard for concussion diagnosis. Medical organizations recommend that the clinician employ a battery of tests that evaluate a number of cognitive domains known to be affected by concussion (13;23). Indeed, an assessment battery that employs measures of concussion related symptoms, neurocognitive functioning, and postural control remains the most sensitive to injury in excess of 90%(6) from which to base the diagnosis.

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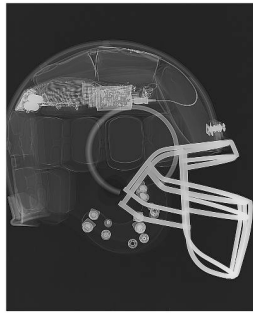


Figure 1.
The Head Impact Telemetry System (HITS) fitted into a football helmet

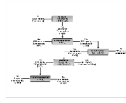


Figure 2.
CART tree indicating rotational acceleration, linear acceleration, and impact location that generate the highest sensitivity (provided in parentheses) to concussion.

Table 1

Participant demographic information presented as means (standard deviation) for the 2007 and 2008 seasons. Demographic data were unavailable from one high school during the 2005 and 2006 seasons.

	2007 Season (n=34)	2008 Season (n=39)
<i>Age (years)</i>	16.9 (.78)	16.7 (.75)
<i>Height (cm)</i>	182.4 (6.8)	179.9 (5.8)
<i>Mass (kg)</i>	87.2 (15.8)	87.3 (16.9)
<i>Previous # concussions</i>	.3 (.67)	.4 (.75)

Table 2

Mean (standard deviation) biomechanical data collected throughout the investigation.

Study Year	Session Type (number of impacts)	Resultant linear acceleration (g)	Resultant rotational acceleration (rad/s²)	Impact duration (ms)
2005	<i>Practices (n=2638)</i>	26.3 (16.3)	1671.0 (1242.5)	10.1 (3.7)
	<i>Games (n=4977)</i>	27.9 (18.2)	1797.4 (1405.7)	10.1 (4.0)
2006	<i>Practices (n=1411)</i>	25.3 (14.8)	1540.5 (1140.1)	10.3 (4.3)
	<i>Games (n=1462)</i>	28.3 (18.2)	1749.7 (1388.2)	10.5 (4.1)
2007	<i>Practices (n=10842)</i>	23.3 (14.5)	1468.6 (1055.0)	10.4 (4.2)
	<i>Games (n= 8387)</i>	24.8 (15.9)	1672.6 (1255.1)	10.1 (3.1)
2008	<i>Practices (n= 14396)</i>	24.4 (13.7)	1598.9 (1061.7)	10.0 (3.1)
	<i>Games (n= 10486)</i>	25.9 (16.0)	1695.9 (1228.1)	10.0 (3.1)

Table 3

Demographic and biomechanical data for each of the 13 concussive injuries captured during the investigation

Position	Age (yrs)	Mass (kg)	Height (cm)	Previous number of concussions	Time from previous concussion (yrs)	Session Type	Impacts prior to injury	Resultant rotational acceleration (rad/s ²)	Resultant linear acceleration (g)	Impact location	Impact duration (ms)	Days for recovery
Quarterback	17.5	68.2	175.3	1	3.2	Game	22	5582.6	102.6	Top	16	1
Offensive Tackle	16.7	93.2	190.5	0		Game	17	5929.4	146.0	Top	7	10
Running Back*	15.0	84.1	180.3	1	n/a	Game	4	6009.4	110.0	Front	7	1
Wide Receiver	15.8	72.3	180.4	0		Game	8	6516.2	74.0	Left	10	2
Defensive Tackle	16.9	100.0	182.9	2	0.9	Game	12	6634.3	107.6	Left	9	8
Running Back	16.2	86.4	175.3	0		Game	70	6640.7	116.2	Front	7	3
Full Back	15.6	84.1	190.5	0		Game	1	7103.1	122.0	Front	8	8
Quarterback*	17.8	75.0	182.9	1	n/a	Game	2	7384.8	81.5	Back	11	3
Defensive Line	16.5	111.4	170.2	0		Practice	5	7967.1	100.9	Front	11	4
Linebacker	16.5	83.2	175.3	0		Practice	2	7997.2	99.1	Front	9	1
Offensive Line*	16.9	95.5	185.4	1	n/a	Game	47	8173.1	96.1	Front	13	1
Cornerback	16.4	70.5	180.3	0		Game	9	8529.7	97.6	Front	10	1
Defensive Tackle	16.2	100.0	182.9	0		Game	25	9515.6	111.3	Front	8	4
<i>Mean (standard deviation)</i>	16.4 (0.6)	86.9 (14.3)	180.3 (6.7)	0.3 (0.7)	2.0 (1.6)		17.2 (20.4)	7229.5 (1157.6)	105.0 (18.0)		9.7 (2.6)	4.2 (3.3)

* All demographic and recovery data were not available for these athletes