Cumulative Exposure Risk of Concussion for Youth and High School Football Head Impacts

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ABSTRACT

Sports-related concussion is the most common athletic head injury with football having the highest rate. Traditionally, research on the biomechanics of football-related head impacts has been focused at the collegiate level. Less research has been performed at the youth and high school level, despite undetermined rates of concussion among youth football players. The objective of this study is to develop and present a cumulative exposure risk metric and use it to analyze cumulative risk at various levels of play. Head impact exposure was measured by instrumenting the helmets of 111 youth and high school football players with helmet mounted accelerometer arrays. Age groups analyzed in this study include 6-8 years, 9-12 years, 12-14 years, and 14-18 years. The risk associated with each linear and/or rotational acceleration measured for each player was calculated based on linear, rotational, and combined probability concussion risk functions. These data were combined to define the cumulative exposure risk (CER) for the season for each player for each risk function. CERs for all players for each age group were summed to calculate the estimated number of concussions experienced for the age group. The three concussion risk functions (linear[1], rotational[2], combined probability (CP)[3]) were used to calculate the number of predicted concussions for each age group over the course of the season given each risk function. A non-parametric Wilcoxon test of multiple comparisons was performed to identify differences between groups. Results demonstrate age-dependent variations in CER. Each CER metric resulted in significantly lower cumulative exposure for the 7-8 and 9-12 age groups compared to the 12-14 and 14-18 age groups. There was no significant difference in exposure between the 7-8 and 9-12 age groups, nor between the 12-14 and 14-18 age groups. . The predicted number of concussions was found to vary significantly between different risk functions as well from less than 1 to 34 concussions. The CER metric presented in this study is novel as it accounts for the frequency and severity of each player's impacts. The results from this study contribute to the understanding of cumulative head impact exposure in football which will further our understanding of the biomechanics of head injury.

INTRODUCTION

It is estimated that 1.6 to 3.8 million sports-related concussions occur each year in the United States with football having the highest incidence rate. There are approximately 5 million athletes playing tackle football each year, with the greater majority (98%) of the population between the ages of 6 to 18 years of age. Traditionally, research on the biomechanics of football-related head impacts has been focused at the collegiate level. Less research has been performed at the high school and youth level, despite the large numbers of children participating and the unknown rates of concussion among a population with rapidly developing brains.

Exposure to football-related head impacts is traditionally captured using the Head Impact Telemetry (HIT) System. Key biomechanical metrics collected from the HIT system include impact location, peak linear acceleration, and peak rotational acceleration. Exposure is commonly reported in terms of median and 95th percentile due to the highly right-skewed nature of the head impact data. The first study documenting the exposure of youth athletes was reported by Daniel et al. In this study, the HIT System was used to collect head impacts for 7 football players between the ages of 7 and 8. More recently, a number of youth football studies have been expanded to include ages up to 14 years of age. The number of impacts per season for ages 7-8 (19 players) [24], 9-12 (50 players) [6], and 12-14 (10 players) [10] reported were 161 ± 111, 240 ± 147, and 341 ± 254 impacts per player, respectively. In comparison, the number of impacts per season measured at the high school and collegiate level is 500 and 1000 impacts [1, 3, 20, 23]. Injurious impacts have been reported at > 80 g for collegiate and high school athletes[3, 20]. The single season data of youth impacts reveal 11 impacts > 80 g for ages 7-8, 36 impacts for ages 9-12, and 62 impacts for ages 12-14, with the majority occurring during practices. Youth football players are thus experiencing high magnitude impacts approaching those of high school and collegiate players.

Quantifying the cumulative effects of head impacts has been of increasing interest. Broglio et al has reported the cumulative burden of head impacts in high school football by summing the peak linear and rotational acceleration of each impact. The reported values for the high school athletes reveal an average annual cumulative linear acceleration of 16,746 g and an average annual cumulative rotational acceleration of 1,090,067 rad/s^2 [2]. The values reported were 55% lower than those measured at the collegiate level. Although this method captures the total number of linear and rotational accelerations experienced for a player in a single season, this method may also be misleading because of the nonlinear relationship between peak acceleration level and risk. More recently, Urban et al described an alternative method for capturing cumulative exposure by summing risk calculations for each player's individual impacts using previously developed analytic risk functions[23]. The metric presented in this study is beneficial for fully capturing each individual's cumulative exposure to the risk of concussion because it accounts for the frequency and severity of each player's impacts.

The objective of this study is to compare the cumulative exposure for 4 age groups participating in youth and high school football. The cumulative exposure risk (CER) metric was used to assess group differences in exposure. Additionally, the CER metric for each risk function was compared to the number of clinically diagnosed concussions collected for the age groups to evaluate the metric that best captures the true number of concussions for each age group. These data are beneficial in understanding the age-dependent mechanisms of concussion in football and will lead to better understanding of the metrics that may be used to quantify player exposure. Specifically, these data will have importance in correlating pre- and post-season changes in the brain with neuroimaging and neuropsychological intruments.

METHODS

The study protocol was approved by the Wake Forest School of Medicine and Virginia Tech Institutional Review Board and participant assent and parental consent were appropriately obtained. Impact data were collected for the entire season, including preseason practices and scrimmages, regular season practices and games, and playoff practices and games. Head impact exposure was measured by instrumenting the helmets of youth and high school football players with one of the two accelerometer arrays: the commercially available Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH) or a custom 6 degree of freedom (6DOF) head acceleration measurement device [7, 12, 17]. Each player participating in the study was provided a Riddell Revolution or Riddell Revolution Speed helmet instrumented with the HIT System.

For this study, the HIT System included a sideline base unit with a laptop computer connected to a radio receiver and an encoder unit for each helmet. This system collects impact data on the sidelines from each encoder equipped with either six single-axis accelerometers (commercially available system) or 12 accelerometers oriented tangentially to the crown of the player's helmet (6DOF). A detailed description of the HIT system encoder units have been previously reported [1-5, 7-9, 11, 17, 18, 20, 22]. During play, data collection occurred each time an instrumented helmet received an impact where an accelerometer exceeded 14.4g. The recorded hit includes 40 ms of data sampled at 1000 Hz. The data was wirelessly transmitted to the sideline computer where kinematic linear and rotational accelerations are computed. The data output includes peak g's, direction of impact, or other biomechanical indicators. All data were screened to remove any false impacts that did not result from the helmet being worn on the players' head during play (i.e., dropped helmets). A complete description of the processing algorithm and validation has been previously described [7]. All rotational acceleration data were processed as per Rowson et al [21].

For the purpose of this study, the football players were subdivided based on the youth and high school age divisions for each team (7-8 years old, 9-12 years old, 12-14 years old, and 14-18 years old). Each player within the respective age group played against teams of similar age and weight for the respective age group. Data was appropriately sampled using a Weibull distribution fit as described by Urban et al. The collected risk of concussion over the course of the season was calculated using CER[23]. This metric is calculated from the risk of concussion for each impact for each player using three different risk functions previously described in the literature. The three risk functions include the logistic regression equations (Table 1) and regression coefficients (Table 2, Table 3) for (1) linear acceleration [20], (2) rotational acceleration [21], and for (3) the combined probability (CP) from linear and rotational acceleration [19]. These data were summed to obtain the CER for the season for each player given each risk function. CERs for all players for each age group were summed to calculate the estimated number of concussions experienced for the whole age group. The resulting CER for each risk function was compared between groups to assess cumulative exposure for each age group. A non-parametric Wilcoxon test of multiple comparisons was performed to identify differences between groups for each risk function. Lastly, each team CER was normalized by number of players within each group to remove the effect of age group size in order to evaluate the overall exposure for each age group relative to one another.

Table 1. Logistic regression equations for the three risk functions used in the prediction of injury.

Logistic Regression Equation	**Study**	
$R(a) = \frac{1}{1 + e^{-\alpha+\beta x}}$	Rowson et al 2011 Rowson et al 2012	(1)
$CP = \frac{1}{1 + e^{-(\beta_0+\beta_1 a+\beta_2 \alpha+\beta_3 a\alpha)}}$	Rowson et al 2012	(2)

Table 2. Logistic regression coefficients for the linear and rotational injury risk functions.

Risk Function	Study	α	β
Linear	Rowson et al 2011	-9.805	0.051
Rotational	Rowson et al 2012	-12.531	0.002

Table 3**.** Logistic regression coefficients for the combined probability risk function.

Risk Function	Study	β_0	β_1	β_2	β_3
Combined Probability (CP)	Rowson et al 2012	-10.2	0.0433	0.000873	-9.2E-07

RESULTS

A total of 111 football players on 5 youth teams and 1 high school varsity team participated in this study. Three of the youth teams in this study competed in local recreational or school-based teams and 2 of the teams competed under American Youth Football regulation. This study group included 12 mites (7-8 years old), 50 junior (9-12 years old), 10 middle school (12-14 years old), and 39 high school (14-18 years old) football players. The ages ranged from 7 to 18.5 years. A total of 34,603 impacts were measured in all practices and games which are subdivided by age group in
Table 4.

Table 4. Description of subject group analyzed in this study.

Age Group	Number of Players	Number of Impacts	Age (years)	Mass (kg)
7 to 8	12	2709	8 ± 0.3	33 ± 9
9 to 12	50	11978	11 ± 1.1	44 ± 7
12 to 14	10	3414	13 ± 0.8	55 ± 10
14 to 18	39	16502	17 ± 0.7	89 ± 16

The linear accelerations ranged from 10.0 to 152.3 g with an increasing acceleration magnitude and impact frequency with increasing level of play from 7 to 12 years of age. Similarities were observed between the middle school and high school age groups. The median peak linear accelerations were 16 g (7-8 years), 19 g (9-12 years), 21 g (12-14 years), and 21 g (14-18 years). The 95th percentile peak linear accelerations were 36 g, 46 g, 60 g, and 58 g, respectively. Rotational acceleration increased in magnitude with increasing level of play, however similarities were observed between the junior and middle school age groups. The median peak rotational acceleration was 605 rad/s^2, 890 rad/s^2, 887 rad/s^2, and 973 rad/s^2, respectively, with 95th percentile values of 1878 rad/s^2, 2142 rad/s^2, 2647 rad/s^2, and 2481 rad/s^2.

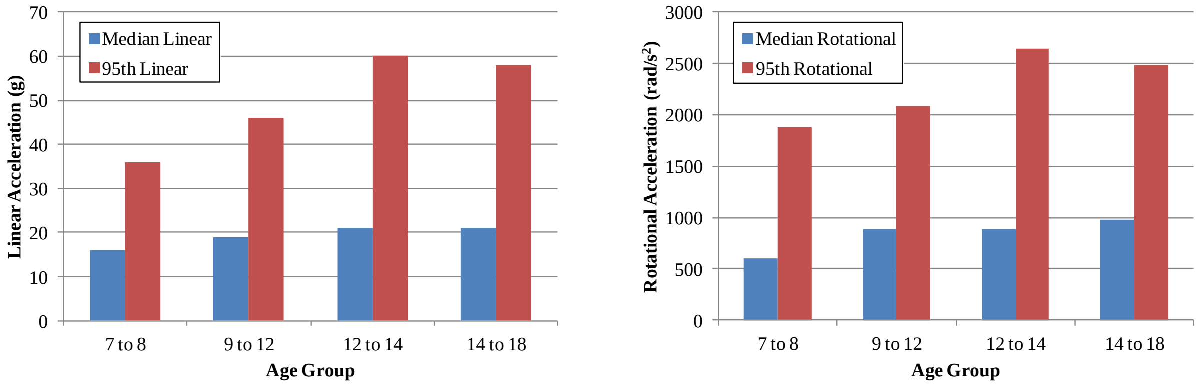

Figure 1. Median and 95th percentile peak linear (left) and rotational (right) acceleration for each age group.

The calculated CER varied within each age group by player, as well as between age groups. Additionally, the calculated CER values varied significantly by risk function employed. The values for CER_{Linear}, $CER_{Rotational}$, and CER_{CP} ranged from 0.002 to 0.727, 0.0003 to 3.567, and 0.017 to 4.822, respectively. Six percent (7/111) of the $CER_{Rotational}$ values for each player were greater than 1 (100% risk of concussion) and 13.5% (15/111) of the CER_{CP} values for each player were greater than 1. None of the CER_{Linear} values exceeded 1. The contribution of either linear versus rotational acceleration for each impact varied between player. However, the majority of players with the highest CER values, also recognized as the players with the highest frequency and magnitude of impacts, remained within the top 10% of all players. The median and inter-quartile range (IQR) values of CER_{Linear}, $CER_{Rotational}$, and CER_{CP} are provided in Table 5.

Table 5. Median calculated number of concussions by player and each age range from the CER calculated using each risk function. IQR = Inter-quartile Range

			Player Median CER [IQR]			Age Group Predicted Concussions		
Age Group	# Players	# Reported Concussions	CER Linear	CER Rotational	CER CP	Season CER Linear	Season CER Rotational	Season CER CP
7 to 8	12	0	0.037 [0.046]	0.017 [0.013]	0.116 [0.078]	0.44	0.56	1.67
9 to 12	50	4	0.045 [0.052]	0.022 [0.043]	0.149 [0.193]	3.04	2.85	9.48
12 to 14	10	2	0.098 [0.220]	0.132 [0.908]	0.373 [1.445]	1.86	6.23	10.67
14 to 18	39	2	0.132 [0.191]	0.191 [0.405]	0.497 [0.934]	7.42	15.25	33.75

The non-parametric Wilcoxon test of multiple comparisons reveals age dependent variations in cumulative exposure. The $CER_{Linear,}$ $CER_{Rotational}$, and CER_{CP} were found to be significantly lower for the 7-8 age group compared to the 12-14 and 14-18 age groups. Additionally, the 12-14 age group was found to have significantly greater CER values compared to the 9-12 age group, who was found to have significantly lower CER values compared to the 14-18 age group. All associated Z-scores and p-values are provided in Table 6.

Table 6. Wilocoxon test of multiple comparisons test results for each risk function.

		CER Linear		**CER Rotational**		**CER CP**	
Level	**Comparison**	**Z - score**	**p-value**	**Z - score**	**p-value**	**Z - score**	**p-value**
7 to 8	**9 to 12**	-1.31	0.19	-1.47	0.142	-0.935	0.35
7 to 8	**12 to 14**	-2.868	0.004*	-2.868	0.004*	-2.736	0.006*
7 to 8	**14 to 18**	-4.652	<.0001*	-4.163	<.0001*	-4.341	<.0001*
9 to 12	**14 to 18**	-5.734	<.0001*	-5.486	<.0001*	-5.8	<.0001*
12 to 14	**9 to 12**	2.807	0.005*	3.005	0.003*	3.044	0.002*
12 to 14	**14 to 18**	-0.632	0.527	-0.037	0.97	-0.285	0.775

The summed CER for an age group, referred to as the season CER, is the number of concussions estimated for the age group given the impact frequency and magnitude for each player. In this single season of football there were 8 clinically diagnosed concussions, with at least one concussion on each team, with exception of the 7-8 year olds. Within each age group, there were 4 concussions in the 9-12 age group, 2 in the 12-14 age group, and 2 in the 14-18 age group. The estimated number of concussions for each age group varied for each risk function from less than 1 for the 7-8 age group predicted by CER_{Linear} to 33.75 for the 14-18 age group predicted by CER_{CP}. The calculated values are provided in Table 5. The normalized season CER values for each age group demonstrate similar decreased cumulative exposure for the 7-8 and 9-12 age group, with increasing cumulative exposure with age up to age 12-14, with a subsequent decline in normalized cumulative exposure to age 14-18 (Figure 2).

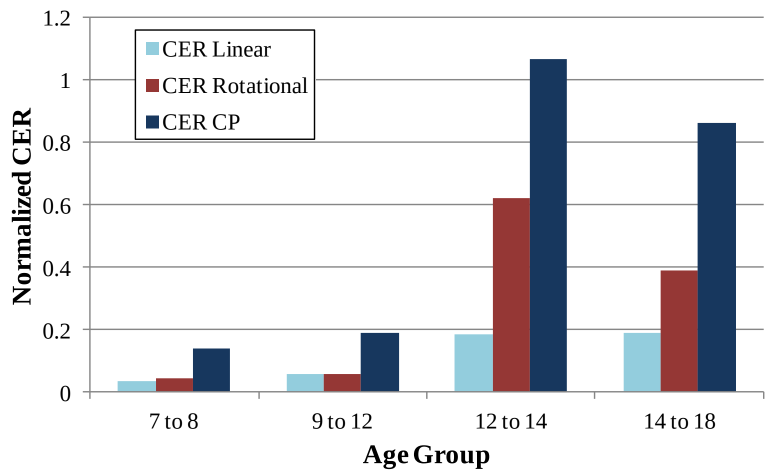

Figure 2. Normalized season CER values for each age group and risk function.

DISCUSSION

The goal of this study was to examine the group difference in cumulative exposure for a wide range of ages in youth football. The focus of the analysis is on youth due to the lack of biomechanical data for this age group and the necessity to identify age specific injury criterion. Impact data was collected for a total of 111 youth and high school athletes participating in tackle football. Increases in impact magnitude were observed with increasing age, however similarities were observed between the 12-14 and 14-18 age groups. Additionally, a cumulative exposure metric was utilized to compare group differences in exposure, which revealed significant differences between age groups.

The cumulative exposure metric utilized in this study is unique as it captures the risk associated with each impact. By using such a metric, the magnitude and frequency of impacts is accounted for when determining a player's full exposure to the risk of concussion over the course of the season. The non-parametric Wilcoxon test for multiple comparisons reveals significant differences between populations. Each CER metric resulted in significantly lower cumulative exposure for the 7-8 and 9-12 age groups compared to the 12-14 and 14-18 age groups (Table 6). There was no significant difference in exposure between the 7-8 and 9-12 age groups, nor between the 12-14 and 14-18 age groups. Similarities between these age groups may provide further insight into the development of youth specific injury metrics and risk functions.

Previously, Broglio et al presented a method to capture the cumulative exposure to head impacts. When this method is applied to the data set used in this study, an increase in the average annual linear acceleration is observed with age (Figure 3). On the contrary, the average annual rotational acceleration reveals slightly higher average annual rotational acceleration in the 9-12 age group (Figure 3) compared to the 12 to 14 age group. Although this method captures valuable information regarding exposure, it fails to incorporate the contribution of higher level impacts to the exposure within each group (i.e., the increased cumulative exposure observed within the 12 to 14 age group). Additionally, previous methods do not capture the effects of combined linear and rotational acceleration. Previous studies have suggested that a combined linear and rotational acceleration injury metric may better predict injury [12, 16].

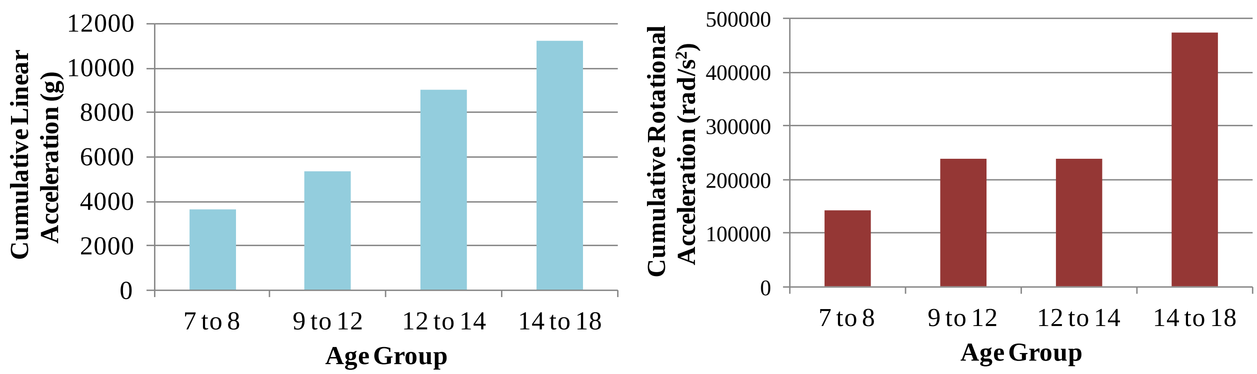

Figure 3. Average cumulative linear and rotational acceleration per player for a single season per Broglio et al.

A useful reference value for the CER metric is one. It is assumed that if CER exceeds 1 for a single player, that one concussion would be expected to have occurred. By that rationale, $CER_{Rotational}$ and CER_{CP} were the best predictors of the number of concussions for many of the age groups assuming some level of underreporting for these groups. It is estimated that underreporting rates for concussions range from 1 in 2 to 1 in 10 [14, 15, 19]. The risk functions utilized in this study were developed with varied underreporting rates of 53% for the linear and rotational risk functions[15, 20, 21] and 10x for the combined probability risk function[14, 19]. Although, $CER_{Rotational}$ and CER_{CP} were found to adequately predict the number of concussions for much of the population, $CER_{Rotational}$ was found to under predict the number of concussions for the 9-12 age group.

The median and 95th percentile peak values increase from age 7 to 18. The 12-14 age group was found to have similar or slightly higher exposure measurements (median: 21 g, 887 rad/s^2, 95th percentile: 60 g, 2647 rad/s^2) compared to the older (14-18) population (median: 21 g, 973 rad/s^2, 95th percentile: 58 g, 2481 rad/s^2). However, these data may be population/study-specific as the 14-18 age group contained a wide spread of playing levels represented in a population size of 39, compared to the 12-14 age group with only 10 players. Additionally, one player on the middle school team accounted for nearly 45% of the CER for the whole age group and was found to have the highest CER_{CP} for the entire population. This player in particular had frequent impacts to the crown of his head[4, 13]. Further studies are necessary to further investigate exposure differences between these two populations.

CONCLUSIONS

The results of this study will provide a better understanding of the cumulative head impact exposure for a wide range of pediatric developmental age groups. A cumulative metric that has an association with risk of concussion, such as CER, may be a valuable tool in understanding the biomechanical basis of head injury that may occur over the course of the football season. These data encourage the necessity to develop youth specific risk functions and injury metrics to better capture the population at risk for injury. Furthermore, CER has been found to be a valuable metric in determining population-wide differences in exposure and has implications for correlating with pre- and post-season neuroimaging and has potential for comparison with neuropsychological testing. The results from this study contribute to the understanding of cumulative head impact exposure in football which will further our understanding of the biomechanics of head injury.

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