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Cumulative Head Impact Burden in High School Football

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Abstract

Impacts to the head are common in collision sports such as football. Emerging research has begun to elucidate concussion tolerance levels, but sub-concussive impacts that do not result in clinical signs or symptoms of concussion are much more common, and are speculated to lead to alterations in cerebral structure and function later in life. We investigated the cumulative number of head impacts and their associated acceleration burden in 95 high school football players across four seasons of play using the Head Impact Telemetry System (HITS). The 4-year investigation resulted in 101,994 impacts collected across 190 practice sessions and 50 games. The number of impacts per 14-week season varied by playing position and starting status, with the average player sustaining 652 impacts. Linemen sustained the highest number of impacts per season (868); followed by tight ends, running backs, and linebackers (619); then quarterbacks (467); and receivers, cornerbacks, and safeties (372). Post-impact accelerations of the head also varied by playing position and starting status, with a seasonal linear acceleration burden of 16,746.1*g*, while the rotational acceleration and HIT severity profile burdens were 1,090,697.7 rad/sec^2 and 10,021, respectively. The adolescent athletes in this study clearly sustained a large number of impacts to the head, with an impressive associated acceleration burden as a direct result of football participation. These findings raise concern about the relationship between sub-concussive head impacts incurred during football participation and late-life cerebral pathogenesis, and justify consideration of ways to best minimize impacts and mitigate cognitive declines.

Key words: acceleration; chronic traumatic encephalopathy; concussion

Introduction

Concussion is an inherent risk to sport participation. High school athletes represent the single largest group of physically active individuals, making injuries to this cohort a significant public health concern. While injury rates vary by sport and gender, the percentage of football athletes that sustain a concussion in a given season is consistent across all levels of play (Guskiewicz et al., 2000,2003; Pellman et al., 2004; Powell and Barber-Foss, 1999). The greatest volume of injuries therefore occurs at the high school level, where nearly 1.2 million players take the field each fall. The numbers of collegiate and professional athletes are far fewer (68,000 and 1700 respectfully), yet the medical coverage afforded these athletes is appreciably better than their high school counterparts. Indeed, only 42% of high schools have access to a certified athletic trainer, many of whom are not full-time employees (National Athletic Trainers' Association, 2009).

Sport- and recreation-related concussions are a growing medical concern, with annual injury estimates increasing from 300,000 (Thurman et al., 1998) a decade ago, to nearly 4 million (Langlois et al., 2006) today. While many of the acute effects of concussion have been well defined (McCrea et al., 2003), there is now a growing concern over how concussions may affect long-term cognitive functioning (Guskiewicz et al., 2005,2007a; McKee et al., 2009,2010; Omalu et al., 2005,2006), motor control (Martini et al., 2011; Sosnoff et al., 2011), and mental health (Broshek and Freeman, 2005). More recently, there has also been speculation that sub-concussive impacts to the head, that is, impacts not resulting in clinically-identifiable concussion, may also adversely affect cerebral function (Gavett et al., 2011; McKee et al., 2009). This speculation is highlighted by documented changes in cerebral function (i.e., visual working memory declines), and altered dorsolateral prefrontal cortex activation as assessed by functional magnetic resonance imaging in high school football athletes in the absence of clinical signs of concussion (Talvage et al., 2010).

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The quantification of impacts to the head during football participation is relatively new to the medical literature. The modern research era began with the work of Pellman and associates (Pellman et al., 2003), who reconstructed 25 of 182 concussive high-velocity impacts captured on video in professional football athletes. The impact reconstructions implemented Hybrid III crash test models equipped with a 3-2-2-2 accelerometer array that estimated the cranial center of mass acceleration. Linear acceleration was suggested as the key factor for concussion, although rotational acceleration was also suggested to be a contributing factor, and has been linked to cytoskeleton damage in animal models (Potts et al., 2009). Pellman and colleagues made no attempt to quantify the total number or volume of sub-concussive impacts incurred in a season or career of the professional athlete. The next series of investigations implemented the Head Impact Telemetry System (HITS; Simbex, Lebanon, NH) in collegiate and high school athletes. Schnebel and colleagues implemented the HITS in both collegiate and high school athletes across one season of play. Data analysis indicated that the collegiate players sustained larger-magnitude impacts, those exceeding 60 and 98*g*, more frequently than high school athletes (Schnebel et al., 2007). Collegiate level investigations have focused on the magnitude and location of concussive impacts (Guskiewicz et al., 2007b), and the mean linear and rotational acceleration values based on player position, session type, and impact location (Mihalik et al., 2007). Other investigations of impact biomechanics have followed these same lines, with work attempting to define a threshold for concussion using combined data from collegiate and high school athletes (Greenwald et al., 2008), and high school athletes alone (Broglio et al., 2010). One investigation describing impacts by player position, session type, and impact location in high school athletes indicated that high school players may sustain up to 1100 impacts in a season, but no attempt was made to quantify the cumulative burden of those impacts (Broglio et al., 2009). These works have narrowed the variables associated with concussion, and collectively suggest that linear acceleration, rotational acceleration, and impact location, each appear to play a role in the biomechanical threshold for concussion. However, the cumulative exposure to head impacts incurred by an athlete at each level of play remains unknown. Therefore, the purpose of this investigation is to better describe exposure to impacts incurred by high school football athletes during a season and career.

Methods

As part of an ongoing investigation of concussion biomechanics occurring during high school football, 95 male players were enrolled for participation from 2007 through 2010. All athletes were members of the same Class 3A football team. Prior to enrollment all athletes were informed of the intent and methods of the investigation, and completed an institutional review board-approved informed consent document. Parental consent was also obtained prior to data collection.

Each athlete was issued a Riddell (Elyria, OH) Revolution helmet (0–2 years old) by the team prior to starting the season. The helmet was fitted with a HITS encoder that permitted the tracking of impacts incurred during normal football participation. The HITS encoder consists of six single-axis accelerometers, a wireless telemetry unit, a battery, and an onboard data storage unit arranged in a horseshoe configuration and encased within waterproof plastic. The encoder communicates with a sideline computer that downloads and stores data pertaining to all impacts in real time. When out of range of the computer or if the computer is not available, the encoder can record and store up to 100 impacts in the absence of the sideline computer. Helmets equipped with a HITS encoder look and function identically to non-HITS helmets, and their use has been approved by the National Operating Committee on Standards for Athletic Equipment (NOCSAE). The HIT System has been used in a number of investigations of head impacts, in football (Brolinson et al., 2006; Crisco et al., 2010; Duma et al., 2005; Greenwald et al., 2008), ice hockey (Mihalik et al., 2007), and boxing (Beckwith et al., 2007), and has been validated against Hybrid III dummies for both location and impact magnitude (Crisco et al., 2004).

For an impact to be recorded a single accelerometer must exceed a 15-*g* threshold, although the ensuing resultant linear acceleration may be less than 15*g*. After impact a total of 40 msec of data are stored, including 8 msec prior to the impact and 32 msec following impact. Software provided by the manufacturer calculates the peak linear acceleration, rotational acceleration (derived from the x-axis and y-axis angular accelerations), HIT severity profile (HITsp, a principle component analysis calculation based on linear and rotational acceleration, as well as impact location and duration; Greenwald et al., 2008), impact location, and a date and time stamp for later download and analysis. A more detailed description of the HITS technology and data recording and management has been reported elsewhere (Greenwald et al., 2008).

For the purpose of this investigation, concussion was defined using the American Academy of Neurology definition, which states "Concussion is a trauma-induced alteration in mental status that may or may not involve loss of consciousness" (American Academy of Neurology, 1997). The concussion diagnosis was made by a certified athletic trainer (present at all sessions), or physician (present at games). Injuries were not graded because of the general lack of support for the use of grading scales (McCrory et al., 2009) and a lack of evidence supporting the use of grading scales to accurately reflect injury severity (Lovell et al., 2004). Data were recorded during all practices and games, and were screened on a daily basis by the primary investigator to ensure that errant impacts (e.g., a dropped helmet) were excluded from the database.

Data analysis

Descriptive statistics (i.e., mean, standard deviation, and median) were calculated for the number of impacts, linear and rotational acceleration, and HITsp. Since there is no accepted method to quantify cumulative impact burden, the sum of the linear and rotational accelerations, as well as the HITsp values associated with each individual head impact over the course of the study were calculated for every athlete. These sums are reported as cumulative linear acceleration, cumulative rotational acceleration, and cumulative HITsp. Impact data are divided by player position groups: linemen (center, guard, and offensive and defensive tackle); quarterbacks; tight end/running back/linebacker (TE/RB/LB); and wide receivers, cornerbacks, and safeties (WR/CB/S); and the kicker; as well as by session type (practice, game, or combined).

Results

Data were collected from 95 athletes across the 4-year investigation for a total of 156 player-seasons (2007: $n=32$; 2008: $n=40$; 2009: $n=42$; 2010: $n=43$). Some athletes participated in the study over more than one season (1 year; $n=42$; 2 years: $n=46$; 3 years: $n=5$, 4 years: $n=2$). Four athletes left the study due to orthopedic injury or for personal reasons before completing a full season of data collection. Partial season data from these individuals were included in the final dataset. Demographic information (mean ± standard deviation) for all participants at the time of enrollment were: age = 16.68 ± 0.81 years, weight = 85.59 ± 18.29 kg, and height = 180.15 ± 6.74 cm. Twenty-three athletes reported a prior history of concussion (0.33 ± 0.70 previous concussions, range 1–6). Over the course of the 4-year investigation (mean 14-week season) a total of 102,238 impacts were collected across 190 practice and 50 game sessions. A total of 244 errant impacts were removed from the dataset, leaving 101,994 impacts for analysis. The data also included 20 concussive events from 19 athletes that were analyzed along with the other data. A separate analysis of the concussive events and their subsequent outcomes can be found elsewhere (Broglio et al., 2011; Eckner et al., 2011).

The number of head impacts varied by session type and player position group. In practices, linemen sustained an average of 10.7 ± 9.7 (range 1–70) impacts per session, compared to 3.1 ± 4.0 (range 1–22) for quarterbacks, 4.5 ± 4.9 (range 1–37) for the WR/CB/S group, and 7.1 ± 8.6 (range 1–76) for the TE/RB/LB group. The number of impacts increased two- to fourfold during game situations, where linemen sustained an average of 28.7 ± 25.8 (range 1–195) impacts per session, compared to 25.6 ± 19.3 (range 1–109) for quarterbacks, 15.7 ± 20.5 (range 1–177) for the WR/CB/S group, and 24.0 ± 21.8 (range 1–197) for the TE/RB/LB group. Table 1 describes the annual number of impacts sustained by players in each position group over the course of the investigation. During the study the average player sustained 652 (median 626) impacts per season. The minimum number of impacts sustained by a participant in a season was 5, while one athlete sustained 2235 impacts during a season.

The magnitude of linear acceleration associated with impacts during practices varied only slightly across player positions, with linemen sustaining a mean linear acceleration of 24.4 ± 13.5*g*; quarterbacks 27.0 ± 18.2*g*; the WR/CB/S group 24.1 ± 14.6*g*; and the TE/RB/LB group 25.5 ± 15.4*g*. The magnitude of linear acceleration associated with impact during games was only slightly higher, with linemen sustaining a mean linear acceleration of 25.1 ± 14.9*g*; quarterbacks 28.6 ± 19.5*g*; the WR/CB/S group 26.6 ± 18.2*g*; and the TE/RB/LB group 27.1 ± 17.5*g*. Figure 1 presents the distribution of linear accelerations endured by the athletes in each position group over an average season, as well as during a single practice or game session. Over the course of the study the average player sustained a cumulative linear acceleration of 16,746.1*g* per season. Linemen sustained the greatest annual cumulative linear accelerations (21,435.9*g*), followed by the TE/RB/LB group (16,676.4*g*), quarterbacks (13,122.5*g*), and the WR/CB/S group (10,363.9*g*). The lowest cumulative linear acceleration sustained during a season was by the kicker (91.4*g*), while the highest was by a lineman with a cumulative total of 55,152*g*.

The average magnitude of rotational acceleration was similar between position groups during practices, with linemen sustaining a mean rotational acceleration of 1572.9 ± 1045.7 rad/sec^2; quarterbacks 1506.0 ± 1262.1 rad/sec^2; the WR/CB/S group 1571.4 ± 1134.0 rad/sec^2; and the TE/RB/LB group 1632.5 ± 1150.1 rad/sec^2. The magnitude of rotational accelerations during games was higher, with linemen sustaining a mean 1658.5 ± 1191.0 rad/sec^2; quarterbacks 1786.9 ± 1421.1 rad/sec^2; the WR/CB/S group 1771.1 ± 1366.2 rad/sec^2; and the TE/RB/LB group 1789.4 ± 1354.3 rad/sec^2. Figure 2 presents the distribution of rotational accelerations endured by the athletes in each position group over an average season, as well as during a single practice or game session. Over the course of the study the average player sustained a cumulative rotational acceleration of 1,090,697.7 rad/sec^2 per season. Linemen sustained the

Table 1. Annual Number of Head Impacts Sustained by Players During Practices, Games, and Over an Entire Season

Practices	*Mean*	*Standard deviation*	*Median*	*Minimum*	*Maximum*
Linemen	509.4	239.6	494	64	1463
Quarterbacks	146.0	69.6	165	43	227
Receivers, cornerbacks, and safeties	204.0	105.9	189	32	463
Tight ends, running backs, and linebackers	335.2	179.3	340	22	742
Kicker	5	n/a	n/a	n/a	n/a
Games					
Linemen	364.6	265.9	336	15	1164
Quarterbacks	320.6	203.5	315	6	545
Receivers, cornerbacks, and safeties	189.8	160.7	149.5	11	651
Tight ends, running backs, and linebackers	290.8	186.9	249	11	703
Season totals					
Linemen ($n=41$)	868.3	434.9	872	73	2235
Quarterbacks ($n=4$)	466.6	243.2	519	49	662
Receivers, cornerbacks, and safeties ($n=28$)	372.3	236.9	318	45	895
Tight ends, running backs, and linebackers ($n=27$)	619.3	296.9	617	74	1140
Kicker ($n=1$)	5	n/a	n/a	n/a	n/a

Positions are not mutually exclusive, as some players may have played multiple positions in different years.

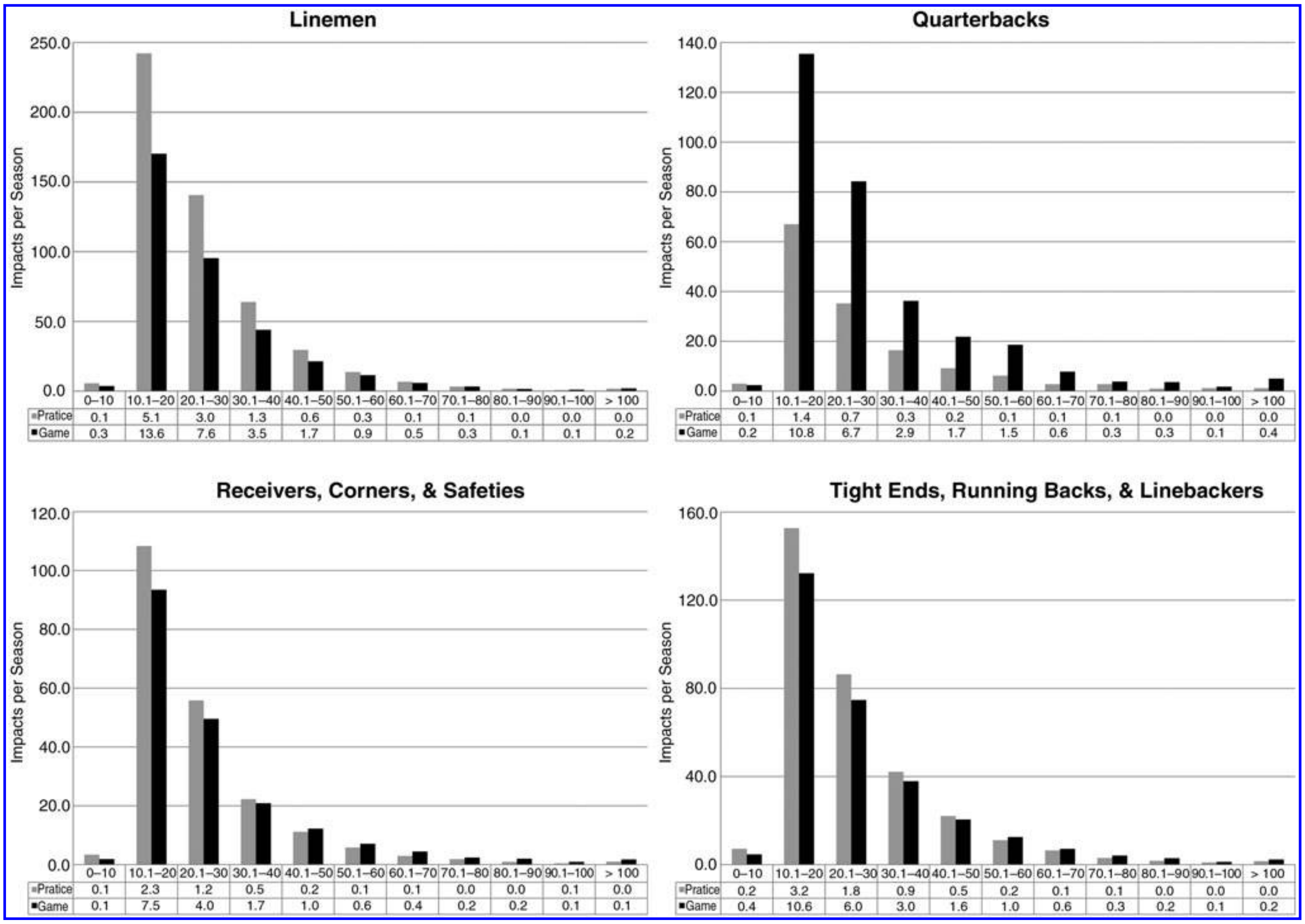

FIG. 1. Frequency distribution of linear acceleration (*g*'s) by player position group and session type. The histogram bars represent the number of impacts sustained in a average season, while the bottom rows represent the number of impacts in an average session (practice or game).

greatest cumulative rotational accelerations (1,396,423.9 rad/sec^2), followed by the TE/RB/LB group (1,084,226.0 rad/sec^2), quarterbacks (792,744.5 rad/sec^2), and the WR/CB/S group (683,749.5 rad/sec^2). The lowest cumulative rotational acceleration was again sustained by the kicker (6073.7 rad/sec^2), and the highest was by a lineman, at 3,775,044.2 rad/sec^2.

Noting the complex relationship between linear and rotational head acceleration associated with impact, we also analyzed HITsp values. The unitless HITsp accounts for both linear and rotational acceleration, as well as impact location and duration. The average HITsp magnitude was similar between position groups during practices, with linemen sustaining a mean value of 14.7 ± 6.9, quarterbacks 14.8 ± 7.9, the WR/CB/S group 14.4 ± 7.2, and the TE/RB/LB group 15.3 ± 7.7. The HITsp magnitude associated with game impacts was only slightly higher, with linemen sustaining a mean value of 15.1 ± 7.7, quarterbacks 15.9 ± 9.6, the WR/CB/S group 15.7 ± 10.0, and the TE/RB/LB group 16.2 ± 9.2. Figure 3 presents the distribution of HITsp values endured by the athletes in each position group over an average season, as well as during a single practice or game session. Over the duration of the study the average player sustained an annual cumulative HITsp value of 10,020.8. Linemen sustained the greatest cumulative HITsp values (12,905.9), followed by the TE/RB/LB group (9979.7), quarterbacks (7256.1), and the WR/CB/S group (6155.2). The minimum HITsp value over a season was sustained by the kicker (45.2), while a lineman sustained the maximum, at 33,212.1.

When comparing a single practice session to a single game, the athletes in all position groups uniformly sustained more head impacts at each level of linear and rotational acceleration, and at each HITsp during games (Figs. 1–3). However, when comparing the cumulative annual burden of head impacts at each magnitude of linear and rotational acceleration and HITsp, there are different trends between the player position groups. The cumulative annual linear and rotational accelerations and HITsp values sustained by linemen during practices were greater than or equal to those sustained during games at all impact magnitudes. In contrast, exactly the opposite trend was present in quarterbacks, who sustained greater cumulative annual impact burdens for each measure at every magnitude during games compared to practices. Yet a different trend was present in the TE/RB/LB and WR/CB/S groups. In these athletes the cumulative annual impact burdens at lower magnitudes were greater during practices than games, whereas at higher impact magnitudes the cumulative annual impact burden was higher during games. Indeed, the linemen in this investigation sustained 59% of

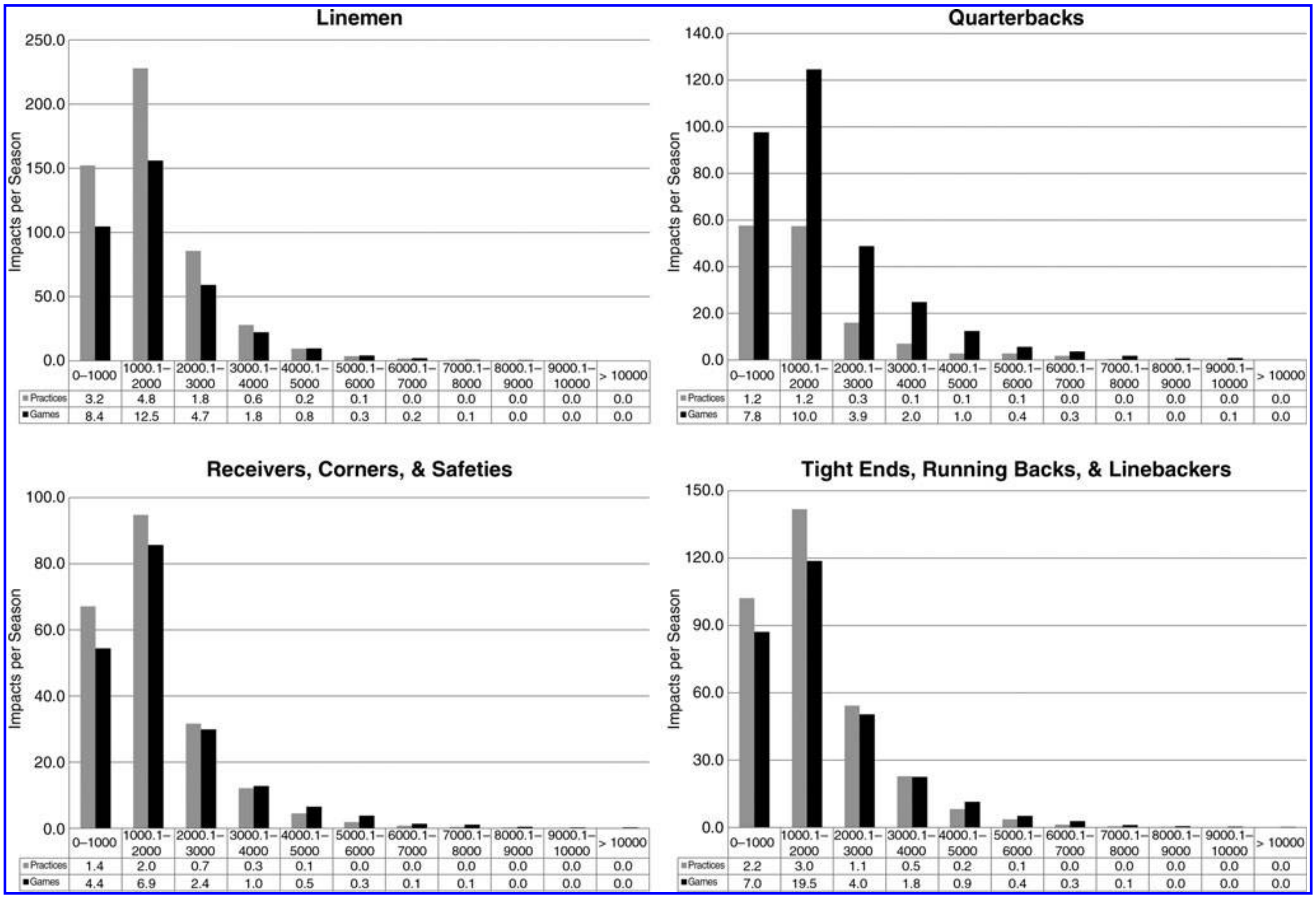

FIG. 2. Frequency distribution of rotational acceleration (in radians/second/second [rad/sec^2]) by player position group and session type. The histogram bars represent the number of impacts sustained in a average season, while the bottom rows represent the number of impacts in an average session (practice or game).

their impacts during practices, compared to 54% among the tight ends, running backs, and linebackers; 52% among the receivers, cornerbacks, and safeties; and 31% in the quarterbacks (Table 1). Quarterbacks presumably sustained the least number of impacts during practices because of their protected status on the team.

Finally, we evaluated the cumulative number of head impacts, linear acceleration, rotational acceleration, and HITsp values endured over a career in the 7 athletes who participated in the study for 3 or 4 years. Table 2 presents the cumulative data in these athletes over their 3- or 4-year high school football careers. These athletes averaged 659 impacts per year and 2134 impacts over their careers. On average, they sustained an annual cumulative linear acceleration of 17346.2*g*, a cumulative rotational acceleration of 1,125,335.1 rad/sec^2, and a cumulative HITsp value of 10,283.8. These values were 56,386*g*, 3,651,883 rad/sec^2, and 33360, respectively, over their 3- or 4-year high school football careers.

Discussion

This investigation was conducted to better describe and characterize the number and cumulative burden of head impacts sustained by high school football players over a typical season. The high school football players in our sample sustained an annual average of 652 impacts, with a wide range, from as few as 5 to as many as 2235 impacts. It has been demonstrated that impacts to the head during football participation result in both linear and rotational accelerations, but attempts to quantify the cumulative burden of these measures are not available in the scientific literature. It is striking to see that the average annual cumulative linear acceleration observed in our sample reached 16,746.1*g*, and the average annual cumulative rotational acceleration reached 1,090,697.7 rad/sec^2. Similarly, when linear and rotational acceleration, as well as impact location and duration, are simultaneously taken into account, an average annual cumulative HITsp value of 10,021 was observed. More impressive are the cumulative impact values observed over a high school football career in those athletes who participated in this study for 3 or 4 years, which averaged 56,386*g* for cumulative linear acceleration, 3,651,883 rad/sec^2 for cumulative rotational acceleration, and 33,360 for the HITsp. There was a great deal of variance in both the total number of impacts sustained and the associated acceleration values in this dataset, which is likely a reflection of both player position and the amount of playing time seen by each individual athlete. That is, starting athletes received more repetitions in practices and games than non-starting athletes; therefore they sustained a greater number of head impacts with higher associated cumulative linear

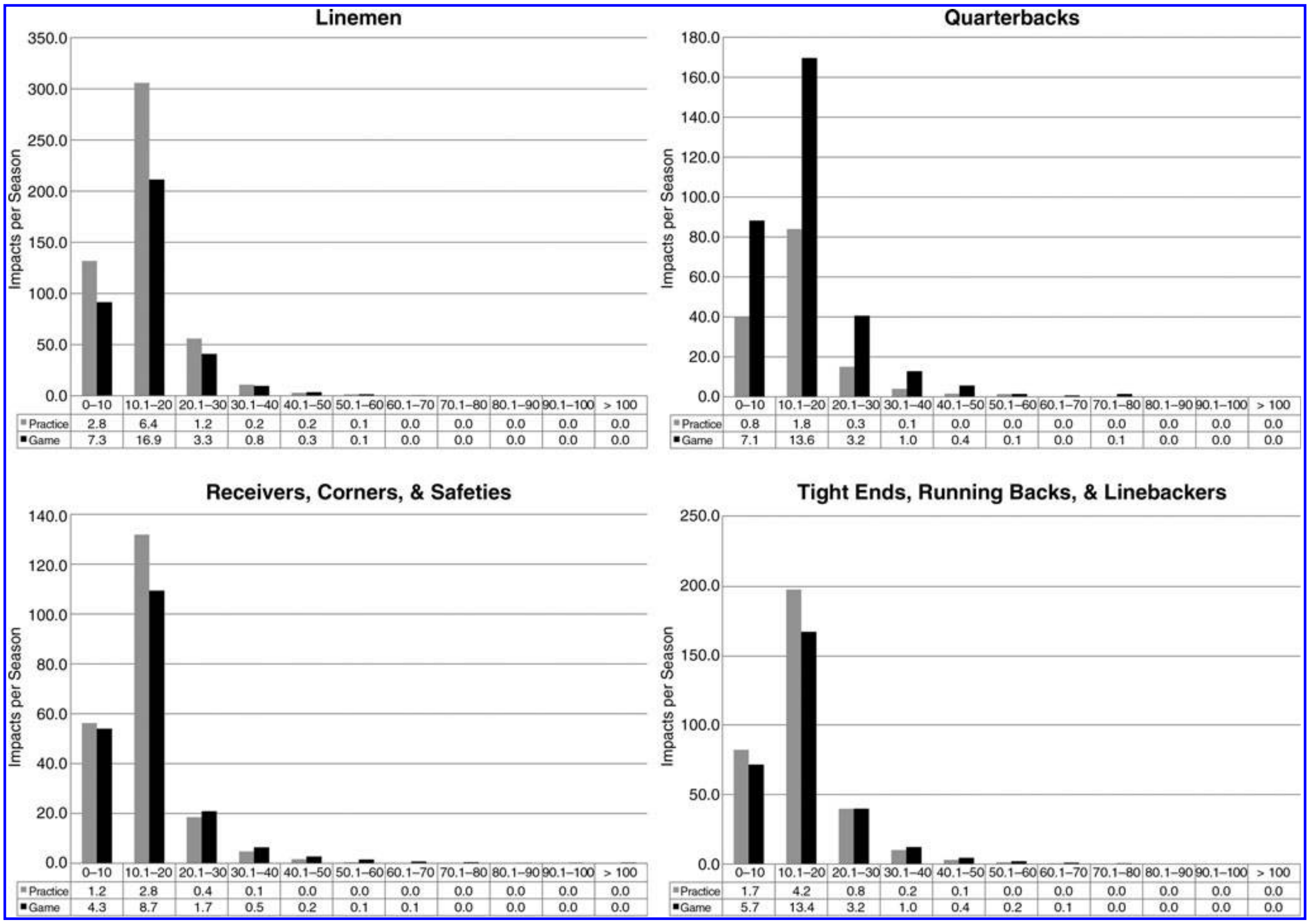

FIG. 3. Frequency distribution of Head Impact Telemetry severity profile (HITsp) by player position group and session type. The histogram bars represent the number of impacts sustained in a average season, while the bottom rows represent the number of impacts in an average session (practice or game).

acceleration, rotational acceleration, and HITsp values. For example, the minimum values reported here (5 impacts, 91.4*g*, and 6074 rad/sec^2) were for the team's kicker, while the maximum values (2235 impacts, 55,152*g*, and 3,775,044 rad/sec^2) occurred in a starting defensive tackle.

There has been little work reporting how many head impacts football players sustain at other levels of play. One investigation (Schnebel et al., 2007) employed HITS technology and indicated that 40 collegiate football players sustained a total of 54,154 head impacts during a single season of 93 practices and 12 games. Thus these athletes sustained an average of 1354 impacts per season. The same investigation also fitted the HIT system into the helmets of 16 high school football players and recorded a total of 8326 impacts, averaging 520 impacts per athlete across a season of 15 practices and 9 games. In comparison, the athletes in our investigation sustained more head impacts per year than previously reported at the high school level, but only about half as many as those reported at the collegiate level. These differences are likely explained by the number of sessions during which impact data were recorded, as our athletes participated in approximately 50 practices and 12 games per year. If the previous research at the collegiate level reporting on 93 practices and 12 games represents a typical collegiate season, then the average collegiate football player would be expected to sustain approximately 5416 head impacts over a 4-year collegiate career. In total, a typical starting football player could therefore be expected to sustain over 8000 impacts to the head during a combined 4-year high school and 4-year collegiate career.

Differences in the magnitude of impacts at different levels of play will directly influence the cumulative linear and rotational acceleration loads sustained by football players. Prior work at the college level suggests that the mean linear acceleration associated with head impacts ranges from 20.9 (Brolinson et al., 2006) to 22.25*g* (Mihalik et al., 2007). If the number of practice and game sessions is equivalent across schools, then the cumulative linear acceleration for collegiate football players would be expected to range from 28,298.6 to 30,126.5*g* per year. This value is 1.7 to 1.8 times greater than that observed in the high school athletes in this study. When summed over a 4-year collegiate career, the average football player would sustain an estimated 116,850*g* of cumulative linear acceleration during college, and approximately 183,834*g* during a combined 4 years of high school and 4 years of collegiate football participation. To date there is no published information concerning mean rotational accelerations at the collegiate level. Consequently, differences in rotational acceleration across competition levels remain undetermined.

TABLE 2. IMPACT CHARACTERISTICS OF 3- AND 4-YEAR HIGH SCHOOL FOOTBALL ATHLETES

				Practices					Games					Season totals				
		Subject ID	Position	No. of sessions	No. of impacts	Mean	Standard deviation	Cumulative	No. of sessions	No. of impacts	Mean	Standard deviation	Cumulative	No. of sessions	No. of impacts	Mean	Standard deviation	Cumulative
Linear resultant acceleration (*g*)	3-Year career	27	QB	111	741	20.7	12.8	15,354.7	35	948	26.8	17.2	25,384.1	146	1689	24.1	15.7	40,738.7
		37	WR	121	861	23.7	14.3	20,395.8	35	1326	28.8	21.8	38,130.5	156	2187	26.8	19.3	58,952.6
		38	WR	81	532	24.0	15.5	12,755.8	27	354	26.3	16.7	9305.6	108	886	24.9	16.0	22,061.4
		43	LB	82	1327	25.6	14.7	33,974.4	24	1383	28.6	18.5	39,574.1	106	2710	27.1	16.8	73,548.5
		60	LB	127	1539	23.7	14.0	36,486.8	34	1532	26.9	16.4	41,194.0	161	3071	25.3	15.3	77,680.8
	4-Year career	34	LB	93	859	26.2	14.5	22,474.9	26	1203	28.6	18.4	34,429.2	119	2062	27.6	17.0	56,904.1
		35	RB	98	950	25.1	16.5	23,814.0	32	1383	29.6	20.5	40,998.6	130	2333	27.8	19.1	64,812.6
Rotational resultant acceleration (rad/sec^2)	3-Year career	27	QB	111	741	1097.5	949.6	813,271.7	35	948	1389.5	1195.6	1,533,540.4	146	1689	1389.5	1195.6	2,346,812.1
		37	WR	121	861	1527.9	1089.0	1,315,507.7	35	1326	1847.5	1575.5	2,449,777.2	156	2187	1721.7	1412.6	3,793,249.2
		38	WR	81	532	1617.9	1253.5	860,719.4	27	354	1786.1	1199.1	632,281.3	108	886	1685.1	1234.1	1,493,000.7
		43	LB	82	1327	1657.5	1100.9	2,199,503.9	24	1383	1844.0	1405.8	2,550,190.9	106	2710	1752.7	1268.9	4,749,694.8
		60	LB	127	1539	1662.5	1086.9	2,558,646.0	34	1532	1891.1	1329.8	2,897,197.5	161	3071	1776.6	1219.4	5,455,843.5
	4-Year career	34	LB	93	859	1704.1	1187.4	1,463,850.0	26	1203	1840.8	1410.0	2,214,430.3	119	2062	1783.8	1323.3	3,678,280.3
		35	RB	98	950	1515.4	1108.0	1,439,650.8	32	1383	1884.8	1439.0	2,606,650.2	130	2333	1734.4	1326.5	4,046,301.0
HITsp	3-Year career	27	QB	111	741	12.5	5.2	9234.4	35	948	14.5	9.1	13,709.5	146	1689	13.6	7.7	22,943.9
		37	WR	121	861	13.8	6.6	12,062.7	35	1326	16.2	12.6	21,517.0	156	2187	15.3	10.7	33,579.7
		38	WR	81	532	15.0	7.7	7998.4	27	354	16.5	9.0	5833.9	108	886	15.6	8.3	13,832.3
		43	LB	82	1327	15.0	7.8	20,184.3	24	1383	16.4	9.2	2272.1	106	2710	15.7	8.6	42,905.4
		60	LB	127	1539	15.3	7.4	23,718.0	34	1532	17.2	9.2	26,306.7	161	3071	16.2	8.4	50,024.7
	4-Year career	34	LB	93	859	16.0	7.9	13,758.3	26	1203	17.2	9.9	20,644.4	119	2062	16.7	9.2	34,402.8
		35	RB	98	950	14.2	7.8	13,532.1	32	1383	16.1	10.3	22,297.0	130	2333	15.4	9.4	35,829.0

QB, quarterback; WR, wide receiver; LB, linebacker; RB, running back.

The high school football athletes in this study sustained a greater number of head impacts relative to other sports in which contact with the head is common. For example, one investigation implementing the HIT System in 16 Bantam-level ice hockey players (mean age of 14 years) reported 4608 impacts during a season of 54 games and 38 practice sessions (Mihalik et al., 2010). The average player incurred 288 impacts per season, with average linear and rotational accelerations of 21.5*g* and 1441.1 rad/sec^2, respectively. The estimated cumulative linear (6192*g*) and rotational (415,036.8 rad/sec^2) accelerations were far below those recorded in our high school football cohort. Similarly, elite soccer athletes have been reported to sustain an average of 6.6 head balls per game (Tsyvaer and Storli, 1981). This results in approximately 264 head balls during a 40-game regular season. The average linear acceleration sustained with heading is estimated at 49.3 to 54.7*g* (Lewis et al., 2001; Naunheim et al., 2000), so the total linear acceleration would be expected to range from 13,015.2 to 14,440.8*g*, not including practices.

The relationship between linear and rotational acceleration and concussion has been previously described (Broglio et al., 2010). While the threshold for concussion varies greatly between athletes, threshold estimates appear consistent across levels of play, with the greatest injury risk above 95*g* of linear acceleration, 5500 rad/sec^2 rotational acceleration, and when impacts occur to the front, top, or back of the helmet (Broglio et al., 2010; Guskiewicz et al., 2007b; Pellman et al., 2003). The 20 impacts that resulted in a diagnosed concussion are included in this dataset, and are described in detail elsewhere (Broglio et al., in review; Eckner et al., in review). However, we and others have noted that concussions have resulted from accelerations well below the proposed threshold levels (Guskiewicz et al., 2007b), which brings into question how multiple sub-concussive impacts may influence an athlete's susceptibility to injury (Eckner et al., in review).

Some investigators have suggested that concussions or a combination of concussions and sub-concussive head impacts may lead to conditions such as chronic traumatic encephalopathy (CTE; Gavett et al., 2011), mild cognitive impairment (Guskiewicz et al., 2005), and/or depression (Guskiewicz et al., 2007a), although the exact mechanisms by which impacts to the head result in these conditions are not entirely understood. While cumulative impact burden is suspected to play a role in the development of these diseases, the large cumulative impact burdens reported here cannot be interpreted as evidence to support or refute a cause-and-effect relationship between head trauma and cognitive impairment. None of the athletes enrolled in this investigation showed obvious clinical symptoms of CTE or other diseases, nor would they be expected to, since signs and symptoms do not develop until later in life. It is interesting to note, however, that of five football-related CTE cases reported by McKee and associates (McKee et al., 2009), four of the athletes were linemen, the position group that sustained the greatest numbers of impacts as well as the greatest cumulative linear and rotational accelerations in our investigation.

The primary limitation of this study is the use of linear and rotational accelerations and HITsp sums as a measure of impact burden. To our knowledge, there is no precedent in the medical literature for quantifying cumulative impact burden in football. We do feel that repetitive head trauma is likely to have pathological effects on the brain (Gavett et al., 2011; Geddes et al., 1999; McKee et al., 2009), and therefore an attempt to quantify the cumulative impact burden is necessary. Our method of summing the linear acceleration, rotational acceleration, and HITsp values of individual head impacts, however, may not be a direct estimate of the short- and long-term risks to brain health. In addition, we do not propose physiological equivalency of all impacts. That is, our clinical experience suggests that 10 head impacts yielding a linear acceleration magnitude of 15*g* each is not equivalent to a single head impact with a linear acceleration of 150*g*. However, we do feel that the cumulative linear and angular accelerations and cumulative HITsp values reported here represent values that can be used for comparative purposes and therefore merit reporting.

This report is part of an ongoing investigation of concussion biomechanics in high school football. It is the first to quantify the total number of head impacts sustained by athletes at this level over a given season, as well as the cumulative impact burden in linear and rotational acceleration and HITsp associated with them. Our findings indicate that high school football players sustain an astonishingly high number of head impacts each season, with associated cumulative impact burdens that are equally staggering. While cross-sectional investigations in football and other sports have indicated an association between repetitive head trauma and neurohistological changes and later life cognitive impairment, this investigation cannot discern how head impacts influence long-term neurological health. Prospective longitudinal investigations tracking athletes across their high school, collegiate, and professional careers, and subsequently following them through their post-retirement years are needed to definitively answer this question. Nevertheless, the cumulative volume of impacts observed in these high school football players is of significant concern and warrants investigation of how to best minimize this trauma.

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