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Estimating Contact Exposure in Football Using the Head Impact Exposure Estimate

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Abstract

Over the past decade, there has been significant debate regarding the effect of cumulative subconcussive head impacts on short and long-term neurological impairment. This debate remains unresolved, because valid epidemiological estimates of athletes' total contact exposure are lacking. We present a measure to estimate the total hours of contact exposure in football over the majority of an athlete's lifespan. Through a structured oral interview, former football players provided information related to primary position played and participation in games and practice contacts during the pre-season, regular season, and post-season of each year of their high school, college, and professional football careers. Spring football for college was also included. We calculated contact exposure estimates for 64 former football players ($n = 32$ college football only, $n = 32$ professional and college football). The head impact exposure estimate (HIEE) discriminated between individuals who stopped after college football, and individuals who played professional football ($p < 0.001$). The HIEE measure was independent of concussion history ($p = 0.82$). Estimating total hours of contact exposure may allow for the detection of differences between individuals with variation in subconcussive impacts, regardless of concussion history. This measure is valuable for the surveillance of subconcussive impacts and their associated potential negative effects.

Key words: subconcussive impacts; traumatic brain injury

Introduction

The study of concussions has greatly expanded over the past decade, because of growing concern about both acute and cumulative effects in athletes.[1–3] Recurrent concussions have been associated with higher prevalence, higher severity, and earlier onset of negative mental health outcomes such as depression, mild cognitive impairment, and Alzheimer's disease.[4–7] However, researchers have suggested that cumulative subconcussive head impacts alone, in the absence of any diagnosed concussions, may contribute to neurological or cognitive impairments.[8–12]

Although a relationship between previous number of concussions and an increased risk of subsequent concussions has been demonstrated,[1] there is a scarcity of studies examining the relationship between subconcussive impacts and neurological deficits. Visual working memory impairments and altered activation in the dorsolateral prefrontal cortex have been demonstrated in high school football players with no clinically observed symptoms associated with concussion.[13] Similarly, in amateur adult soccer players, presence of abnormal white matter microstructure and poorer neurocognitive performance was independent of history of concussion, suggesting that a biological pathway involved repeated heading of the ball.[14] Further research is needed to gain a more complete understanding of the potential negative effects of subconcussive impacts. However, there are currently no tools for the quantification of previously sustained subconcussive impacts. Numerous studies have used the Head Impact Telemetry System (HITS; Simbex, Lebanon, NH), which utilizes accelerometer data to compute peak linear and rotational head acceleration in real-time during football.[15–17] However, HITS costs ~$1500 per helmet in addition to the costs of the data collection system. Furthermore, HITS cannot assess impacts sustained prior to its implementation.

Despite recent attention on the effects of subconcussive impacts in current and former athletes' long-term health, it is difficult to estimate athletes' total contact exposure. Risk of overall injury has been quantified as a rate per athlete-exposure (A-E), where an A-E is defined as "one student-athlete participating in one practice or competition in which he or she was exposed to the possibility of athletic injury, regardless of the time associated with that participation."[18] Although A-E can assist in determining the rate of overall injury, it does not specifically take contact exposure into account. Sometimes, sports are compared by general contact level, including collision sports (such as football, wrestling, and ice hockey), high contact sports (such as soccer, basketball, and

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lacrosse), and low/noncontact sports (such as volleyball, swimming/diving, and track and field); however, intra-sport differences still exist. Furthermore, although specific positions can be considered, they cannot account for variations in the magnitude or frequency of head impacts on team and individual levels. This has important implications in the collision sport of football, as positional differences have been shown to be associated with varying levels of contact during practice and competition.[17,19]

Significant methodological innovation is required to improve the quality of estimating contact exposure during sports. Such work has implications for the contact exposure estimate and ultimately the understanding of subconcussive impacts and corresponding dose response (e.g., injuries, illnesses, and long-term neurological impairment) experienced in a variety of amateur and professional sports. Additionally, there is much that can be learned about improving the safety of sport (e.g., rule changes, modifying equipment, and behavior modification) based on these exposure estimates. In this article, we present the development of a measure, the head impact exposure estimate (HIEE), to estimate the total hours of contact exposure in football over the majority of an athlete's life span. We present this measure by first, creating an example scenario of a former football athlete; and second, utilizing data from a group of retired National Football League (NFL) and former collegiate football players.

Methods

Calculation of contact exposure estimate

All participants provided informed consent prior to data collection. To calculate our estimate of contact exposure, we created a structured oral athlete interview that collected detailed information about their football career histories. In order to account for possible changes that occur during one's career, participants provided information for each year that they played, beginning with high school, and continuing through college and professional football. Additionally, in order to account for possible differences within a season, information was collected separately for the pre-season and for spring football for college.

First, participants denoted their primary and secondary positions played (i.e., quarterback, offensive line, tight end, offensive back, running back, defensive line, defensive back, linebacker, wide receiver, special teams). Next, participants reported the average number and length of contact practices per week. We emphasized to participants to only consider those practices in which contact occurred (i.e., no strength and conditioning practices). At the high school and college levels, we assumed that the weekly practice schedules for the regular season and post-season were the same. For games, participants reported the number of games they played and the percentage of time that they played in those games (from possible choices including 0%, 25%, 50%, 75%, and 100%). For professional football, data regarding number of games played for each recorded season are publicly available on NFL.com. In cases in which online records and players reports differed, follow-up with players was conducted to reconcile all differences. The majority of these differences were minimal, with athlete reports and online records differing by one game.

Figure 1 explains the calculation of the contact exposure estimate for 1 year of participation. Because we were concerned with the differences in the frequency and the severity of impacts that occur in games compared to practice, we also calculated an adjusted contact exposure estimate that applied a weight, unique to each primary position played, to the number of game contact hours (Table 1). These weights were based on previous findings that compared the frequency and severity (i.e., linear acceleration) of impacts between games and practices in high school and

$$
\#\ \text{practice contact hours}
\begin{cases}
\sum\left(\begin{array}{c}\#\ \text{spring season contact practice sessions per week} \times\\ \#\ \text{weeks in spring season} \times\\ \#\ \text{hours per spring season practice}\end{array}\right) + \\
\sum\left(\begin{array}{c}\#\ \text{pre-season contact practice sessions per week} \times\\ \#\ \text{weeks in pre-season} \times\\ \#\ \text{hours per pre-season practice}\end{array}\right) + \\
\sum\left(\begin{array}{c}\#\ \text{regular season contact practice sessions per week} \times\\ \#\ \text{weeks in regular season} \times\\ \#\ \text{hours per regular season practice}\end{array}\right) + \\
\sum\left(\begin{array}{c}\#\ \text{post-season contact practice sessions per week} \times\\ \#\ \text{weeks in post-season} \times\\ \#\ \text{hours per post-season practice}\end{array}\right)
\end{cases}
$$

$$+$$

$$
\#\ \text{game contact hours}
\begin{cases}
\sum\left(\begin{array}{c}\#\ \text{games in pre-season}^{a} \times\\ \%\ \text{of time active in pre-season games} \times\\ 1\ \text{hour} \times \text{time within game}^{b}\end{array}\right) + \\
\sum\left(\begin{array}{c}\#\ \text{games in regular season} \times\\ \%\ \text{of time active in regular season games} \times\\ 1\ \text{hour} \times \text{time within game}\end{array}\right) + \\
\sum\left(\begin{array}{c}\#\ \text{games in post-season} \times\\ \%\ \text{of time active in post-season games} \times\\ 1\ \text{hour} \times \text{time within game}\end{array}\right)
\end{cases}
$$

[a]Pre-season games in the college level account for spring football game

[b]Time within game (in hours) is 0.50 for defense and offense positions, 0.05 for special teams, and 1.00 for those playing both offense and defense within a game

FIG. 1. Calculation of exposure contact per year in football.

TABLE 1. WEIGHTS FOR TOTAL GAME CONTACT HOURS FOR ADJUSTED CONTACT EXPOSURE ESTIMATE, BY POSITION

	Weight			
	High school		*College and professional*[a]	
Position	*Frequency*	*Severity*	*Frequency*	*Severity*
Quarterback	8.26	1.07	2.60	1.10
Offensive lineman	2.68	1.03	2.19	0.98
Tight end	3.38	1.06	2.19	1.04
Offensive back	3.38	1.06	2.06	1.04
Running back	3.38	1.06	2.06	0.94
Defensive line	2.68	1.03	2.59	0.94
Defensive back	3.49	1.09	2.67	1.05
Linebacker	3.38	1.06	2.58	0.98
Wide receiver	3.49	1.09	2.09	0.98
Special teams[b]	3.00	0.78	3.00	0.78

Example: Among college quarterbacks, the rate of game impact was 2.60 times that of practice impacts.[17]

Example: Among high school quarterbacks, the mean severity of game impacts was 1.07 times that of practice impacts.[20]

[a]College data were utilized for weights for professional level football.

[b]Because of insufficient specials teams data at the high school level, weights from the college level were utilized.

college.[17,20] For example, among college quarterbacks, the rate of game impact was 2.60 times that of practice impacts, and the mean severity of game impacts was 1.10 times that of practice impacts.[17] Therefore, if a college quarterback logged 100.00 game contact hours, his adjusted exposure would be 286.00 (calculated as $100.00 \times 2.60 \times 1.10$). Adjusted exposures for special teams in high school football and for all positions in professional football utilized college level weights.

The contact exposure estimate was first presented with an example scenario. Next we calculated contact exposure estimates within a cohort of 64 former football players, the majority of whom were non-Hispanic white (89.1%), had an average age of 58.4 years (SD = 3.7), and had played the majority of their careers as offensive linemen (31.3%) or linebackers (29.7%). This cohort consisted of former players who had played in the NFL ($n = 32$), and former players who had played up to the college football level only ($n = 32$). NFL and college-only players were matched by age, primary playing position, and concussion history (categorized as low: i.e., zero to one concussions; and high: i.e., two or more concussions). Those who played in the NFL played college and professional football for an average of 13.8 years (SD = 3.2). Those who played only at the college level played for an average 4.1 years (SD = 0.6). Accordingly, it had been an average 27.4 years (SD = 4.0) since former NFL players had retired, and an average of 37.6 years (SD = 4.1) since former college players had retired. Research staff conducted structured oral interviews with these participants on their football career history in order to create the contact exposure estimates. ANOVAs compared unadjusted and adjusted contact exposure estimates by concussion history (low: zero to one concussions vs. high: two or more concussions); group (NFL vs. college-only); and their interaction.

Results

Example scenario

Table 2 shows an example of the calculation of the HIEE. Player X was a member of his high school's varsity football team, in which he played wide receiver. His high school division allowed contact practice during the 1 week pre-season. In his freshmen season, he was active for only 25% of the games. However, his playing time subsequently increased through his sophomore, junior, and senior season. His team made the post-season during his freshman, junior, and senior seasons. In the 1st year of his collegiate career, as a "true freshman," he played as a wide receiver, but made a switch to defensive back at the beginning of his sophomore year. His team made bowl trips during his sophomore and senior seasons. He was drafted by a professional team and was immediately on the active roster in his rookie season, playing in all pre-season and regular season games, as well as one game in the playoffs (i.e., post-season). However, in his 2nd year, he sustained a career-ending injury after week 4 of the regular season, and never played again.

For each year, we first calculated the number of practice contact hours for each segment of the season:

$$\text{number of contact practice sessions per week} \times \text{number of weeks in segment of season} \times \text{number of hours per practice}$$

Therefore, for Player X, in his freshman season of high school, the total number of pre-season practice contact hours was 2.00 ($1 \times 1 \times 2$); the number of regular season practice contact hours was 40.00 ($2 \times 10 \times 2$); and the number of post-season practice contact hours was 4.00 ($2 \times 1 \times 2$). Yearly totals for the pre-season, regular season, and post-season were summed throughout all active playing years at the high school, college, and professional levels to yield the total practice contact exposure. The college level also included spring football contact practices. Upon summing all practice contact hours in each pre-season, regular season, and post-season of his football career, Player X had 822.00 total practice contact hours (I in Table 2).

Next, we calculated the number of game hours for each segment of the season, with each game being 1 hour long. For our calculations, we assumed that individuals in offensive or defensive positions would play for half the game, hence yielding the formula:

$$\text{number of games} \times \text{\% of time active in games across season} \times 0.50\ \text{h}$$

Had a football player played both offense and defense (e.g., during his high school football career), the 0.50 h in the formula would be replaced with 1.00 h as seen here:

$$\text{number of games} \times \text{\% of time active in games across season} \times 1.00\ \text{h}$$

Had a football player played on special teams only, we would assume that his time on the field would have been drastically smaller. Hence, for special teams players, the formula would replace 0.50 h with a smaller time frame, as seen here:

$$\text{number of games} \times \text{\% of time active in games across season} \times 0.05\ \text{h}$$

Player X was exclusively an offensive player through his freshmen year in college, and exclusively a defensive player for the remainder of his playing career. In his freshman season of high school, pre-season game contact hours were 0.00 (as there were no pre-season games); regular season game contact hours were 1.25 ($10 \times 25\% \times 0.50$ h); and post-season game contact hours were 0.25 ($1 \times 50\% \times 0.50$ h). Yearly totals for the pre-season, regular season, and post-season were summed throughout all active playing years at the high school, college, and professional levels to yield the total

Table 2. Football Contact Exposure History for Participant X

	High school					College					Professional			
	FR	*SO*	*JU*	*SE*	*Total*	*FR*	*SO*	*JU*	*SE*	*Total*	*Year 1*	*Year 2*	*Total*	*Overall*
Primary position played	WR	WR	WR	WR		WR	DB	DB	DB		DB	DB		
Practices														
Spring football														
No. contact practices/week (A)						2	2	2	2					
No. weeks (B)						3	3	3	3					
No. hours/ contact practice (C)						2	2	2	2					
Contact hours (A X B X C = D)						12.00	12.00	12.00	12.00	48.00				48.00
Pre-season														
No. contact practices/week	1	1	1	1		4	4	4	4		3	3		
No. weeks	1	1	1	1		3	3	3	3		4	4		
No. hours/ contact practice	2	2	2	2		2	2	2	2		2	2		
Contact hours (E)	2.00	2.00	2.00	2.00	*8.00*	24.00	24.00	24.00	24.00	96.00	24.00	24.00	48.00	152.00
Regular season														
No. contact practices/week	2	2	2	2		3	3	3	3		3	3		
No. weeks	10	10	10	10		12	12	12	12		16	4		
No. hours/ contact practice	2	2	2	2		2	2	2	2		2	2		
Contact hours (F)	40.00	40.00	40.00	40.00	160.00	72.00	72.00	72.00	72.00	288.00	96.00	24.00	120.00	568.00
Post-season														
No. contact practices/week	2		2	2			3		3		3			
No. weeks	1		2	3			2		2		1			
No. hours/ contact practice	2		2	2			2		2		2			
Contact hours (G)	4.00		8.00	12.00	24.00		12.00		12.00	24.00	6.00		6.00	54.00
Total practice contact hours (D + E + F + G = H)	46.00	42.00	50.00	54.00	192.00	108.00	120.00	108.00	120.00	456.00	126.00	48.00	174.00	822.00 (I)
Games														
Pre-season[a]														
No. games (J)						1	1	1	1		4	4		
%time active in season games (K)						50%	50%	100%	100%		100%	100%		
Time within game (in hours)[b] (L)						0.50	0.50	0.50	0.50		0.50	0.50		
Contact hours (J X K X L = M)						0.25	0.25	0.50	0.50	1.50	2.00	2.00	4.00	5.50
Regular season														
No. games	10	10	10	10		12	12	12	12		16	4		
%time active in season games	25%	50%	75%	100%		50%	100%	100%	100%		100%	100%		
Time within game (in hours)[b]	0.50	0.50	0.50	0.50		0.50	0.50	0.50	0.50		0.50	0.50		
Contact hours (*n*)	1.25	2.50	3.75	5.00	12.50	3.00	6.00	6.00	6.00	21.00	8.00	2.00	10.00	43.50
Post-season														
No. games	1		2	3			1		1		1			
% time active in season games	50%		50%	100%			100%		100%		100%			
Time within game (in hours)[b]	0.50		0.50	0.50			0.50		0.50		0.50			
Contact hours (O)	0.25		0.50	1.50	2.25		0.50		0.50	1.00	0.50		0.50	3.75
Total game contact hours (M + N + O = P)	1.50	2.50	4.25	6.50	14.75	3.25	6.75	6.50	7.00	23.50	10.50	4.00	14.50	52.75 (Q)
Total game contact hours, weighted[c]	5.71	9.51	16.17	24.73	56.11	9.11	18.92	18.22	19.63	65.88	29.44	11.21	40.65	162.64 (R)
Contact exposure estimate (I + Q)														874.75
Adjusted contact exposure estimate (I + R)														984.64

Participant X's high school football team only made the post-season in his junior and senior season. His college football team only made the post-season during his sophomore and senior season. In the second season of his professional football career, he sustained a career-ending injury at the end of the fourth game of the regular season.

[a]Pre-season games in the college level account for spring football game.

[b]Time within game (in hours) is 0.50 for defense and offense positions, 0.05 for special teams, and 1.00 for those playing both offense and defense within a game.

[c]Weights are based upon his primary position being wide receiver and defensive back. Example for High school-Junior season: $4.25 \times 3.49 \times 1.09 = 16.17$. Example for College-Sophomore season: $6.75 \times 2.67 \times 1.05 = 18.92$.

FR, freshman season; SO, sophomore season; JU, junior season; SE, senior season; WR, wide receiver; DB, defensive back.

game contact exposure. Contact hours from the spring football game at the college level were included under the pre-season. Upon summing up all game contact hours in each season segment of his football career, Player X had 52.75 total game contact hours (Q in Table 2). The adjusted total game contact hours were 162.64 (R in Table 2).

Finally, the sum of the total practice contact exposures and total game contact exposure yielded our contact exposure measure for the HIEE. For Player X, this was 874.75 (822.00 + 52.75; I + Q in Table 2), with an adjusted total of 984.64 (822.00 + 162.64; I + R in Table 2).

Example with cohort of former collegiate football players and retired NFL players

Descriptions of the unadjusted and adjusted contact exposure estimates are presented in Table 3. There were differences in HIEE between the NFL and college-only players (p values < 0.001). The ANOVA suggested that concussion history and the interaction term for concussion history and football player group (i.e., NFL vs. college-only) was not significant for both unadjusted and adjusted contact exposure estimates.

Discussion

This article presents an interview-based measure to estimate the total hours of contact exposure in football over an athlete's playing career from adolescence. To date, the HIEE is the most nuanced examination of subconcussive impact exposure across an athlete's football career. The measure presented is detailed enough to calculate hours of contact exposure across a career, but feasible enough to prevent fatiguing the respondent. Administration of the structured interview typically takes ~30 min to complete. Information is gathered by year, and furthermore by segments of seasons (i.e. pre-season, regular season, and post-season). This allows for the detection of any changes from year to year, such as changes in playing position, and changes throughout each year, such as playing a different percentage of time during the pre-season and the regular season.

Development of such a measure is an important step in gaining a more complete understanding of the potential negative effects of subconcussive impacts, as it presents a practical method to gather information on contact exposure from large samples of amateur and/or professional contact sport athletes. Although administered retrospectively in our study, future research should examine the validity of this measure in ascertaining contact exposure data prospectively at various development points across an athletic career (high school, college, professional).

Estimating total hours of contact exposure may allow for the detection of differences between individuals who suffered a large number of subconcussive impacts, regardless of concussion history. Our study found that there was no association between the HIEE and concussion history, which may suggest that the incidences of subconcussive and concussive impacts are independent. Therefore, an increase in exposure may not necessarily lead to an equally proportionate increase in the risk of concussion. This lack of association may be attributable to the larger proportion of contact hours accumulated in practices versus competitions. Practices serve as controlled environments in which athletes engage in contact drills but have coaching staff available to direct and correct athlete behavior as they practice skills. Measurements of exposure also does not account for individual player technique. Proper tackling technique with one's head up upon contact could alleviate the risk of concussion. Additionally, other factors may affect concussion risk, such as previous history of concussion[21] and helmet design.[22] Finally, concussion reporting is also associated with numerous factors, such as knowledge and policy.[23] Future research about the correlation between subconcussive and concussive impacts should utilize larger, more diverse samples of football players, while accounting for variations in team and individual tackling technique and knowledge.

Limitations

This study has limitations. We had a small sample size and differences in the distribution of positions. However, we calculated exposure values that accounted for disparities in at-risk times for impacts in practices versus games, and between positions.

Table 3. Mean, Median, and Range of Unadjusted and Unadjusted Contact Exposure Estimates, by Playing Level and Number of Concussions Sustained

	Unadjusted			*Adjusted*[a]		
	Mean (SD)	*Median*	*Range*	*Mean (SD)*	*Median*	*Range*
College only						
Low concussion[b] ($n = 15$)	897.39 (320.16)	773.13	467.25–1590.00	956.98 (323.39)	835.08	550.54–1661.37
High concussion[c] ($n = 17$)	1263.43 (360.16)	1244.13	793.75–2247.00	1347.75 (383.58)	1293.76	824.41–2415.54
College mean	1091.85 (384.30)	1027.13	467.25–2247.00	1164.58 (403.02)	1119.27	550.54–2415.54
NFL						
Low concussion ($n = 16$)	2743.51 (1081.34)	2566.13	1085.75–5070.63	2928.40 (1094.11)	2755.31	1181.15–5263.38
High concussion ($n = 16$)	2611.48 (1391.59)	2680.63	142.88–5445.00	2786.72 (1387.89)	2835.01	447.87–5611.49
NFL mean	2677.50 (1227.73)	2612.44	142.88–5445.00	2857.56 (1231.45)	2755.31	447.87–5611.49
Overall mean	1884.67 (1205.37)	1452.00	142.88–5445.00	2011.07 (1246.61)	1530.57	447.87–5611.49
ANOVA p values						
Low vs. high concussion		0.83			0.82	
College only vs. NFL		< 0.001			< 0.001	
Interaction term		0.28			0.25	

[a]Weights added to game contact hours are based on primary positions played.
[b]Zero to one concussions.
[c]Two or more concussions.

Additionally, all of the information we collected was self-reported and may have been influenced by recall bias. However, most of the information we collected, particularly at the high school level, may not be available in any other format and, therefore, cannot be validated. Nevertheless, football participation was a large part of participants' lives, suggesting that memory of practice structure and playing time would be at least somewhat salient. For the retired NFL athletes, we used statistics reported online (NFL.com) as a reference to ensure that the records were consistent, and internal validity checks indicated that the self-reported information was most often accurate. Regarding concussions, literature has reported selective preservation of older information in patients with Alzheimer disease-related dementia, suggesting that recollection of events involving prior injuries is likely in these retired athletes.[24] We also believe that increased media coverage and general knowledge regarding concussions may have helped recall of concussion history.

The contact exposure estimate also fails to account for participation in football prior to high school, the level at which many players have yet to learn proper tackling techniques. In addition, with ∼3,000,000 youth 6–14 years of age playing tackle football,[25] we are potentially missing a large number of individuals with contact exposure. Our estimations also assumed homogeneity within each segment of the season, and within each year of play. Nonetheless, we asked questions that allowed us to average across each training/competition period of the season (i.e., pre-season, regular season, post-season). For example, if someone said that they only played for 50% of the time during the first half of the regular season games, but for 100% of the time during the second half of the regular season games, we averaged their playing percentage to 75% for the regular season. Furthermore, the weights applied to the estimates assume that the ratios of frequency and severity of impacts in games versus practices that occur at the college level also occur at the professional level and are consistent across teams. Furthermore, these weights are based on research from the past 10 years, and may not apply to athletes who retired 20–30 years ago. Future research should continue to investigate potential differences in head impact severity and frequency based on playing level and playing era. Despite these limitations, findings from this study are important to the development of an epidemiological model for the examination of subconcussive impacts in contact sport. Although this study examines this guided interview in football athletes, a similar measurement approach will contribute to the understanding of impact exposure in other contact sports.

Conclusion

Neurocognitive deficits, and both structural and functional MRI changes, have been found following subconcussive impacts,[8–12] but the data are limited. The use of the HIEE alongside the collection of a concussion history may aid in better estimating how these outcomes are associated with subconcussive and concussive impacts. In addition, future prospective studies should investigate the correlation between HIEE measures and clinical outcomes such as symptomatology, neurocognitive status, balance, and neuroimaging findings. This may allow for clinicians to more accurately make return to play or, ultimately, disqualification decisions for athletes with certain HIEE measures.

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