JOURNAL OF NEUROTRAUMA 28:2079–2090 (October 2011)

DOI: 10.1089/neu.2011.1910

No Evidence for a Cumulative Impact Effect on Concussion Injury Threshold

James T. Eckner,[1] Matthew Sabin,[2] Jeffrey S. Kutcher,[3] and Steven P. Broglio[4]

Abstract

Recent studies using a helmet-based accelerometer system (Head Impact Telemetry System [HITS]) have demonstrated that concussions result from a wide range of head impact magnitudes. Variability in concussion thresholds has been proposed to result from the cumulative effect of non-concussive head impacts prior to injury. We used the HITS to collect biomechanical data representing >100,000 head impacts in 95 high school football players over 4 years. The cumulative impact histories prior to 20 concussive impacts in 19 athletes were compared to the cumulative impact histories prior to the three largest magnitude non-concussive head impacts in the same athletes. No differences were present in any impact history variable between the concussive and non-concussive high magnitude impacts. These analyses included the number of head impacts, cumulative HIT severity profile value, cumulative linear acceleration, and cumulative rotational acceleration during the same practice or game session, as well as over the 30 min and 1 week preceding these impacts. Our data do not support the proposal that impact volume or intensity influence concussion threshold in high school football athletes.

Key words: acceleration; biomechanics; concussion; helmet; injury tolerance

Introduction

Sport- and recreation-related mild traumatic brain injury, or concussion, is a common injury that is now recognized as a major public health issue in the United States (Collins et al., 1999; Kelly, 1999; Langlois et al., 2006). Concussions are caused by the rapid acceleration and deceleration of the brain as a result of biomechanical forces transmitted from an impact directly to the head or indirectly through the body (McCrory et al., 2009). Both linear and rotational accelerations are hypothesized to cause strain in brain tissue that initiates a complex biochemical cascade resulting in the clinical syndrome of concussion (Giza and Hovda, 2001; Guskiewicz and Mihalik, 2011). In recent years, there has been a significant interest in defining concussive injury mechanics, both to better identify concussed athletes and to improve athletic equipment. To date, no reliable threshold for diagnosing concussive injury has been identified.

Although brain injury biomechanics have been studied in various laboratory settings for decades, the *in vivo* quantification of head impacts and concussion injury thresholds is relatively new to the medical sciences and has largely focused on American football. In early efforts, Naunheim and associates (2000) used a single tri-axial accelerometer placed inside the helmet of one high school ice hockey player and two high school football players to measure the linear accelerations of game impacts, as well as simulated soccer heading in one high school soccer player wearing an instrumented football helmet. No concussive impacts were recorded in this small comparative study, which captured 132 football, 128 hockey, and 23 soccer head impacts. More recent studies have implemented the Head Impact Telemetry System (HITS) to record large numbers of head impacts in athletes equipped with the system. Duma and associates (2005) were the first to use HITS in large numbers of athletes during normal game and practice sessions over an entire season. Up to 8 collegiate football players wore instrumented helmets at a time in this initial study, which reported a total of 3,312 impacts in 38 athletes. One athlete monitored in this study sustained a concussion as a result of a head impact with a peak acceleration of 81 *g*. Additional studies reporting on larger numbers of athletes followed shortly thereafter. Brolinson and associates (2006) soon reported linear acceleration measurements for 11,604 head impacts in 52 collegiate football athletes over two seasons, including 3 impacts that resulted in concussion at impact magnitudes ranging from 55.7 *g* to 136.7 *g*. Schnebel and

Departments of [1]Physical Medicine & Rehabilitation and [3]Neurology, and [4]Neurotrauma Research Laboratory, University of Michigan, Ann Arbor, Michigan.
[2]Department of Exercise and Sport Science, Eastern Kentucky University, Richmond, Kentucky.

associates (2007) presented comparative linear acceleration head impact data from 8,326 impacts in 16 high school football athletes and 54,154 impacts in 40 collegiate football athletes. This study captured impact data for 6 concussions, which ranged in magnitude from 98 *g*.

Over time, the HITS was expanded to allow for assessment of both linear and rotational head accelerations (Brolinson et al., 2006). A growing number of large-scale studies have reported on the distribution of both linear and rotational head accelerations experienced by football players at the collegiate (Brolinson et al., 2006; Crisco et al., 2010) and high school levels (Broglio et al., 2009). In addition, linear and rotational acceleration data have now been captured in larger numbers of concussed athletes wearing instrumented helmets. Guskiewicz and associates (2007) reported on 13 concussed collegiate athletes whose injuries occurred at a mean linear acceleration of 102.8 *g* and rotational acceleration of 5,311.6 rad/s^2. Interestingly, the range of these variables that resulted in concussion was quite large: linear accelerations from 60.5 *g* to 168.7 *g* and rotational accelerations 163.4 rad/s^2 to 15,397.1 rad/s^2. Greenwald and associates (2008) then reported on 17 concussed high school and collegiate football athletes. They found that 75% of concussions resulted from impacts exceeding linear and rotational acceleration thresholds of 96 *g* and 7,235 rad/s^2, respectively, but that a weighted principal component score (the HIT severity profile [HITsp]) was a better predictor of concussion than either linear or rotational acceleration alone. This study also found that concussions occurred over a wide range of impact magnitudes and that all of the biomechanical measures used had low positive predictive values (e.g., only 11 of the 3,476 impacts of > 98.9 *g* [0.3%] were associated with the clinical diagnosis of concussion. Broglio and associates (2010) later reported on 13 concussions in high school football players, with mean linear acceleration 105.0 *g* and rotational acceleration 7,229.5 rad/s^2. In this study, a classification and regression tree analysis again indicated that combinations of biomechanical variables had better predictive value than either linear or rotational acceleration alone, and concussions were again observed over a wide range of impact magnitudes (linear acceleration 74.0 *g* to 146.0 *g*; rotational acceleration 5,582.6 rad/s^2 to 9,515.6 rad/s^2). The HITS has recently been modified for use in ice hockey helmets. To date, two studies have described the head impact biomechanics associated with ice hockey at the collegiate (Gwin et al., 2009) and youth (Mihalik et al., 2010) levels, but no ice hockey associated concussions have been reported.

The main similarity among the *in vivo* head impact biomechanics studies that have recorded data on concussive impacts is the finding that concussions result from a wide range of impact magnitudes. Although there are some consistencies between these investigations, a definitive injury threshold has not been established. The current literature clearly demonstrates that impacts associated with higher magnitudes of resultant linear and angular acceleration are more likely to cause concussions than are lower magnitude head impacts. However, in these longitudinal data sets, there are far more head impacts at any given impact magnitude that do not cause concussions than there are those that do. One potential explanation for this observation is that biomechanical concussion thresholds vary among individuals, and many of the higher magnitude head impacts that do not result in concussion are sustained by athletes with inherently higher injury thresholds. A second potential explanation is that the injury threshold within an individual athlete is dynamic, and higher magnitude head impacts not resulting in concussion are occurring during times of increased impact tolerance.

If concussion threshold is indeed dynamic, then one factor that may negatively affect injury tolerance is number and volume of non-concussive impacts (NCIs) sustained by an athlete in the days or hours prior to injury (Greenwald et al., 2008; Guskiewicz et al., 2007; Schnebel et al., 2007). This theory is both intuitively attractive and testable. Therefore, the purpose of this report is to investigate the effect of cumulative head impacts on concussion tolerance. We analyzed the patterns of head impacts preceding 20 concussive impacts in 19 high school football players, and compared these patterns to those preceding the 3 highest magnitude head impacts (as defined by HITsp) that did not result in a concussion in the same athletes. Our primary hypothesis was that concussive head impacts would be preceded by a greater number of head impacts on the day of injury than would the NCIs. To investigate the possibility that cumulative impact magnitude (e.g., cumulative linear acceleration), rather than the number of head impacts, was predictive of concussion, we also analyzed cumulative HITsp, linear acceleration, and rotational acceleration burdens prior to injury. Finally, to investigate the possibility that the "window of vulnerability" might be longer or shorter than 1 day, these same variables were analyzed during the 30 min and 1 week periods of time leading up to the concussive impacts and NCIs.

Methods

As part of an ongoing investigation of concussion biomechanics in male high school football players, 95 athletes from the same Class 3A team were recruited over four football seasons (2007–2010). Prior to data collection, all athletes provided assent to participate and informed written consent was also obtained from their parents/guardians. This study was approved by the Institutional Review Board at the University of Illinois.

Prior to starting the season, the team issued each athlete a Riddell (Elyria, OH) Revolution® helmet that was equipped with a HITS (Simbex LLC; Lebanon, NH) encoder. HITS encoders are composed of six single-axis accelerometers with a battery, data storage unit, and wireless telemetry unit, and can be retrofitted into existing helmet padding without violating National Operating Committee on Standards for Athletic Equipment (NOCSAE) safety standards or otherwise affecting helmet function. The encoders track and record impact data during participation in practices and games, and transmit this information to a sideline computer for storage in real time. Encoders can store data associated with up to 100 impacts in the event that the sideline computer is either out of range or otherwise unavailable. The HITS has undergone laboratory validation for the detection of both impact magnitude and location (Crisco et al., 2004) and has been used in a number of studies investigating concussion biomechanics in football at both the collegiate (Brolinson et al., 2006; Crisco et al., 2010; Duma et al., 2005; Greenwald et al., 2008; Guskiewicz et al., 2007) and high school (Broglio et al., 2009, 2010) levels.

When the acceleration of any single accelerometer exceeds a 15 *g* threshold, the HITS records 40 ms of impact data, including 8 ms prior to and 32 ms following the trigger. The

HITS software calculates a number of impact parameters for later download and analysis, including the impact location, peak linear acceleration, peak rotational acceleration (derived from the x- and y-axis angular accelerations), HITsp, and a date and time stamp. The HITsp is a unitless value derived from a weighted principle component analysis calculation that takes into account linear and rotational accelerations, impact location, and impact duration, and is more predictive of concussion than linear or rotational acceleration alone (Greenwald et al., 2008).

Head impact data were recorded for all participants during every game and practice for the duration of the study period. The data were screened on a daily basis by one of the study investigators (S.P.B.) to ensure that errant impacts (e.g., dropped helmet) were removed from the database. HITS data were used in real time to screen for high magnitude impacts, but not to diagnose concussions. Over the duration of the study, 20 concussions were diagnosed in 19 athletes by either a certified athletic trainer (present at all games and practices) or a team physician (present at games) using the American Academy of Neurology definition of concussion, "a trauma-induced alteration in mental status that may or may not involve loss of consciousness (Kelly and Rosenberg, 1997)." Athletes who sustained high magnitude impacts but did not immediately display any signs of a concussion, report concussive symptoms, or otherwise withdraw themselves from play were evaluated by the on-site physician or certified athletic trainer upon returning to the sideline between series or during a timeout. In some cases, an athlete who sustained a high magnitude head impact and initially denied concussive symptoms, passed the on-field concussion screening evaluation, and continued to play, subsequently reported symptoms of a concussion in the following days. In these instances where the concussion diagnosis was delayed, the athlete assisted one of the study investigators (S.P.B.) in reviewing the HITS data from that session in an attempt to identify the single impact most likely to have resulted in his injury. Given a lack of evidence supporting the use of concussion grading scales as a reflection of injury severity (Lovell et al., 2004) and an overall lack of support for their use in general (McCrory et al., 2009), concussions were not graded for the purpose of this study.

Data analysis

Impact data from the 19 athletes who sustained concussions were extracted from the overall data set and sorted by HITsp value. From these data the three largest HITsp values not associated with concussion (i.e., NCIs) were identified, yielding 57 NCIs. HITsp values were used to identify the NCIs because this weighted composite value is a better predictor of concussion than any of its individual components (peak linear acceleration, peak rotational acceleration, HIC, Gadd Severity Index (GSI) , and impact location) (Greenwald et al., 2008). The NCIs were compared to the concussive impact(s) in the same athlete. For each concussive impact and NCI we extracted 2 time variables, 4 impact variables, and 20 cumulative impact variables representing the collective impact burden preceding the index impact. The time variables included time from beginning of session (min:sec) and time from previous impact (min:sec). The impact variables were impact location (i.e., front, back, top, or side), HITsp value (unitless), peak linear acceleration (g), and peak rotational acceleration (rad/s^2). The cumulative impact variables were calculated from all impacts prior to the index impact on the day of injury; in the 30 min immediately prior to the index impact; and over the entire week prior to the index impact. We also calculated the rate of impacts (i.e., impacts per minute) sustained prior to the index impact during the entire session and in the 30 min preceding the index impact; number of impacts and cumulative HITsp, linear acceleration, and rotational acceleration prior to the index impact on the day of injury, in the 30 min preceding the index impact, and over the week prior to the index impact; and rate of cumulative HITsp, linear acceleration, rotational acceleration (e.g., HITsp per minute) sustained prior to the index impact during the session and in the 30 min prior to the index impact. Cumulative HITsp, linear acceleration, and rotational acceleration were defined as the sums of the HITsp values, peak linear accelerations, and peak rotational accelerations associated with each individual head impact over the specified time interval.

Time plots depicting the HITsp values over the entire session for concussive impacts and NCIs were generated and visually inspected for trends in all 19 athletes. All continuous variables generated from the 20 concussive impacts and the 57 NCIs were analyzed using repeated measures ANOVA to account for within-athlete matching. Impact location was compared between the concussive impacts and NCIs using the Mantel–Haenszel technique to account for matching. In an exploratory analysis, conditional logistic regression was also used to evaluate the predictive value of combinations of time, impact, and cumulative impact variables with HITsp value. Time plots were generated using Excel Office 2007 (Microsoft Corporation, Seattle, WA) and all formal statistical analyses were performed using SAS (Version 9.2, SAS Institute Inc. Cary, NC).

Results

Demographic information for the 19 concussed athletes is presented in Table 1. At the time of enrollment mean (SD) age was 16.8 (0.8) years, height was 180.3 (6.3) cm, and body mass was 84.1 (10.6) kg. On average, these athletes had sustained 1.1 (1.3) prior concussions, which is greater than the overall mean value of 0.3 (0.7) concussions reported by the source group of 95 athletes as a whole. The 19 concussed athletes were followed over a mean (SD) of 2.2 (0.7) seasons with 1,514.9 (631.9) recorded head impacts during their participation in the study. On average, these athletes sustained a number of impacts resulting in larger HITsp ($n = 6.1$ [7.8]), linear acceleration ($n = 7.1$ [10.1]), and rotational acceleration ($n = 11.9$ [13.6]) values than their concussive impacts over the duration of the study period.

The distributions of impact-associated HITsp values, peak linear accelerations, and peak rotational accelerations for all impacts experienced by the source group of all 95 athletes as a whole were positively skewed, and are illustrated in Figure 1. The values representing the overall group's 1st, 25th, 50th, 75th, 90th, 95th, 98th, 99th, and 99.5th percentile for each variable are presented in Table 2.

Visual inspection of the HITsp time plots for the concussive impacts and NCIs did not reveal any obvious trends. In some instances, NCIs were preceded by a far smaller cumulative impact burden than the matched concussive impact in the same athlete. In other cases, the exact opposite trend was

Table 1. Player and Summary Impact Characteristics

Athlete ID	*Age (years)*	*Height (cm)*	*Mass (kg)*	*Position*	*Prior concussions*	*Seasons*	*Total impacts*	*No. HITsp*	*No. linear acceleration*	*No. rotational acceleration*
2	17.5	175.3	68.2	QB	1	2	1,103	4	12	28
7	16.7	190.5	93.2	OL	1	2	1,537	1	0	3
8	17.7	167.6	80.5	FB	0	1	185	8	15[b]	8
10	15.6	190.5	84.1	FB	1	2	1,194	1	1	4
27	19.0	190.5	90.0	QB	0	3	1,689	1	0	2
32[a]	16.2	182.9	100.0	DL	2	2	2,389	0	3	0
32[a]	16.9	182.9	100.0	DL	3	2	2,389	0	3	8
35	16.2	175.3	86.4	RB	0	4	2,334	6	6[b]	26
36	16.4	180.3	70.5	CB	0	2	2,121	3	10	3
37	17.0	180.3	78.2	WR	5	3	2,198	19	104[b]	40[b]
38	17.9	188.0	79.1	WR	0	3	888	2	3	80[b]
42	15.8	180.3	72.3	SS	1	2	1,251	18[b]	41[b]	20
45	16.5	175.3	83.2	OL	0	2	1,498	1	1	1
47	16.5	170.2	111.4	DL	0	2	2,095	6	8	3
61	17.0	180.3	78.2	TE	2	2	1,563	4	8	32[b]
69	17.0	180.3	79.5	LB	2	2	796	22	38	27
71	16.8	175.3	79.6	SS	1	2	1,561	152[b]	203[b]	111[b]
73	17.0	180.3	78.2	LB	1	2	1,884	24	49[b]	44
74	16.8	182.9	85.5	QB	1	2	943	79[b]	90[b]	32[b]
80	15.5	177.8	83.6	RB	0	1	680	2	5	1

Characteristics of the 19 athletes who sustained concussions during the study period including the number of seasons they participated and the total number of impacts recorded. Number of Head Impact Telemetry severity profile (HITsp), number of linear acceleration, and number of rotational acceleration represent the number of individual impacts experienced by each athlete with HITsp, linear acceleration, and rotational acceleration values exceeding those of their concussive impact(s).

[a]Athlete no. 32 sustained 2 concussions during the study period; the first occurred in 2007 and the second in 2008.

[b]At least one non-concussive impact of greater magnitude was experienced by the athlete prior to injury on the day that athlete sustained the concussion.

QB, quarterback; OL, offensive lineman; FB, fullback; DL, defensive lineman; RB, running back; CB, corner back; WR, wide receiver; SS, strong safety; TE, tight end; LB, line backer.

observed. Overall, no meaningful differences were present. Fifty percent of comparisons between NCIs and concussive impacts in the same athlete demonstrated more impacts leading up to the concussive impact as compared to the NCI. Similarly, 52% of comparisons demonstrated a larger absolute value of cumulative HITsp prior to the index impact for concussive impacts as compared to NCIs. We did not generate peak linear or rotational acceleration time plots, but a review of the cumulative linear and rotational acceleration data yielded similar results: 52% of comparisons demonstrated both a greater linear and rotational acceleration burden prior to the concussive impact as compared to the NCI. A summary HITsp time plot illustrating the concussive impact(s) for each athlete as well as the average of their three NCIs is presented in Figure 2. Figure 3 illustrates the cumulative HITsp burden preceding the concussive impact(s) and the average cumulative HITsp burden preceding the NCIs for each athlete.

Except for the HITsp value of the index impact ($p < 0.001$), none of the other time, impact, or cumulative impact variables differed between concussive impacts and NCIs ($p > 0.05$) (Table 3). The mean (SD) values of all 25 continuous time, impact, and cumulative impact variables are presented in Table 4. Although a slightly greater percentage of concussive impacts occurred to the top of the helmet (Fig. 4), overall there were no differences in the distributions of impact locations between the concussive impacts and the NCIs ($p = 0.326$). Conditional logistic regression did not identify any of the time, location, cumulative impact number, or cumulative HITsp variables as predictive of concussion when controlling for the HITsp value of the index impact.

Discussion

This is the first report to systematically evaluate the influence of non-concussive head impacts on concussion threshold. Our analyses show that, overall, the cumulative burden of head impacts preceding concussive impacts was no different from the cumulative impact burden preceding NCIs of similar (or greater) magnitude in the same athletes. We felt it important to analyze these data using more than one approach, because no single impact parameter can completely describe head impact biomechanics, and because the duration of a "window of vulnerability" related to a reduced concussion threshold is unknown. The lack of difference in cumulative impact burden preceding concussive impacts and NCIs was consistent regardless of how it was calculated. Indeed, there was no difference in the number of impacts, cumulative HITsp, cumulative linear acceleration, or cumulative rotational acceleration value preceding the index impact. Nor were there differences when the window of vulnerability was defined as the entire session, the 30 min prior, or the entire week preceding the index impact. Lastly, there was no difference when the cumulative impact burden was quantified as a rate of one of the above cumulative impact parameters over 30 min or over the entire session preceding the index impact.

We chose to test the hypothesis that sub-concussive head impacts reduce an athlete's concussion threshold by comparing concussive impacts to NCIs in the same athlete based on the following rationale: We speculated that if an athlete sustained a concussion as a result of a head impact of a given magnitude, then any "bigger" head impact would have also resulted in a concussion in the same athlete. Alternatively stated, any head impact of greater magnitude than a concussive head impact should also cause a concussion in a given athlete at a given point in time. All but one of the concussed athletes in our study tolerated head impacts of greater magnitude (as measured by HITsp value) than their concussive impact at some point during the study period. This simple observation suggests that an athlete's concussive injury threshold is not static over time. It is not clear however, what was responsible for the dynamic nature of an athlete's biomechanical concussion threshold that allowed that athlete to tolerate a bigger impact without sustaining a concussion. We felt that comparing the cumulative impact burden preceding concussive impacts and the largest non-concussive head impacts tolerated by the same athlete represented a powerful model to assess the contribution of cumulative head impact burden to the athlete's biomechanical injury threshold.

Using HITsp values to identify the largest magnitude impacts is limited, as no single variable completely describes head impact biomechanics. We chose to identify NCIs using HITsp values based on a single study identifying this weighted principal component value as being more predictive

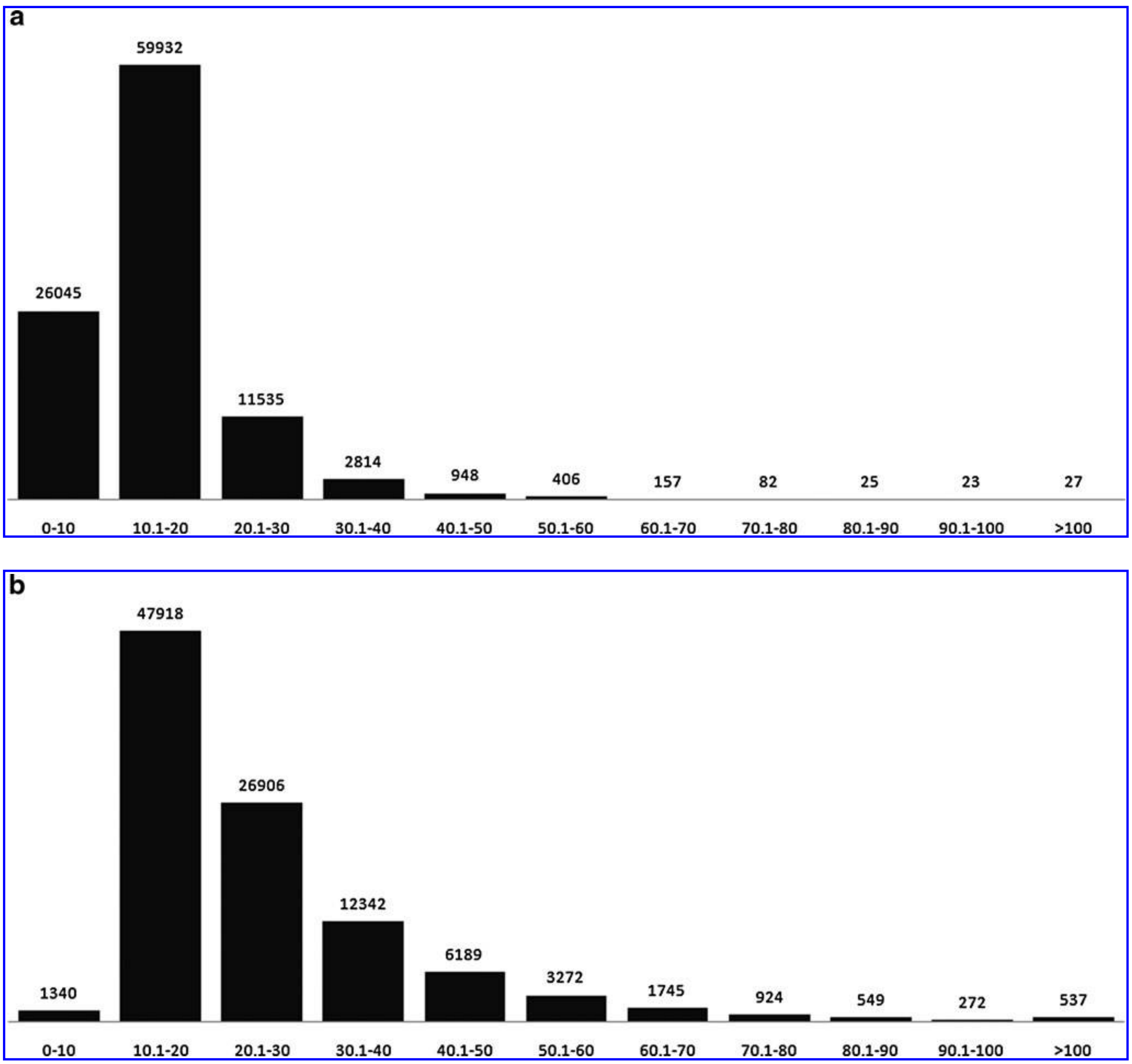

FIG. 1. Frequency histograms of the Head Impact Telemetry severity profile (HITsp) **(a)**, peak linear acceleration **(b)**, and peak rotational acceleration **(c)** values for all head impacts sustained by the source group of all 95 athletes who participated in the study. The values above each bar represent the number of impacts falling within that impact magnitude bin.

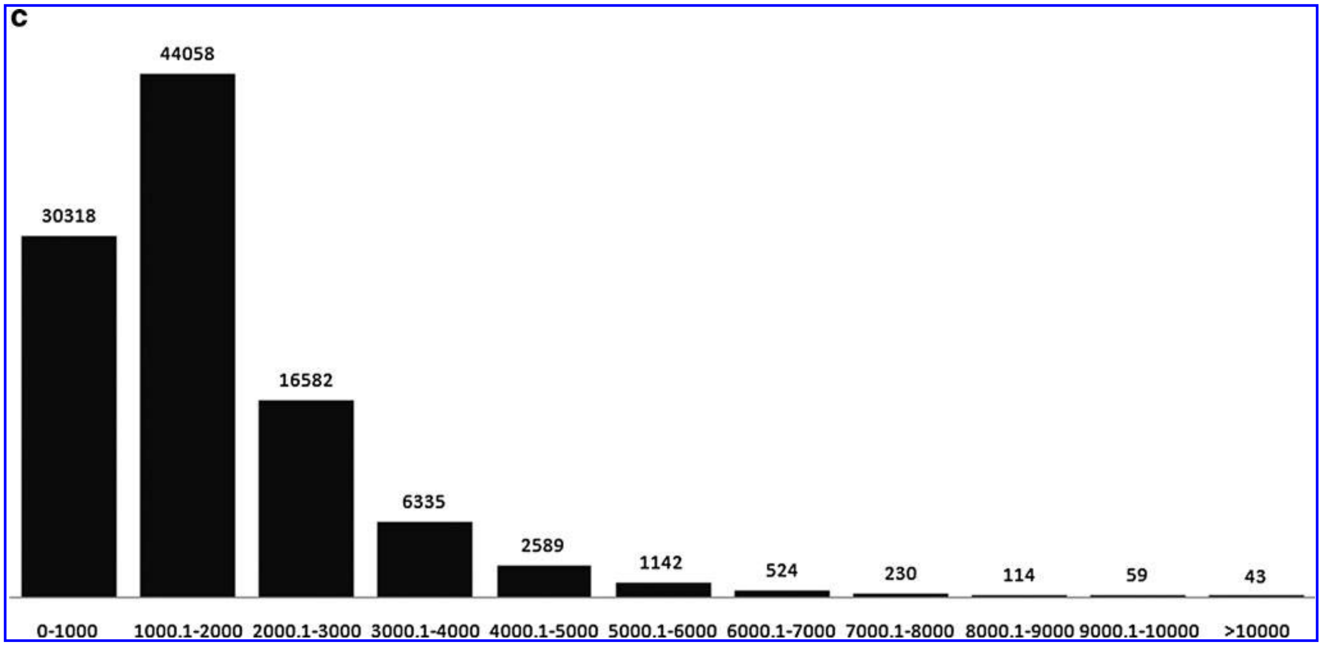

FIG. 1. (Continued).

of concussion than peak linear or rotational acceleration, Head Injury Criterion, or Gadd Severity Index (Greenwald et al., 2008). In light of this potential limitation we repeated all of our analyses using NCIs identified from the greatest peak linear acceleration and greatest peak rotational acceleration. Analysis of the alternatively-defined NCIs resulted in identical findings, with a number of minor exceptions. When NCIs were defined based on peak linear acceleration, the HITsp value was no longer significantly different between concussive impacts and NCIs (63.4 ± 20.0 vs. 62.5 ± 25.2, $p = 0.845$), whereas the difference in peak linear acceleration did reach statistical significance ($93.6 \pm 27.5\,g$ vs. $125.2 \pm 21.6\,g$, $p < 0.001$). Similarly, when NCIs were defined based on peak rotational acceleration, the HITsp value did not differ between concussive impacts and NCIs (63.4 ± 20.0 vs. 61.0 ± 22.2, $p = 0.652$), but the difference in both peak linear and rotational acceleration did ($93.6 \pm 27.5\,g$ vs. $104.7 \pm 18.7\,g$, $p = 0.046$; $6{,}402.6 \pm 1{,}753.9$ rad/s^2 vs. $9{,}055.4 \pm 1{,}858.4$ rad/s^2, $p < 0.001$; respectively). As with the difference identified between the HITsp values of concussive impacts and NCIs identified in our primary analysis, we believe that these findings are artifacts resulting from the way in which NCIs were defined. The distribution of impact location also changed when NCIs were alternatively defined based on linear acceleration ($p < 0.001$) and rotational acceleration ($p < 0.001$). For NCIs based on linear acceleration, 31 (54%) were to the top of the helmet, 12 (21%) were to the back, 10 (18%) were to the front, and 4 (7%) were to the side. For NCIs based on rotational acceleration, 37 (65%) were to the back of the helmet, 17 (30%) were to the front, 3 (5%) were to the side, and none were to the top of the helmet. In essence, the non-concussive head impacts with the greatest HITsp values were distributed similarly to the concussive impacts, whereas far more of the non-concussive head impacts with the greatest peak linear accelerations were to the top and back of the helmet and far more of those with the greatest peak rotational accelerations were to the front and back. We therefore feel that the similar results garnered from differing approaches converge to further support a lack of a cumulative impact effect on concussion tolerance.

Table 2. Impact Distribution

Percentile rank	*HITsp*	*Linear acceleration* (g)	*Rotational acceleration (rad/s^2)*
1%	6.0	9.6	96.8
25%	10.0	15.3	902.4
50%	13.8	20.5	1394.0
75%	17.2	30.2	2082.7
90%	23.3	44.4	3087.9
95%	29.0	55.5	3901.3
98%	37.9	71.2	5037.6
99%	46.0	83.3	5941.5
99.5%	54.5	95.7	6817.1

Percentile ranking of all head impacts recorded over the 4-year study period in the source group of 95 athletes by Head Impact Telemetry severity profile (HITsp) values, linear acceleration (g), and rotational acceleration (rad/s^2).

The ongoing physical and cognitive development of the research cohort may have also influenced our findings. As many of these athletes are in their prime developmental years, it is possible that concussion tolerance may change from one year to the next. This would draw into question our comparison of concussive impacts to NCIs that did not occur during the same season. To examine this possibility, we also repeated all of our analyses using NCIs defined as the three non-concussive head impacts with the greatest HITsp values in the same athlete during the same season. When these data were analyzed, we found that none of the 26 time, impact, or

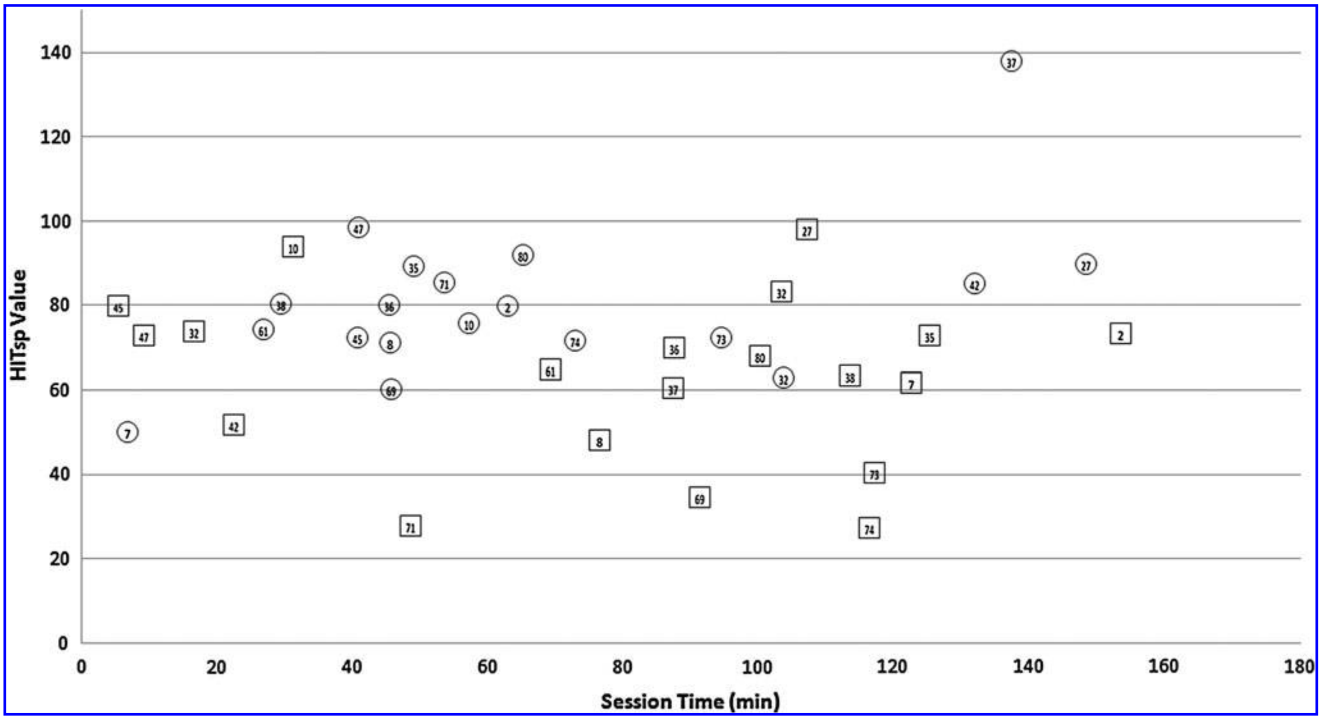

FIG. 2. Summary plot illustrating the elapsed time from the start of the session and the Head Impact Telemetry severity profile (HITsp) value of the concussive impact and the mean elapsed time and HITsp value of the 3 non-concussive high magnitude head impacts for each athlete. Concussive impacts are depicted with the athlete's ID enclosed in a square; non-concussive impacts are depicted with a circle.

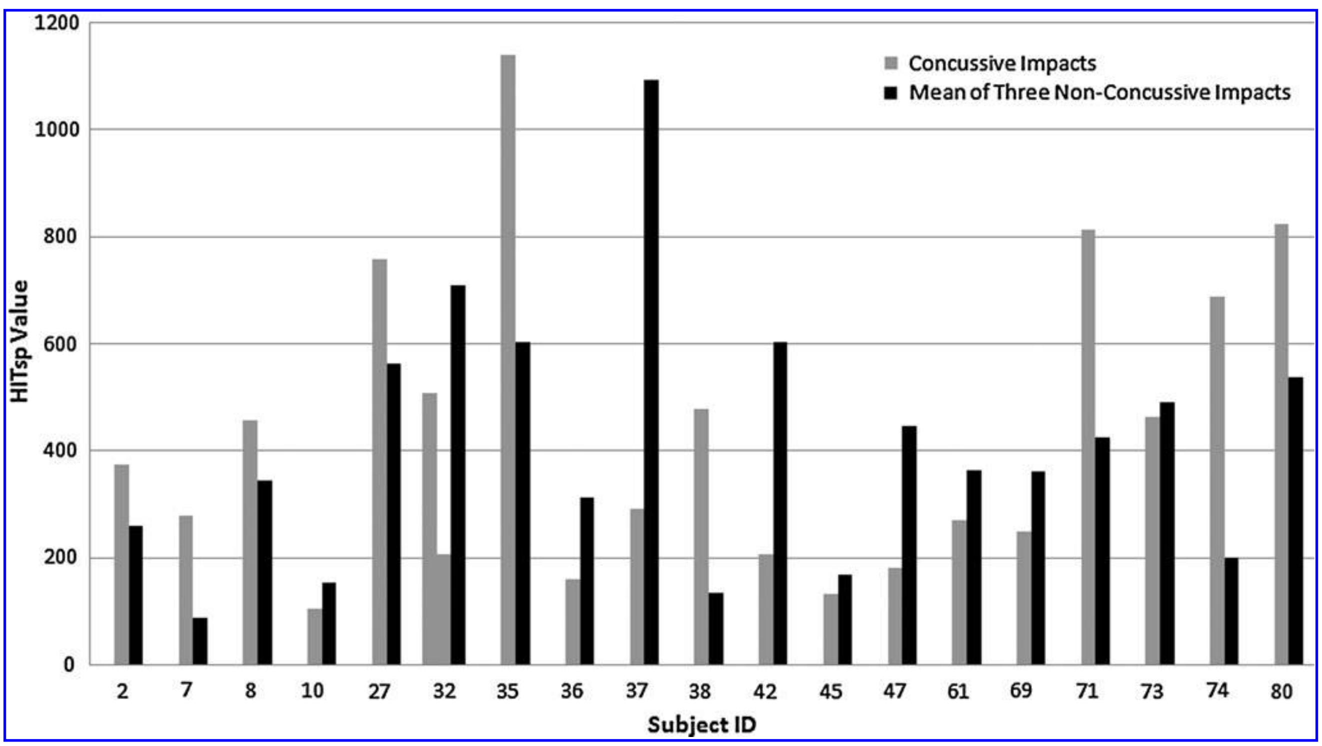

FIG. 3. Cumulative Head Impact Telemetry severity profile (HITsp) burden sustained by each athlete on the day of injury prior to concussive impacts (gray) and non-concussive impacts (black). Non-concussive impact values represent the mean of the three non-concussive impacts for each athlete.

Table 3. Individual Impact Characteristics: Time, Number, and HITsp

Athlete ID	*Impact type*	*Session time (min:sec)*	*Time from previous impact (min:sec)*	*Impact number within session*	*Impacts in prior 30 min*	*Impacts in prior week*	*HITsp*	*HITsp Percentile*	*Cumulative HITsp (session)*	*Cumulative HITsp (30 min)*	*Cumulative HITsp (week)*
2	Concussive	153:39	6:37	23	12	41	73.4	99.6	374.5	218.4	625.4
2	NCI	63:05	2:55	12.3	6.0	31.7	80.1		258.7	160.6	575.0
7	Concussive	122:49	5:42	18	3	74	61.9	99.9	278.8	82.7	1,026.6
7	NCI	7:08	5:19	4.0	4.0	79.0	50.2		87.7	87.7	1,105.7
8	Concussive	76:51	0:26	26	15	64	48.2	95.7	441.3	275.6	1,321.1
8	NCI	45:37	0:51	13.7	10.0	48.7	71.2		344.5	254.3	1,000.9
10	Concussive	31:25	31:25	2	1	84	94.1	99.9	105.5	94.1	1,058.9
10	NCI	57:17	0:35	7.7	3.3	116.0	75.9		152.7	104.3	1,565.0
27	Concussive	107:06	0:42	54	33	106	98.1	99.9	757.5	451.9	1,631.6
27	NCI	148:26	28:17	31.3	8.0	86.3	90.0		563.3	207.6	1,333.0
32	Concussive	103:29	7:08	26	15	110	83.3	100.0	507.6	327.3	1,734.8
32	Concussive	16:51	0:46	13	13	87	74.0	99.9	205.4	205.4	1,323.3
32	NCI	103:48	1:25	48.7	15.0	181.7	63.1		708.4	255.2	2,514.3
35	Concussive	125:14	14:02	71	14	146	73.0	99.7	1,139.4	210.6	2,263.4
35	NCI	49:12	0:31	27.0	14.7	75.0	89.5		603.0	348.0	1,451.5
36	Concussive	87:52	19:02	10	2	74	70.0	99.9	160.6	82.0	1,043.9
36	NCI	45:33	13:44	13.7	9.0	122.7	80.3		312.3	228.2	2,107.3
37	Concussive	87:36	39:04	19	1	66	60.5	99.1	291.2	60.5	996.0
37	NCI	137:31	2:39	58.3	14.0	114.3	138.1		1,093.4	362.0	1,983.3
38	Concussive	113:37	7:03	29	7	52	63.6	99.8	478.7	169.0	781.2
38	NCI	29:42	5:02	4.0	2.3	35.7	80.5		133.3	104.7	613.6
42	Concussive	22:51	3:47	9	9	39	52.0	98.6	207.1	207.1	588.1
42	NCI	131:59	0:23	35.7	7.0	87.3	85.4		602.7	201.4	1,375.6
45	Concussive	5:44	4:46	3	3	37	80.0	99.9	133.0	133.0	817.0
45	NCI	40:55	4:33	6.0	4.0	64.0	72.5		168.3	131.9	1,131.8
47	Concussive	9:21	0:54	6	6	108	73.0	99.7	181.0	181.0	1,694.1
47	NCI	41:03	1:13	22.3	11.0	108.0	98.7		445.6	264.8	1,806.1
61	Concussive	69:16	1:21	13	10	47	65.0	99.7	270.4	230.1	758.9
61	NCI	26:59	2:59	17.3	15.7	62.3	74.5		364.2	346.1	1,183.3
69	Concussive	91:20	2:12	18	4	35	34.6	97.2	249.8	76.8	460.5
69	NCI	45:58	0:26	22.0	11.3	44.0	60.5		360.7	218.0	683.0
71	Concussive	48:58	1:35	45	29	115	27.9	90.3	812.7	538.4	2,146.3
71	NCI	53:34	1:53	20.3	16.0	84.7	85.5		424.2	360.1	1,563.0
73	Concussive	117:07	15:54	29	8	84	40.5	98.7	463.7	141.6	1,285.6
73	NCI	94:48	5:14	32.0	20.3	61.0	72.5		490.9	348.1	881.8
74	Concussive	116:30	0:43	37	14	94	27.4	91.6	687.7	282.5	1,614.5
74	NCI	72:53	22:07	9.3	3.7	45.3	71.7		201.0	116.9	801.7
80	Concussive	100:22	0:00	48	15	75	68.1	99.7	823.6	313.6	1,168.0
80	NCI	65:20	1:00	28.0	9.0	51.0	92.2		537.6	222.7	831.8

Impact characteristics describing select time, impact, and Head Impact Telemetry severity profile (HITsp) variables for each athlete. Non-concussive impacts (NCI) values represent the average of the 3 NCIs for each athlete. HITsp percentiles are presented as within-athlete values (therefore, a HITsp percentile value of 100% represents the greatest HITsp value experienced by the athlete during the study period).

Table 4. Summary Impact Characteristics

Impact Variable	*Concussive Impact mean (SD)*	*NCI mean (SD)*
Session time (min:sec)	80:24 (43:43)	66:21 (55:10)
Time from previous impact (min:sec)	8:09 (10:49)	5:19 (14:07)
Impact number	25.0 (18.3)	21.8 (20.4)
Impact rate-session (impacts/min)	0.4 (0.2)	0.5 (0.5)
Impacts during previous 30 min	10.7 (8.6)	9.7 (7.4)
Impact rate-30 min (impacts/min)	0.4 (0.3)	0.3 (0.2)
Impacts during previous week	76.9 (30.4)	78.9 (49.6)
HITsp	63.4 (20.0)[a]	80.7 (22.5)[a]
Cumulative HITsp burden-session	429.3 (282.8)	413.3 (320.3)
HITsp rate-session (HITsp/min)	7.5 (6.0)	12.7 (15.2)
Cumulative HITsp burden-30 min	214.1 (125.6)	227.5 (129.8)
HITsp rate-30 min (HITsp/min)	7.1 (4.2)	7.6 (4.3)
Cumulative HITsp burden-week	1,217.0 (504.2)	1,289.9 (706.7)
Peak linear acceleration (g)	93.6 (27.5)	104.0 (22.7)
Cumulative linear acceleration burden-session (*g*)	755.9 (560.1)	682.6 (566.0)
Linear acceleration rate-session (*g*/min)	12.9 (10.1)	20.8 (27.8)
Cumulative linear acceleration burden-30 min (*g*)	377.9 (240.8)	354.3 (225.4)
Linear acceleration rate-30 min (*g*/min)	12.6 (8.0)	11.8 (7.5)
Cumulative linear acceleration burden-week (*g*)	2,154.9 (1,033.0)	2,200.2 (1,276.3)
Peak rotational acceleration (rad/s^2)	6,402.6 (1753.9)	7,338.0 (2,282.2)
Cumulative rotational acceleration burden-session (rad/s^2)	47,735.0 (34,551.5)	45,646.3 (38,989.9)
Rotational acceleration rate-session (rad/s^2/min)	822.3 (680.5)	1,379.7 (1,640.8)
Cumulative rotational acceleration burden-30 min (rad/s^2)	23,387.7 (15,550.0)	24,158.2 (14,871.1)
Rotational acceleration rate-30 min (rad/s^2/min)	779.6 (518.3)	805.3 (495.7)
Cumulative rotational acceleration Burden-week (rad/s^2)	135,340.2 (62,558.7)	142,315.2 (87,672.4)

Summary of time, impact, and cumulative impact variables for concussive and non-concussive high magnitude head impacts.
[a]Significant at $p = 0.001$ ($p > 0.05$ for all other comparisons).
HITsp, Head Impact Telemetry severity profile; NCI, non-concussive impact.

cumulative impact variables were significantly different between concussive impacts and NCIs. The reason we chose to base our primary analysis on NCIs defined as those head impacts with the greatest HITsp values recorded over the entire study period as opposed to those recorded only during the same season as the athlete's concussion, was that use of the latter definition resulted in a drop in the number of NCIs of greater magnitude than the concussive impact from 44/57 (77%) to 33/60 (55%). Given our rationale for comparing concussive impacts to NCIs, we elected to carry out our primary data analysis using the definition for NCIs that maximized their HITsp magnitude. To further maximize the number of high magnitude NCIs, we also analyzed the data set including only those NCIs whose HITsp value exceeded that of the concussive impact. This resulted in an imbalanced data set, but the ultimate results of the analysis again did not differ from those of our primary analysis.

Prior studies involving athletes have supported the intuitive notion that concussion is most likely to occur following higher magnitude head impacts, with some variability in concussion tolerance limits among studies. Pellman and associates (2003) reconstructed 31 concussive head impacts in National Football League players based on video analysis from multiple views using Hybrid III anthropomorphic test devices (crash test dummies). Linear acceleration was suggested to have the strongest correlation with concussion and the authors proposed that concussions are most likely to occur in helmeted impacts at a low end threshold of 70–75 *g*. We observed that 75% of the concussions in our sample occurred at peak linear acceleration values at or above this threshold. However, 95% of the NCIs in our primary analysis, as well as 2,267 (2.2%) of the NCIs in our source database of 101,994 head impacts, also occurred at or above 70 *g*. Shortly thereafter, Zhang and associates (2004) proposed concussion threshold values by applying the Wayne State University brain injury model to reconstructions of 24 helmet to helmet collisions in professional football players. They reported that linear acceleration thresholds of 66 *g*, 82 *g*, and 106 *g*, and rotational acceleration thresholds of 4,600 rad/s^2, 5,900 rad/s^2, and 7,900 rad/s^2 were associated with a 25%, 50%, and 80% probability of concussion, respectively. Again, our data suggest that the probability of sustaining concussion at each of these linear and rotational acceleration thresholds is far lower than this. Guskiewicz and associates (2007) found that concussions occurred over a wide range of impact magnitudes in 13 collegiate football players, with mean peak linear and rotational acceleration values of 102.8 *g* and 5,311.6 rad/s^2, respectively. The authors suggested a low end linear acceleration concussion threshold of 60–80 *g* to be more appropriate than the 70–75 *g* threshold proposed in Pellman's National Football League study. The mean peak linear acceleration of 93.6 *g* in our study is slightly lower, whereas the mean peak rotational acceleration of 6,402.6 rad/s^2 is slightly higher than those observed in the University of North Carolina study. Our finding that there were far more non-concussive head impacts of greater magnitude than the proposed low end concussive threshold is similar to Guskiewicz's findings, which were further elaborated in two companion papers (McCaffrey et al., 2007; Mihalik et al., 2007). The North Carolina group also noted that 6 of the 13 concussions they

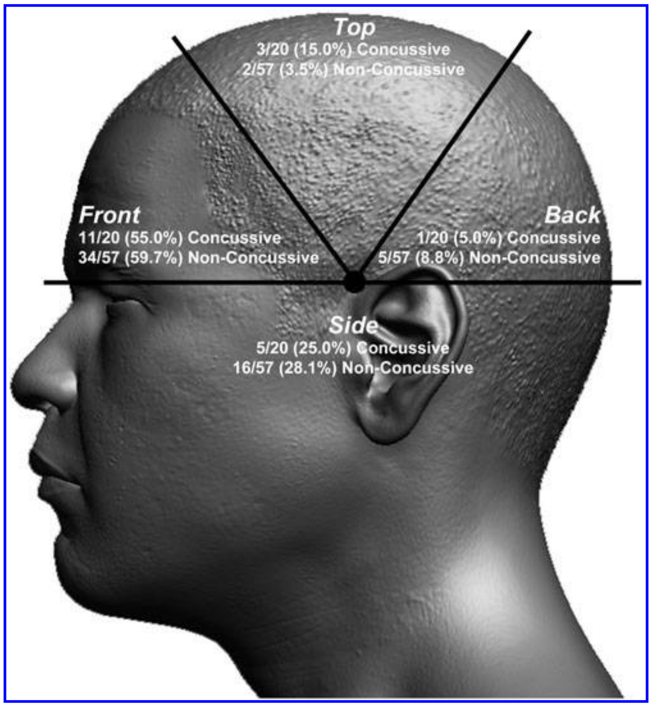

FIG. 4. Impact location distribution for the 20 concussive and 57 non-concussive high magnitude head impacts.

described were a result of impacts to the top of the athlete's helmet and they speculated that top-of-helmet impacts may result in a higher rate of concussion than other impact locations. Our findings differ in this regard, as only 3 of 20 concussions resulted from impacts to the top of the athlete's helmet, with far more concussions in our sample resulting from frontal impacts. We did, however, note a non-significant trend in our primary analysis of more top-of-helmet concussive impacts as compared to NCIs.

More recent studies have examined combinations of biomechanical variables as concussion predictors. Greenwald and associates (2008) studied data collected over 3 years from 259 collegiate football players at six universities and 259 high school football players at seven institutions to develop the weighted principal component score, HITsp, that we have used in our own primary analysis presented here. The authors found HITsp to be a better predictor of concussion than either linear or rotational acceleration alone, with 75% of concussions occurring at HITsp values of 63. A lower percentage of the concussions we observed (60%) resulted from impacts with HITsp values exceeding this threshold, but we again observed that the vast majority of supra-threshold head impacts did not result in concussion. Likewise, Broglio and associates (2010) presented a classification and regression tree analysis that combined multiple impact measures in 13 concussed high school football players. The authors demonstrated that head impacts with rotational acceleration exceeding $5{,}582\,\text{rad/s}^2$, linear acceleration exceeding $96.1\,g$, and impact location to the front, side, or top of the helmet were the most predictive of concussion. Direct comparison to our current report is uninformative, as these data represent a subset of the larger data set reported herein.

Although it is clear from the existing literature that large magnitude impacts elicit concussions, it remains unclear why so many head impacts of equal or greater magnitude do not. This report is the first to compare concussive impacts to NCIs of similar magnitude in the same athletes by examining the potential additive effect of the non-concussive head impacts preceding them. Contrary to previous hypotheses, our data suggest against the presence of an adverse cumulative effect of non-concussive head impacts on an athlete's concussion threshold. Additional studies in independent data sets will need to replicate this finding before its general acceptance. However, alternative explanations for the dynamic nature of an athlete's concussion threshold should also be investigated. Although it is likely that concussion thresholds differ among athletes because of intrinsic factors, this report focused on the role of cumulative impact biomechanics. Alternative explanations for intra-individual fluctuations in an athlete's concussion threshold remain speculative at this time, but some possibilities may include: intra-individual fluctuation in cerebral blood flow, cerebrospinal fluid volume, or cerebrospinal fluid viscosity as a function of hydration status; cellular energy efficiency as a function of hydration status or glucose availability; physical fatigue; sleep deprivation; concurrent illness; or biochemical changes associated with exercise such as lactic acid accumulation.

The results of this study must be interpreted in the context of its limitations. Our attempt to quantify cumulative impact burdens presented a challenge. The additive sum of the HITsp, linear acceleration, and rotational acceleration values of many individual head impacts does not have the same physical meaning as a single head impact of the same magnitude, nor have these cumulative values been demonstrated to predict injury risk. However, we feel that until a validated measure of cumulative impact burden is available, that exploration of these values is warranted for comparative purposes. Further, although HITS has been shown to be highly accurate in predicting accelerations at the center of a spherical head form in a laboratory (Crisco et al., 2004), it may not accurately reflect acceleration of the brain within the skull or directly represent the strain patterns affecting brain tissue. This may be especially true for off-center head impacts, where the helmet slides or rotates with respect to the head, or during impacts with significant helmet deformation. At the present time, the HITS is the best *in vivo* measure of head impact biomechanics available for studying athletes. A final limitation of this study pertains to uncertainty both in diagnosing concussions and in defining the concussive impacts that caused them. Athletes commonly fail to report concussion symptoms to their athletic trainer, team physician, or coach (McCrea et al., 2004). As a result, it is possible that some of the NCIs in used in this study may have been unreported concussive impacts. Furthermore, the fact that some athletes continued to play without immediately reporting their concussive symptoms may have led to error in determining which head impacts resulted in the concussion. This is most suspicious in athlete #73 who experienced at least one NCI of greater HITsp, linear acceleration, and rotational acceleration prior to the presumed concussive impact on the day of injury and did not experience loss of consciousness or demonstrate any other obvious concussion signs marking the time of injury. Unfortunately, unless athletes are forthcoming in reporting their subjective symptoms, sports medicine providers will continue to be at risk for missed or delayed concussion diagnoses.

Many sports medicine providers have witnessed an athlete whose concussion occurred after what appeared to be a routine impact to their head. In many of these cases, the number or magnitude of head impacts preceding the injury may appear to have been explanatory. These empirical observations gave birth to the concept of an additive effect of sub-threshold head impacts on an athlete's concussion susceptibility. Although this concept is intuitive and attractive, it has never been tested in a systematic manner. After multiple approaches to data selection and analysis, this study fails to support the theory of a cumulative impact effect. This novel finding needs to be replicated, but suggests that other mechanisms are responsible for the dynamic nature of an athlete's concussion threshold. Practically speaking, sports medicine providers must remain vigilant for signs and symptoms suggesting concussion in athletes across a wide range of head impact magnitudes and histories. There is presently no data to support the addition of impact history data to concussion screening algorithms.

Acknowledgments

We thank Scott Hamilton and the Unity Rockets football team (Tolono, IL), John Storsved, and Susan Mantel, all of whose support made this project possible. We also thank James A. Ashton-Miller and James K. Richardson for their advice regarding our data analysis. Dr. Eckner also thanks the Rehabilitation Medicine Scientist Training Program for its support of his research.

Author Disclosure Statement

No competing financial interests exist.

References

Broglio, S.P., Schnebel, B., Sosnoff, J.J., Shin, S., Fend, X., He, X., and Zimmerman, J. (2010). Biomechanical properties of concussions in high school football. Med. Sci. Sports Exerc. 42, 2064–2071.

Broglio, S.P., Sosnoff, J.J., Shin, S., He, X., Alcaraz, C., and Zimmerman, J. (2009). Head impacts during high school football: a biomechanical assessment. J. Athl. Train. 44, 342–349.

Brolinson, P.G., Manoogian, S., McNeely, D., Goforth, M., Greenwald, R., and Duma, S. (2006). Analysis of linear head accelerations from collegiate football impacts. Curr. Sports Med. Rep. 5, 23–28.

Collins, M.W., Lovell, M.R., and McKeag, D.B. (1999). Current issues in managing sports-related concussion. JAMA 282, 2283–2285.

Crisco, J.J., Chu, J.J., and Greenwald, R.M. (2004). An algorithm for estimating acceleration magnitude and impact location using multiple nonorthogonal single-axis accelerometers. J. Biomech. Eng. 126, 849–854.

Crisco, J.J., Fiore, R., Beckwith, J.G., Chu, J.J., Brolinson, P.G., Duma, S., McAlloister, T.W., Duhaime, A.C., and Greenwald, R.M. (2010). Frequency and location of head impact exposures in individual collegiate football players. J. Athl. Train. 45, 549–559.

Duma, S.M., Manoogian, S.J., Bussone, W.R., Brolinson, P.G., Goforth, M.W., Donnenwerth, J.J., Greenwald, R.M., Chu, J.J., and Crisco, J.J. (2005). Analysis of real-time head accelerations in collegiate football players. Clin. J. Sport Med. 15, 3–8.

Giza, C.C., and Hovda, D.A. (2001). The neurometabolic cascade of concussion. J. Athl. Train. 36, 228–235.

Greenwald, R.M., Gwin, J.T., Chu, J.J., and Crisco, J.J. (2008). Head impact severity measures for evaluating mild traumatic brain injury risk exposure. Neurosurgery 62, 789–798.

Guskiewicz, K.M., and Mihalik, J.P. (2011). Biomechanics of sport concussion: quest for the elusive injury threshold. Exerc. Sport Sci. Rev. 39, 4–11.

Guskiewicz, K.M., Mihalik, J.P., Shankar, V., Marshall, S.W., Crowell, D.H., Oliaro, S.M., Ciocca, M.F., and Hooker, D.N. (2007). Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. Neurosurgery 61, 1244–1252.

Gwin, J.T., Chu, J.J., McAllister, T.A., and Greenwald, R.M. (2009). In situ measures of head impact acceleration in NCAA Division I men's ice hockey: Implications for ASTM F1045 and other ice hockey helmet standards. Journal of ASTM International 6, 1–10.

Kelly, J.P. (1999). Traumatic brain injury and concussion in sports. JAMA 282, 989–991.

Kelly, J.P., and Rosenberg, J.H. (1997). Practice parameter: the management of concussion in sports (summary statement). Report of the Quality Standards Subcommittee. Neurology 48, 581–585.

Langlois, J.A., Rutland–Brown, W., and Wald, M.M. (2006). The epidemiology and impact of traumatic brain injury: a brief overview. J. Head Trauma Rehabil. 21, 375–378.

Lovell, M.R., Collins, M.W., Iverson, G.L., Johnston, K.M., and Bradley, J.P. (2004). Grade 1 or "ding" concussions in high school athletes. Am. J. Sports Med. 32, 47–54.

McCaffrey, M.A., Mihalik, J.P., Crowell, D.H., Shields, E.W., and Guskiewicz, K.M. (2007). Measurement of head impacts in collegiate football players: clinical measures of concussion after high- and low-magnitude impacts. Neurosurgery 61, 1236–1243.

McCrea, M., Hammeke, T., Olsen, G., Leo, P., and Guskiewicz, K. (2004). Unreported concussion in high school football players: implications for prevention. Clin. J. Sport Med. 14, 13–17.

McCrory, P., Meeuwisse, W., Johnston, K., Dvorak, J., Aubry, M., Molloy, M., and Cantu, R. (2009). Consensus Statement on Concussion in Sport 3rd International Conference on Concussion in Sport held in Zurich, November 2008. Clin. J. Sport Med. 19, 185–200.

Mihalik, J.P., Bell, D.R., Marshall, S.W., and Guskiewicz, K.M. (2007). Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences. Neurosurgery 61, 1229–1235.

Mihalik, J.P., Greenwald, R.M., Blackburn, J.T., Cantu, R.C., Marshall, S.W., and Guskiewicz, K.M. (2010). Effect of infraction type on head impact severity in youth ice hockey. Med. Sci. Sports Exerc. 42, 1431–1438.

Naunheim, R.S., Standeven, J., Richter, C., and Lewis, L.M. (2000). Comparison of impact data in hockey, football, and soccer. J. Trauma 48, 938–941.

Pellman, E.J., Viano, D.C., Tucker, A.M., Casson, I.R., and Waeckerle, J.F. (2003). Concussion in professional football: reconstruction of game impacts and injuries. Neurosurgery 53, 799–812.

Schnebel, B., Gwin, J.T., Anderson, S., and Gatlin, R. (2007). In vivo study of head impacts in football: a comparison of National Collegiate Athletic Association Division I versus high school impacts. Neurosurgery 60, 490–495.
Zhang, L., Yang, K.H., and King, A.I. (2004). A proposed injury threshold for mild traumatic brain injury. J. Biomech. Eng. 126, 226–236.

Address correspondence to:
Steven P. Broglio, Ph.D., A.T.C.
University of Michigan
School of Kinesiology
1402 Washington Heights
Ann Arbor, MI 48109-2013

E-mail: broglio@umich.edu