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Brain trauma exposure for American tackle football players 5 to 9 and 9 to 14 years of age

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ABSTRACT

American football helmets used by youth players are currently designed and tested to the same standards as professionals. The National Operating Committee on Standard and Safety requested research aiming at understanding the differences in brain trauma in youth American football for players aged five to nine and nine to fourteen years old to inform a youth specific American football standard. Video analysis and laboratory reconstructions of head impacts were undertaken to measure differences in head impact frequency, event types, and magnitudes of maximum principal strain (MPS) for the two age groups. Overall frequencies and frequencies for five categories of MPS representing different magnitudes of risk were tabulated. The MPS categories were very low (<0.08), low (0.08–0.169), medium (0.17–0.259), high (0.26–0.349) and very high (>0.35). Both cohorts experienced a majority of head impacts (>56%) at very low magnitude of MPS. Youth American football players aged 9–14 yrs. sustained a greater frequency of head impacts at MPS between 0.08 and 0.169 % associated with changes in brain structure and function. There were no differences in overall frequency, or in frequency of head impacts in other categories of MPS. The proportion of impacts considered injurious (MPS > 0.08) was greater in the 5–9 group (44%), than the 9–14 group (39%), and impacts above 0.35 % were only reported for the younger age group. The larger helmet-to-shoulder ratio in the younger age groups may have contributed to this finding suggesting that youth American football players under the age of nine would benefit from a child-specific football helmet.

1. Introduction

Repetitive head impacts (RHI) in American football are associated with a variety of neurological impairments including but not limited to changes in brain structures (Alosco, et al., 2018; Stamm, et al., 2015b), neuropsychiatric, and executive function impairments (Alosco, et al., 2017), and chronic traumatic encephalopathy (CTE) (Mez, et al., 2017). In youth American football players, associations between RHI and changes in white matter have been reported in athletes as young as seven years old (Bahrami, et al., 2016; Foss, et al., 2019). Researchers investigating the age of first exposure to tackle football in former professionals report an association between exposure prior to the age of 12 and an increased risk for poor long-term neuropsychological and cognitive outcomes (Alosco, et al., 2017; Stamm, et al., 2015a), decreased thalamic volume (Schultz, et al., 2018) and changes in white matter structures (Stamm, et al., 2015b). In high school football players, changes in functional connectivity and brain metabolism were observed as a result of RHIs (Abbas, et al., 2015a; Abbas, et al., 2015b; Poole et al, 2015). The growing concern for brain health in youth American football players has called for increased safety measures including an age-appropriate helmet. The National Operating Committee on Sport Safety Equipment (NOCSAE) funded research aimed at understanding differences in brain trauma in youth American football for players aged five to nine and nine to fourteen years old to inform a youth specific American football standard.

While youth football may appear to be similar to adult football, there

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are important differences including the frequency, magnitude, and type of head impact events. With increased age, athletic and technical skills improve resulting in an increase in frequency and severity of head impacts (Cobb, et al., 2013; Daniel, Rowson, & Duma, 2014; Young, Daniel, Rowson, & Duma, 2014). Larger head-to-body ratio and weaker necks are implicated in the ability of youth to control their head and helmet during impacts, increasing their risk for brain trauma (Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014; Vickers & Stuart, 1943). All American football helmets, including youth helmets, are presently designed and tested to the same standards. This research is intended to describe brain trauma experienced by different age groups to inform design and certification requirements for a youth-specific football helmet standard.

Brain trauma risk in sport is typically measured by the incidence of reported concussions. Reporting rates for concussion are inconsistent and low in general (McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004; Meehan, Mannix, O'Brien, & Collins, 2013) especially in youth sport where there are seldom medical professionals at practices and games (Rizzone, Diamond, & Gregory, 2013). Youth athletes do not have the necessary skills and knowledge to recognize symptoms and report concussions (Gourley et al., 2010; McCrea et al., 2004). In some cases, head-impact sensors are used to measure the frequency and magnitudes of head impacts experienced by players. Although head impact sensors are useful to quantify head impact frequency, obtaining accurate magnitude measurements is challenging, especially for rotational motion (Jadischke, Viano, Dau, King, & McCarthy, 2013). Peak linear and rotational acceleration are useful in establishing head protection standards but limited in providing injury risk. Brain tissue deformation such as maximum principal strain (MPS) obtained using laboratory reconstructions and finite element modeling of head impacts provides a better measure of brain tissue trauma (Cournoyer & Hoshizaki, 2019b; Kleiven, 2007; Patton, McIntosh, & Kleiven, 2013; Post, et al., 2015; Zhang, Yang, & King, 2004). Head impacts and their frequency can then be classified according to levels of MPS representing different risks associated with brain injuries, termed brain trauma exposure. This method of categorizing frequency according to ranges of MPS was successful at identifying three principal brain trauma exposure player position profile in professional American football and associated with clinical outcomes and playing positions (Karton, Hoshizaki, & Gilchrist, 2020).

The purpose of this research was to compare brain trauma exposure of youth American football players for two age groups, five to nine (5–9) and nine to fourteen (9–14) year-olds. Video analysis, laboratory reconstructions, and finite element modeling of documented head impacts were used to provide information to inform a youth specific helmet standard.

2. Methods

2.1. Video analysis

A total of 60 youth American football games including players from five to 14 years old were analyzed to determine the frequency and catalog the necessary information to perform the laboratory event reconstructions. The videos were divided into two categories: age 5–9 and 9–14 years. Thirty teams for each age group were analysed by documenting the head impacts for 7 players from one of the two teams on the field (1 quarterback, 1 running back 1 wide receiver, 1 offensive lineman, 1 defensive lineman, 1 linebacker, and 1 defensive back). This was done to manage the video analysis time to 8–10 h/game. A breakdown of the skill levels and ages of the videos analyzed is provided in Table 1.

The player chosen for each position varied between games (when possible) to ensure a fair representation of all players on the field. For example, for offensive linemen, the position followed varied between center, guard, and tackle to capture the full range of possibilities at those positions. Each of the seven player/positions chosen were followed during the entirety of a football play to document each head impact. In case of substitution, the player taking the initial player's place would be followed.

Confirmed head impacts were defined as a contact to the head resulting in head acceleration (movement). To avoid overestimation of the frequency count, impacts that were partially obstructed or for which the impact location could not be identified through video analysis were labelled as suspected impacts and were not included in the analysis. Every head impact recorded was reviewed by a senior researcher experienced in American football video analysis. The following information was cataloged to inform the laboratory reconstructions: event type, impact location, and impact velocity. Event types consisted of head-to-head, head-to-shoulder, head-to-ground, head-to-hip/thigh, head-to-back/torso, head-to-knee/shin, or head-to-arm/hand. Impact locations were classified as front, front boss, side, rear boss, rear, and crown (Fig. 1) and according to vertical placement into three heights: center of gravity (COG), above and below COG.

The velocity of each impact was visually assessed and categorized as very low (0–2 m/s), low (2–4 m/s), moderate (4–6 m/s), or high (6 m/s +). Impact velocity was confirmed when possible using Kinovea (version 0.8.20, Bordeaux, France) by determining the distance between the head and the impacting surface a set time prior to the impact (between 0.12 and 0.20 s) and dividing it by the time to impact. Impact velocity was calculated when the following criteria were met: 1) A calibration grid could be placed on the playing surface to accurately determine distances 2) the head and the impacting surface could be seen without obstruction in the desired time frame and 3) the impact occurred in a view that was orthogonal to the camera angle to decrease the measurement errors (Post, et al., 2018). The inclusion criteria to calculate the velocity using Kinovea were met for 145 impacts out of 1395 confirmed impacts (10.4%) and matched the visual category assessment in 85.5% of cases (Cronbach alpha = 0.923). In the 14.5% for which the visual category assessment did not match Kinovea, the actual velocity calculation with Kinovea was within 0.2 m/s of the category assigned visually. The velocities recorded were consistent with previous research reporting impact velocities for these age groups (Campolettano, Gellner, & Rowson, 2018). Overall, the method for visual

Table 1
Breakdown of youth football games included in the video analysis of the 5–9 and 9–14 age groups.

Age group	League	Category	State	Age	Weight range (kg)	Number of games
5–9	Pop warner	Tiny mite	California	5–7	15.9–34.0	4
		Junior Mitey-Mite		7–8	N/A	8
		Mitey-Mite		7–9	20.4–45.4	18
	Total					30
9–14	Middle school football	N/A	Virginia	12–14	N/A	6
	Youth Football League	Seniors	Virginia	11–13	38.5–61.2	7
	Youth Football League	Juniors	Virginia	9–11	26.7–49.9	3
	Pop warner	Junior Varsity	California	10–12	40.8–70.3	9
	Pop warner	Pee Wee	California	9–11	34–58.9	5
	Total					30

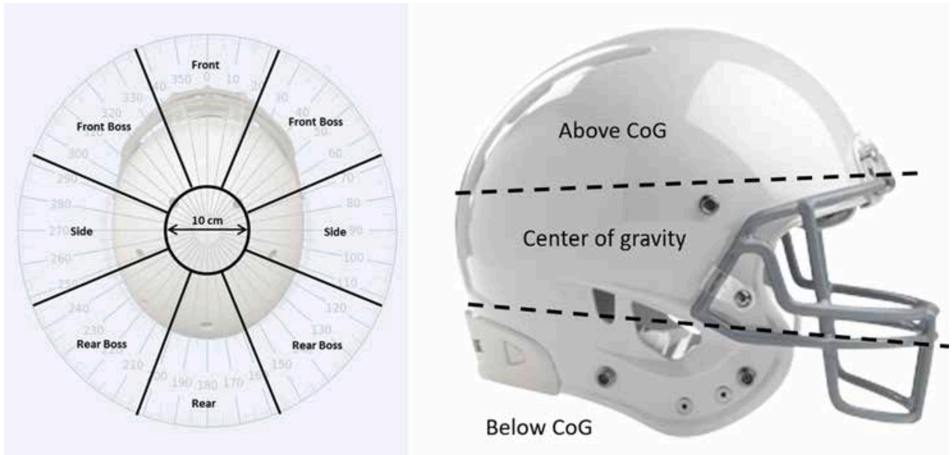

Fig. 1. Impact locations used for video analysis.

assessment for velocity category was deemed accurate for the purpose of this research.

2.2. Laboratory reconstructions

Impact frequency was calculated for each condition (events × impact location × vertical placement × impact velocity category). Head-to-head, head-to-ground, and head-to-shoulder events were selected for laboratory reconstructions as they made up 91% (682) and 85% (535) of all impacts in the 5–9 and the 9–14 age groups respectively. The impact conditions for which a frequency (>0) was observed were reconstructed in laboratory using a small NOCSAE (red) head form as both age groups have head circumference dimensions that correspond to this head form (Nelhaus, 1968). The head form was fitted with 9 accelerometers arranged in a 3–2–2–2 array to obtain linear and rotational acceleration–time curves (Padgaonkar, Krieger, & King, 1975) as well as an appropriately-sized and fitted youth American football helmet. DTS TDAS pro and a CFC 180 filter were used to process the acceleration time curves. The median value of velocity categories used in the video analysis was used for each category, with impacts reconstructed at 1.0 m/s, 3.0 m/s and 5.0 m/s, and all impacts included for analysis were within 0.1 m/s of the target velocity. Head-to-ground impacts were conducted as free drops using a monorail drop rig without a neck. The neck was not used as it was limiting the number of impact locations that could be replicated. Free drops are performed by using a halo that supports the headform while reaching the desired height and is then released with the headform. The halo is designed to continue is trajectory while the headform hits the anvil, and therefore not interfering with head kinematics. The head form was dropped onto a steel anvil covered by a foam surrogate composed of 2.3 cm of VN 600 on top of 5 cm of VN 602 to replicate the compliance of a sample of artificial turf (ACT Global sports turf, Austin, Texas, USA) to allow the halo to move freely around the anvil. Fig. 2 displays the comparison of the surrogate anvil to a sample of artificial turf for linear and rotational acceleration time-curves at 3 and 4.5 m/s.

Head-to-head impacts were reconstructed using the small NOCSAE headform fitted with an appropriately sized helmet as a pendulum (impacting mass = 5.2 kg). Head-to-shoulder impacts were done using a

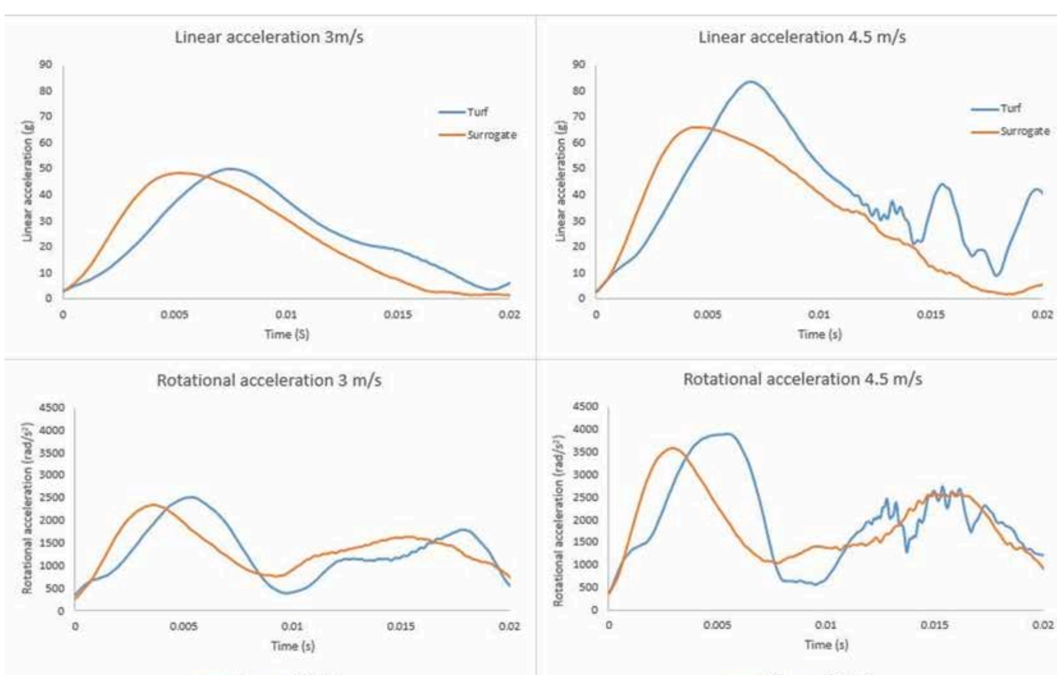

Fig. 2. Comparison of linear and rotational acceleration time curves for falls on a surrogate turf anvil and a sample of artificial turf.

pendulum fitted with 7 cm of VN 602 foam and a youth American football shoulder pad (Rousseau & Hoshizaki, 2015). The impacting mass for head-to-shoulder impacts were determined using a percentage of average body mass for the median age of each group (Rousseau & Hoshizaki, 2015). The impacting masses for the reconstructions were 3.8 and 6.8 kg for the 5–9 and 9–14 age groups respectively. A 50th percentile unbiased neck that limits directional bias was used for both age groups (Walsh et al., 2018). An age-specific unbiased neck could not be used could not be used with the NOCSAE headform as its center of mass is located slightly anteriorly to the neck and would cause the entire system to lean forward. Fig. 3 shows an example of the reconstruction methods for each impact event type.

A finite element model designed for 6 year-olds was used to obtain the peak maximum principal strain (MPS) for the impacts that were reported for the 5–9 age group. The 6 year-old model has 169,849 elements and the brain is modeled as hyperelastic. The brain material properties and validation are described by Koncan et al. (2019). The University College Dublin Brain Trauma Model (UCDBTM) (Horgan & Gilchrist, 2003) was used for the 9–14 age group. The UCDBTM was scaled to 96% of its original size to match the head circumference of an 11.5 year old, the median age of this group (Nelhaus, 1968). The UCDBTM has 32,994 elements and is modelled as viscoelastic. The brain material properties for the UCDBTM are reported by Horgan & Gilchrist (2003). The two finite element models are expected to give different brain responses for similar loading conditions as they used different brain tissue and model characteristics (Horgan & Gilchrist, 2003; Koncan et al, 2019). Different finite element models were used for the comparison between the two age groups to account for differences in brain material properties between the two age groups. The difference in magnitudes of brain tissue deformation between the two models is dependent on loading conditions (Koncan et al, 2019).

Maximum principal strain is a brain deformation metric used to determine the severity of a head impact and its magnitude has been shown to associate with specific clinical outcomes such as asymptomatic impacts (Zanetti, et al., 2013); concussions (Kleiven, 2007; Patton, McIntosh, & Kleiven, 2013; Rousseau & Hoshizaki, 2014; Zhang, Yang, & King, 2004) loss of consciousness and impact seizures (Cournoyer & Hoshizaki, 2019a; Cournoyer & Hoshizaki, 2019b), and persistent post-concussion syndrome (Post, et al., 2015). Categories of MPS were developed to attribute a relative risk value to the impact conditions to these clinical outcomes as described by Karton et al. (2020). The categories were established using research involving laboratory reconstructions of head impact events and anatomical tissue analysis. The moderate category of MPS (0.17–0.269) represents reported values for 50% risk of concussion (Bain & Meaney, 2000; Kleiven, 2007; Zhang, Yang, & King, 2004). The high category of strain (0.27–0.345) was established to represent a high risk of concussive injury as established by the average reported values for concussions (Patton et al., 2013; Rousseau & Hoshizaki, 2014). The very high category includes all impacts with strains in excess of 0.35 and is associated with severe clinical outcomes such as persistent symptoms, loss of consciousness and impact seizures (Cournoyer & Hoshizaki, 2019a; Cournoyer & Hoshizaki, 2019b; Post, et al., 2015). Strains below the moderate category were classified as very low (Ahmadzadeh, Smith, & Shenoy, 2015; Maxwell et al., 1997; Singh et al., 2006; Yuen et al., 2009; Karton et al., 2016) and low (Oliver, et al., 2016; Zanetti, et al., 2013), and represent asymptomatic head impacts. The methodology used for this study was approved by the Ethics Review Board of the University of Ottawa (H-03–18-509).

2.3. Statistical analysis

A Shapiro-Wilk test determined the data was not normally distributed. Mann-Whitney U tests were performed to determine differences in the overall frequency per game, and the frequency by category of MPS ($\alpha = 0.05$).

3. Results

There was a total of 590 head impacts over 30 games (210 player games) for an average of 19.7 ± 10.7 impacts per game in the 5–9 year age group and 805 impacts were recorded for an average of 26.8 ± 15.3 impacts per game for the 9–14 year age group. The overall frequency of confirmed and suspected head impacts for each player position is presented in table 2. Only the confirmed impacts were used in the statistical comparison. There was no significant difference between the two age groups ($p = 0.053$) in head impact frequency per game. The distribution of head impacts according to head impact events is shown in Fig. 4.

The overall distribution of head impacts by magnitude of MPS for all 30 games for both age groups is displayed in Fig. 5A. The total number of impacts, the impact velocity and peak linear and rotational acceleration associated with each level of MPS is presented in Table 3. The majority of impacts experienced by youth American football players were of MPS magnitude lower than 0.08 with 57% and 60% for the 5–9 and the 9–14 age groups respectively. For the 5–9 year-olds, 24 % of head impacts were categorized as low, 17% as moderate, and 1% for both high and very high MPS categories. In the 9–14 age group, 29% of impacts were categorized as low, 10% as moderate, and 1% as high. There were no reported impacts in the very high category for this age group.

The 9–14 year-olds experienced a significantly greater frequency of

Table 2
Overall frequency per player position. The number in parenthesis represented the number of suspected impacts documented.

	Overall frequency per player position for 30 games of youth American tackle football							
	QB	RB	WR	OL	DL	LB	DB	Total
5–9 year-olds	90 (24)	127 (42)	25 (10)	70 (32)	117 (39)	91 (25)	70 (26)	590 (198)
9–14 year-olds	70 (33)	185 (48)	47 (6)	151 (32)	175 (34)	119 (46)	58 (19)	805 (218)

Fig. 3. Methods used for reconstructions. Left: Monorail drop rig with turf anvil for head-to-ground impacts. Center: Small NOCSAE head form and helmet as a pendulum for head-to-head impacts. Right: Pendulum with VN nitrile foam and a shoulder pad for head-to-shoulder impacts.

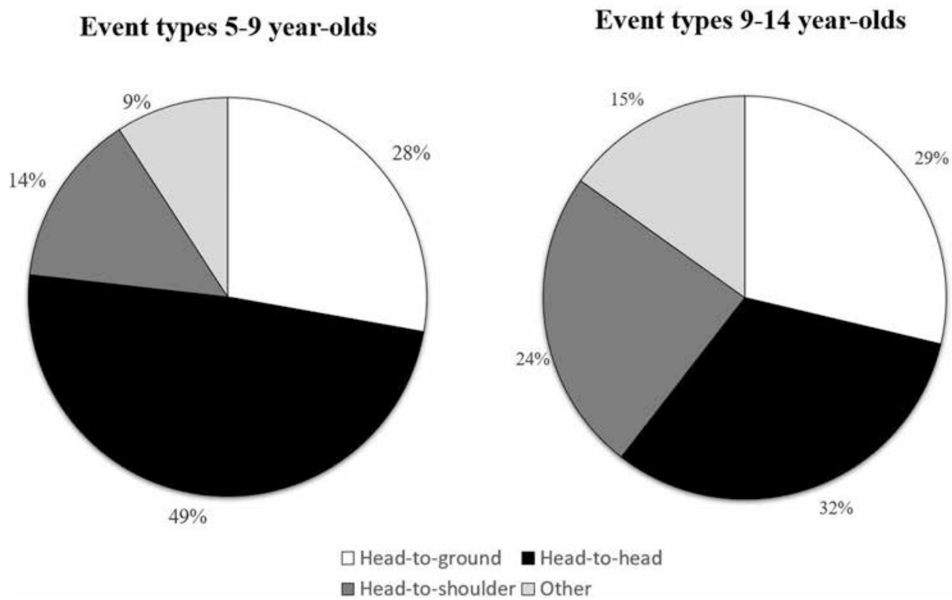

Fig. 4. Distribution of head impacts in youth American football players by event types. The “other” category includes head-to-torso/back, head-to-hip/thigh, head-to-arm/hand, and head-to-knee/shin.

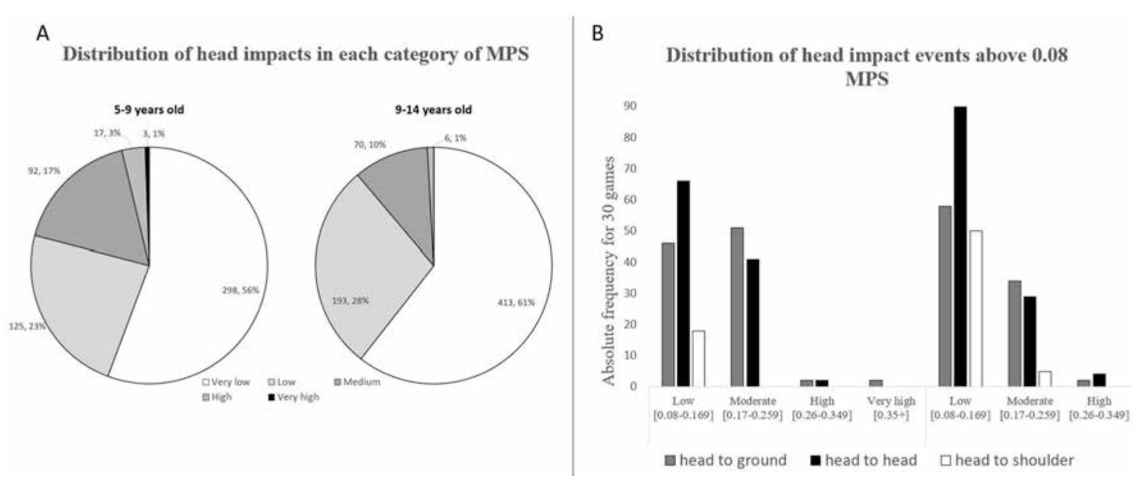

Fig. 5. A. Frequency of head impact by category of MPS for youth American football players aged 5–9 and 9–14 years old. The numbers in the legend (in brackets) represent the range of MPS for each category. 5B Distribution of head impact events in the low, moderate, high, and very high category of MPS for 5–9 and 9–14 years old youth American football players.

Table 3
Total number of impacts, impact velocity, mean peak linear and rotational acceleration for each category of MPS.

Category of MPS	5–9 year-olds Number of impacts	Mean impact velocity	Mean peak lin. acc.	Mean peak rot. acc.	9–14 year-olds Number of impacts	Mean impact velocity	Mean peak lin. acc.	Mean peak rot. acc.
Very Low (<0.08)	298	1.5 ± 0.9	11.3 ± 12.3	547 ± 317	413	1.3 ± 0.7	7.3 ± 4.6	420 ± 170
Low (0.08–0.169)	125	3.0 ± 0.8	20.2 ± 18.5	1140 ± 650	193	2.9 ± 0.7	23.4 ± 17.1	1298 ± 604
Moderate (0.17–0.259)	92	3.2 ± 0.6	31.8 ± 14.6	1840 ± 610	70	4.1 ± 1.0	32.1 ± 21.3	2037 ± 780
High (0.26–0.0349)	17	4.3 ± 1.2	43.8 ± 11.2	3368 ± 560	6	5.0 ± 0	37.8 ± 19.8	3860 ± 1178
Very High (>0.35)	3	5.0 ± 0	47.8 ± 26.5	2766 ± 780	0	–	–	–

impacts per game in the low category of MPS. There was no statistically significant difference detected between the two groups for any of the other MPS categories. The average number of impacts per games in each category of MPS and the *p*-value from the Mann-Whitney U tests are shown in Table 4. Statistical significance is demonstrated in bold.

4. Discussion

The purpose of this study was to compare the overall head impact frequency per game, and the frequency per game in each of the MPS categories for youth American football players aged 5–9 and 9–14 years old. The frequency of head impacts in the low MPS category was

Table 4
Comparisons of the average frequency of head impacts per game in each category of MPS.

Category of MPS	Average frequency of head impacts per game (SD) 5–9 year-olds	9–14 year-olds	*p*-value
Very Low (<0.08)	10.2 (7.3)	13.7 (9.1)	0.104
Low (0.08–0.169)	**4.3 (2.7)**	**6.6 (4.7)**	**0.030**
Moderate (0.17–0.259)	3.1 (2.4)	2.3 (3.0)	0.074
High (0.26–0.0349)	0.1 (0.4)	0.2 (0.4)	0.236
Very High (>0.35)	0.1 (0.3)	0.0 (0.0)	0.119

significantly different between the two groups, with the 9–14 year-olds experiencing a greater impact frequency ($p = 0.030$). Impacts in this category of strain represented approximately one quarter to one third of the head impacts reported in this study. Although impacts of this magnitude are not commonly associated with diagnosed concussions (Kleiven, 2007; Zhang, Yang, & King, 2004), they are important to document as they are associated with acutely asymptomatic injuries leading to changes in brain structures and cognitive impairments (Bahrami, et al., 2016; Breedlove et al., 2014; Tsushima, Geling, Arnold, & Oshiro, 2016). When compared with studies using sensors to measure head impact frequencies for the same age groups, the frequencies reported in this manuscript are about 50% lower, even when considering suspected impacts (Cobb, et al., 2013; Daniel, Rowson, & Duma, 2014; Young, Daniel, Rowson, & Duma, 2014). This is likely due to a difference in methodology with video analysis resulting in more conservative values.

While not statistically significant, the frequency of head impacts in the moderate category was greater in the younger age group ($p = 0.073$). Impacts in this category of strain represent a risk for concussions (Kleiven, 2007; Zhang, Yang, & King, 2004) and may reflect differences in event types experienced by the younger age group. Understanding how youth football players sustain brain trauma is important in the development of a helmet testing standard. Fig. 5B displays the frequency of impacts caused by head-to-ground, head-to-head, and head-to-shoulder events for the low, moderate, high, and very high category of strain.

For both groups, about one quarter of all overall impacts were caused by falls (head-to-ground) with younger players sustaining a greater proportion of head-to-ground impacts at higher impact velocities when compared to their older counterparts. The 9–14 age groups sustained the vast majority (69%) of their head-to-ground impacts at velocities below 2 m/s, whereas 49% of head-to-ground impacts observed for the 5–9 year-olds were in the 2–4 m/s velocity category. This may reflect their inability to control the inertia of the helmeted head during a fall contributing to greater magnitudes of MPS. Almost half of all impacts experienced by younger athletes were head-to-head, as opposed to 32% in the 9–14 age group. In contrast, the 5–9 year-olds sustained fewer head-to-shoulder impacts with 14% as opposed to 29%. This may be explained by the differences in head-to-body ratio between the two groups (Vickers & Stuart, 1943). In youth athletes, the head represents a greater proportion of the body, which is increased by wearing a helmet (Fig. 6). The proportion of the circumference of the head in relation to chest circumference in youth are 92% and 84% for 50th percentile 6 and 10 year-olds respectively (Vickers & Stuart, 1943). Fig. 5B demonstrates that head impacts in the moderate, high, and very high categories of MPS in the 5–9 age group are solely the results of head-to-ground, and head-to-head impacts explaining the greater frequency of head impacts in the moderate and very high category in this group since these impacts were characterized by greater magnitudes of MPS when compared to head-to-shoulder impacts. American football players aged 5–9 yrs may be at greater risk of concussion than their older counterparts due to the increased frequency of head-to-head impacts and greater falling velocities documented for the 5–9 year-olds. Youth American football players under 9 years old may benefit from a child-specific American football helmet, smaller in size and lower in mass, to decrease the frequency of head-to-head impacts and help them manage the inertia of their head during falls resulting in fewer impacts at higher magnitudes of MPS. In addition, the mean peak linear and rotational acceleration documented in this study are lower than the current standard for American football helmet and were consistent with previous literature using sensors (Cobb, et al, 2013; Daniel, Rowson, & Duma, 2014; Young, Daniel, Rowson, & Duma, 2014). It may be beneficial to consider lowering the pass/fail criteria for child-specific helmet to protect against the magnitudes of impacts sustained by players in this age group.

Impacts below 0.08 MPS represented by the very low category was not included in this evaluation as there is little evidence to suggest that impacts at this level are detrimental to brain health in adults. Changes in brain structure and function associated with youth football have been reported in the literature (Alosco, et al., 2017; Bahrami, et al., 2016; Foss, et al., 2019; Schultz, et al., 2018; Stamm, et al., 2015a; Stamm, et al., 2015b) supporting the need for research investigating the effects of these impacts on brain health in youth athletes as they represented

Fig. 6. Differences in helmet-to-shoulder width ratio between youth American football players aged 5–9 (left) and 9–14 years old (right).

grater than 57% of all impacts collected.

4.1. Limitations

Using video analysis to determine head impact frequency in youth American football is challenging. The lack of multiple camera angles and the style of play in youth football keeping players in close proximity created difficulty in detecting head impacts. Head impacts were recorded only when the reviewer could confirm without a doubt that there was a contact with the head that resulted in motion, and only if impact location could be confirmed. Therefore, the absolute head impact frequencies presented in this study are conservative when compared to research using helmet accelerometers for similar age groups (Cobb, et al., 2013; Daniel, Rowson, & Duma, 2014; Young, Daniel, Rowson, & Duma, 2014). However, given the high number of impacts recorded during the analysis, the overall distribution of head impacts according to relative risk is unlikely to be impacted by this limitation.

Unlike the impacts sustained by the younger age group, the impact magnitudes for the 9–14 year-olds were calculated using a scaled finite element model of an adult model and did not include age-specific brain material properties. No finite element model currently exists for 9–14 year old boys however the brain material properties of children aged 9–14 do not significantly differ to adults (Chatelin, Vappou, Roth, Raul, & Willinger, 2012). Similarly, the small NOCSAE head form was developed to match the mass and shape of a 50th percentile 10-year old male (NOCSAE, 2011). In this study, it was used for both groups since it represented the range of head circumferences of both age groups (Nelhaus, 1968). Similarly, a 50th percentile unbiased neckform was used to reconstruct head-to-head and head-to-shoulder impacts for both age groups. This may have masked differences in head kinematics and affecting the maximum principal strain values. A recent study suggested that the influence of neck stiffness had minimal effect on kinematics and brain tissue deformation in collisions impacts in youth American football (Cournoyer et al., 2021). The influence of neck strength may have a greater influence in prevention of head-to-ground impacts or reducing the final head impact velocity. This hypothesis is supported by the greater frequency of impacts at higher impact velocity of head-to-ground impacts in the younger age group. In this study, head-to-ground impacts were reconstructed without the use of a neckform to allow for more accurate impact conditions (impact locations and angles). More research is needed to determine how neck strength can help reduce the risk of brain trauma during falls for these age groups.

In summary, the majority of head impacts observed for both age groups studied involved very low strain magnitudes (<0.08). American youth football players aged 9–14 yrs. experienced a greater number of head impacts with maximum principal strain values between 0.08 and 0.169 when compared to the 5–9 yr. age group. This level of trauma is typically associated with asymptomatic head injuries. While there was no statistical significance in head impact frequency for the other magnitude categories or head impacts per game, the moderate and very high magnitude head impact frequencies were higher for the younger age group. Impacts at these magnitudes represented a risk for concussive injuries and were caused by a greater frequency of head-to-head impacts and greater velocities for head-to-ground impacts. The unique impact events creating head trauma in American youth football supports developing a youth-specific helmet.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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