Association between biomechanical parameters and concussion in helmeted collisions in American football: a review of the literature

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Object. The authors' goal was to better define the relationship between biomechanical parameters of a helmeted collision and the likelihood of concussion.

Methods. The English-language literature was reviewed in search of scholarly articles describing the rotational and translational accelerations observed during all monitored impact conditions that resulted in concussion at all levels of American football.

Results. High school players who suffer concussion experience an average of 93.9*g* of translational acceleration (TA) and 6505.2 rad/s^2 of rotational acceleration (RA). College athletes experience an average of 118.4*g* of TA and 5311.6 rad/s^2 of RA. While approximately 3% of collisions are associated with TAs greater than the mean TA associated with concussion, only about 0.02% of collisions actually result in a concussion. Associated variables that determine whether a player who experiences a severe collision also experiences a concussion remain hypothetical at present.

Conclusions. The ability to reliably predict the incidence of concussion based purely on biomechanical data remains elusive. This study provides novel, important information that helps to quantify the relative insignificance of biomechanical parameters in prediction of concussion risk. Further research will be necessary to better define other factors that predispose to concussion.

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Key Words • **concussion** • **translational acceleration** • **rotational acceleration**

Concussion occurs when kinetic energy from a collision is transferred to underlying neural elements, resulting in tensile strain and postinjury neural dysfunction.[25] Because accurate measurement of tensile strain during helmeted impacts is not feasible, alternative parameters, such as head acceleration, have been tracked.[4] Previous research has sought to better define the relationship between peak translational and rotational acceleration and concussion.[18] However, various studies have published conflicting results as to what constitutes a "dangerous" level of acceleration.[3,12,18] The purpose of this literature review is to better define the relationship between TA, RA, and concussion and to identify additional variables that merit further analysis in future studies.

Abbreviations used in this paper: HIT = Head Impact Telemetry; NOCSAE = National Operating Committee on Standards for Athletic Equipment; RA = rotational acceleration; TA = translational acceleration.

Methods

Records from MEDLINE and PubMed were searched to identify all studies pertaining to concussion in American football. The terms "translational acceleration," "rotational acceleration," "concussion," "American football," "biomechanical parameters," and "peak impact conditions" were used as Medical Subject Heading terms and text words. The reference lists of these articles were examined to identify additional relevant research.

A focused search was then performed to assess the average translational and rotational accelerations associated with actual collisions resulting in concussive episodes. An additional search was then performed to identify studies that reported individual recordings of accelerations associated with collisions that had resulted in concussion. This was done so that a weighted mean of all individual translational and rotational accelerations associated with concussions could be calculated. A third search was conducted to identify studies that had reported peak accelerations (measured as top 1% and 5% of impacts) for both high school and collegiate levels to gain an idea of how collisions that resulted in concussion compared with a composite, unfiltered distribution of collisions.

Results

After an extensive review of the literature, 7 papers were identified that reported the average translational and rotational accelerations associated with actual collisions resulting in concussive episodes (Table 1).[2,3,5,7,9,14,20,21] Five of these studies dealt with collegiate athletes, and 2 reported values obtained from high school players. Of the approximately 560,000 collisions that were recorded, 98 collisions (0.02%) resulted in concussion.

Two studies identified the individual accelerations experienced by 23 concussed high school players (Table 2). These players experienced, on average, 6505.2 rad/s^2 of RA and 93.9*g* of TA during the collisions that resulted in concussion. This search was then repeated for college athletes, yielding 3 studies that reported the accelerations experienced by 21 concussed players (Table 3). These players experienced, on average, 5311.6 rad/s^2 of RA and 118.4*g* of TA during the collisions that resulted in concussion.

Two studies were identified that reported peak accelerations obtained from the top 1% of measured impacts, at the high school and collegiate levels (Table 4). In the report by Schnebel et al.,[21] the top 1% of college impacts was associated with a TA of 127.8*g*. In contrast, the top 1% of impacts at the high school level was associated with a TA of 114.5*g*.

In all of the aforementioned studies, players wore helmets equipped with the HIT system (Simbex) to measure accelerations using a wireless device that provided real-time data from helmeted collisions.[2,3,5,7,9,14,20,21] The HIT system consists of a player unit, signal receiver, and laptop computer system located on the sidelines. Translational (linear) acceleration was measured directly, while peak RA was estimated from a TA vector and an assumed point of rotation. The accuracy of the HIT system has been validated in previous studies.[7] In addition to the description above, the study by Rowson et al.[20] provided an estimate of RA tolerance derived from direct acceleration measurements from an instrumented human volunteer using a 6-df device.

Concussion definitions were consistent throughout the studies. Broglio et al.[2,3] and Rowson et al.[20] used the following definition of concussion provided by the American Academy of Neurology: "A trauma-induced alteration in mental status that may or may not involve loss of consciousness." Guskiewicz and colleagues[14] defined concussion as an injury resulting from a blow to the head that caused an alternation in mental status and one or more of the following symptoms: headache, nausea, vomiting, dizziness/balance problems, fatigue, trouble sleeping, drowsiness, sensitivity to light or noise, blurred vision, difficulty remembering, and difficulty concentrating. Schnebel et al.[21] defined concussion as a traumatically induced neurological dysfunction, manifested primarily by transient alternations in consciousness and cognition.

Concussions in all studies were diagnosed based on a combination of detailed history, clinical evaluation, and review of game film.[5,7,21] Additionally, a comparison was made between player's baseline cognitive status (as assessed by various programs, including HeadMinder and ImPACT) and the individual's postinjury evaluation.[2,5,7] When an injury appeared serious or symptoms remained persistent, additional neuropsychological and neuroimaging tests were performed on a selective basis. While some studies (for example, that by Guskiewicz et al.[14]) used symptom grading in their assessment, this was not true for all studies (Broglio et al.[2] did not grade injuries because of the general lack of support and evidence for the use of grading scales).

Discussion

The quest to better understand the relationship between the biomechanical parameters of a collision and the physiognomic repercussions has been ongoing for more than half a century. In an early landmark study, Lissner et al.[16] performed drop tests on cadaveric specimens at Wayne State University and detailed the relationship between TA, impulse duration, and skull fracture (of particular note, concussions during this era were often defined as "posttraumatic episodes of unconsciousness" and researchers using cadaveric specimens often hypoth-

TABLE 1: Studies reporting the average translational and rotational accelerations associated with concussive episodes*

Authors & Year	High School vs College	No. of Impacts	No. of Concussions	Mean TA *(g)*	Mean RA (rad/s^2)
Duma et al., 2005	college	3,312	1	81	5,590
Guskiewicz et al., 2007	college	104,714	13	102.8	5,311.6
Brolinson et al., 2006	college	11,604	3	103.3	NR
Funk et al., 2012	college	37,128	4	145	NR
Rowson et al., 2012	college	301,034	57	NR	5,022
Broglio et al., 2010	high school	54,247	13	96.1	5,582.3
Broglio et al., 2011	high school	101,994	20	93.6	6,402.6
total		559,786	98 (0.02%)		

* NR = not reported.

TABLE 2: Recordings of accelerations associated with individual collisions resulting in concussion in high school players

Authors & Year	Designation	RA of Collision (rad/s^2)	TA of Collision *(g)*	Days of Recovery
Broglio et al., 2011	Player 1	5,582.6	102.6	1
	Player 2	5,929.4	146	10
	Player 3	5,581.9	74.6	NR
	Player 4	7,103.1	122	8
	Player 5	7,992.9	130.6	NR
	Player 6	9,515.5	111.3	4
	Player 7	6,634.3	107.6	8
	Player 8	6,640.7	116.2	3
	Player 9	8,529.7	97.6	1
	Player 10	5,933	66.3	NR
	Player 11	3,317.5	114.4	NR
	Player 12	6,516.2	74	2
	Player 13	7,997.2	99.1	1
	Player 14	7,967.1	100.9	4
	Player 15	4,870.2	85.3	NR
	Player 16	4,664.6	52.7	NR
	Player 17	4,280.4	48	NR
	Player 18	4,655.3	66.5	NR
	Player 19	4,858.1	52.9	NR
	Player 20	9,481.5	102.7	NR
Broglio et al., 2010*	Player 21	6,009.4	110	1
	Player 22	7,384.8	81.5	3
	Player 23	8,173.1	96.1	1
mean		6,505.2	93.9	

* Ten of the 13 concussion data points initially published in the Broglio et al. 2010 study were republished in the Broglio et al. 2011 study (these 10 data points are listed under Broglio et al. 2011 in the table). Thus, only the 3 data points that were not republished are illustrated under Broglio et al. 2010 in this table.

esized that the energy required for skull fracture would be roughly equivalent to the amount of energy necessary to result in concussive injury). Additional studies, also performed at Wayne State University, sought to better elucidate the relationship between TA, impulse duration, and degree of concussion in a canine model.[13] In 1966, Gadd[11] used this data curve to describe a new entity know as the severity index to predict the threshold of life-threatening injury. The formula used to calculate the severity index exponentially weighted TA to a power of 2.5 prior to integration with respect to time.[10] In 1973, the NOCSAE incorporated this measure in its recommendations for sports helmets. The pass-fail value for severity index was changed to its current value of 1200, in line with changes in federal motor vehicle safety standards in 1996.

The search for a "threshold" acceleration, below which concussive injury is prevented, has continued into the 21st century.[18,22] In 2003, Pellman and colleagues[18] purported that a peak translational acceleration of 98.9*g* was associated with a 74% risk of cerebral injury, arguing that helmet constructs should be measured by their ability to limit TA. Subsequent reports have suggested that the frequency of injuries reported by Pellman et al. are grossly overestimated, attributing inaccuracies to selection bias associated with inclusion and measurement of only those impacts associated with concussion.[3] In recent years, many reports have offered insight regarding the predictive value of additional surrogate parameters in helmeted impacts. A comprehensive study by Greenwald et al.[12] reported that a combination of variables, including TA, RA, impact location, and head injury criterion, provided the highest sensitivity with regard to prediction of concussion.

Despite a considerable amount of speculation, the literature search performed in this review highlights the indistinct and complex relationship between acceleration and concussive symptoms. Tables 2 and 3 list the average TAs experienced by high school and collegiate players who experienced a concussion (93.9*g* and 118.4*g*, respectively). A review of Table 4 helps to gauge the relative severity of these statistics. The aforementioned TAs are lower than the mean numbers reported for the top 1% of collisions for each respective level, but greater than the mean numbers reported for the top 5% of collisions, placing the mean TA associated with collision somewhere between the 95th and 99th percentiles. This estimation is consonant with the report by Schnebel et al.,[21] who estimated that most concussions were associated with accelerations involving the top 3% of impacts. However, while

TABLE 3: Recordings of accelerations associated with individual collisions resulting in concussion in collegiate players

Authors & Year	Designation	RA of Collision (rad/s²)	TA of Collision (*g*)	Days of Recovery
Funk et al., 2007	Player 1	NR	81	NR
	Player 2	NR	139	NR
	Player 3	NR	172	NR
	Player 4	NR	200	NR
Guskiewicz et al., 2007	Player 5	163.35	60.51	NR
	Player 6	5,923.27	63.84	NR
	Player 7	3,637.48	77.68	NR
	Player 8	5,299.57	84.07	NR
	Player 9	3,274.05	85.1	NR
	Player 10	8,994.40	99.74	NR
	Player 11	1,085.26	100.36	NR
	Player 12	6,837.62	102.39	11
	Player 13	2,811.45	107.07	NR
	Player 14	6,632.77	109.23	NR
	Player 15	7,974.22	119.88	NR
	Player 16	1,020.0	157.5	NR
	Player 17	15,397.07	168.71	NR
Funk et al., 2012*	Player 18	NR	98	NR
	Player 19	NR	164	NR
	Player 20	NR	178	NR
mean		5,311.6	118.4	

* One of the 4 concussion data points initially published in the Funk et al. 2007 study was republished in the Funk et al. 2012 study. Thus, only the 3 data points that were not republished are listed under Funk et al. 2012 in this table.

these accelerations are encountered on a relatively frequent basis in American football (by definition, approximately 1 in 33 collisions), concussions are, in fact, decidedly rare events. Table 1 illustrates that across 7 studies and nearly 560,000 collisions, only 98 concussions (approximately 1 concussion per every 5000 collisions) were reported. Otherwise stated, while approximately 3% of collisions are associated with TAs greater than the mean TA associated with concussion, only about 0.02% of collisions actually result in a concussion.

It is intuitive to surmise that the more violent a collision, the more likely the players involved will suffer concussions. This notion is supported by decades of animal, human, and cadaveric research, which has noted an increased incidence of intracranial injury with increasing head accelerations.[11,13,16] Thus, it is not surprising that the vast majority of interventions meant to decrease head injury have addressed biomechanical factors. In the 1970s, in particular, many changes were made in attempt to decrease the collision-related head accelerations. Widespread adoption of the NOCSAE criteria for helmet safety in 1974 resulted in an approximately 50% decline in the severity index relative to helmets' prior certification score.[15,17] This was followed by a 1976 rule that prohibited initial contact of the opponent's helmet when tackling or blocking.[6] Improvements in helmet technology have paralleled changes in regulation. One notable example is the switch from suspension helmets to padded helmets, which have been shown to increase the time of force application and decrease peak acceleration.[1] Incremental biomechanical advances in newer padded helmets have been documented in other studies.[24] However, despite numerous improvements in both the rules of the game and helmet design and technology, concussions continue to be a common problem.

TABLE 4: Peak accelerations from the top 1% of measured impacts, as measured by various studies, for high school and collegiate levels

Authors & Year	No. of Impacts	College vs High School	Game vs Practice	Mean TA (*g*), Top 1%	Mean TA (*g*), Top 5%	Mean RA (rad/s²), Top 1%
Schnebel et al., 2007	54,154	college	game + practice	127.8	84	NR
	8,326	high school	game + practice	114.5	77.9	NR
Greenwald et al., 2008	289,916	high school + college	game	103.4	NR	6,990.5

Based on information collected in this study, approximately 2 in 10,000 collisions result in a concussion. This figure is consistent with previous studies that have estimated approximately 3 concussions per 10,000 collisions.[19] As mentioned above, it is relatively frequent for impact accelerations to surpass the average mean acceleration associated with concussions; however, less than 1% of collisions that surpass the average mean acceleration associated with concussion actually result in concussion. In light of the wide variations noted above between the magnitude of acceleration in a collision and the appearance of postconcussive sequelae, additional research has focused on the identification of other influential variables. One such putative variable involves the contribution of cumulative subconcussive impacts. While older studies suggested that cumulative subconcussive impacts might potentially play a role in predisposing players to concussive symptoms, a more recent study by Broglio et al.[2] failed to find an association between cumulative impact profiles and concussive symptoms.[5] However, it remains possible that genetic and age-related factors may influence the biological recovery of neurons following subclinical injury and that the influence of cumulative subconcussive impacts may vary across subgroups. In addition to the potential contribution of cumulative subconcussive impacts, a recent study by Zhang et al.[25] applied National Football League (NFL) concussion data to a finite element model and found that the amount of shear stress placed on brainstem structures might be an important and largely unheralded risk factor for development of concussion. A study by Viano et al.[23] demonstrated various areas of strain concentration or "hot spots" following reenactment of NFL collisions that eventuated in concussion. Both of these studies highlight the very important consideration that a number of biomechanical and anatomical variables specific to a collision influence the relatively small region of the brain that is subject to the greatest amount of deformation. Moreover, which regions of the brain were subjected to increased strain in previous collisions, the magnitude of these strain(s), and genetic and temporal aspects of recovery result in additional degrees of variability. In light of the intricate nature of these contributing factors, it is not surprising that traditional methods seeking to define a simple, biomechanical threshold of concussive injury have fallen short.

Hope remains that future scientific developments will further elucidate the full set of variables that determine the cumulative threshold of tissue strain and acute and chronic neurological dysfunction. One potential next step for advancement would involve the marriage of current systems used to track in vivo biomechanical parameters with finite element technology used to predict patterns of tissue strain in response to various biomechanical variables. While both the great number of variables involved and the inherent limitations of study of human subjects makes systematic analysis of this topic difficult, further analysis is warranted.

Conclusions

While approximately 3% of collisions are associated with TAs greater than the mean TA associated with concussion, only about 0.02% of collisions actually result in a concussion. Despite the exhaustive collection of biomechanical data that has occurred over the past 15 years, the ability to reliably predict the incidence of concussion based purely on biomechanical data remains elusive. Further research of other influential variables will be necessary to fully elucidate this disparity.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Forbes. Acquisition of data: Forbes, Awad. Analysis and interpretation of data: Forbes, Awad. Drafting the article: Forbes, Cheng. Critically revising the article: Forbes, Zuckerman, Carr. Reviewed submitted version of manuscript: Forbes. Approved the final version of the manuscript on behalf of all authors: Forbes.

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