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Research article

Youth Australian Footballers Experience Similar Impact Forces to the Head as Junior- and Senior-League Players: A Prospective Study of Kinematic Measurements

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Abstract
The aims of this study were to investigate the frequency, magnitude, and distribution of head impacts sustained by youth AF players over a season of games and report subjective descriptions on the mechanism-of-injury and sign and symptoms experienced. A prospective observational cohort study with participants (n = 19) (age range 13-14 yr., mean ± SD 13.9 ± 0.3 yr.) wearing a wireless impact measuring device behind their right ear over the mastoid process prior to game participation. Participants completed an individual post-game logbook providing feedback responses on recalling having a direct hit to their head with another player or the surface. Players experienced a mean (SD) of 5 (±4) impacts per-player per-game. The peak linear rotation (PLA) median, (95th percentiles) were 15.2*g* (45.8*g)*. The median (95th percentile) peak rotational acceleration (PRA) were 183,117 deg/s^2 (594,272 deg/s^2). Median (95th percentile) Head Impact Telemetry Severity profile were 15.1 (46.1) and Risk Weighted Exposure Combined Probability were 0.0012 (0.7062). Twelve participants reported sustaining a head impact. Players reporting a head impact had a faster mean impact duration ($t_{(25)} = 2.4$; p = 0.0025) and had a lower median PLA(g) ($F_{(23,2)} = 845.5$; p = 0.0012) than those who did not report a head impact. These results show similar measurements to the older junior- (aged 17-19) and senior-league (20+) players. Furthermore, players who reported sustaining a direct or indirect impact during games had similar measurements to those who did not, thus highlighting the difficulty of concussion recognition, at least with youth. Future research may need to establish the relationship between concussion-like symptoms in the absence of an impact and in relation to concussion evaluation assessments such as the King-Devick and SCAT5.

Key words: Australian Football, sports related concussion; biomechanics, head impacts.

Introduction

Australian football (AF) is a contact game (Orchard et al., 1998) with tackling and collisions between players and the ground (Hrysomallis et al., 2006; Orchard et al., 1998). These collisions have the potential to result in head impacts that may lead to sports-related concussion (SRC); a mild traumatic brain injury associated with a range of symptoms (McCrory et al., 2013; Pearce et al., 2015). In the 9 to 17-year-old group, the overall incidence rate of SRC in AF has been reported at 0.6 (95% CI: 0.2 to 1.0) per 1,000 Athlete Exposures (A-E) with the older group (ages 14-17) recording 0.8 (95% CI: 0.1 to 1.5) per 1,000 A-E (Hecimovich and King, 2017). The exact forces resulting in SRC remains unknown and has been reported to be more likely due to rotational acceleration of the brain (Hoshizaki and Brien, 2004). It is still uncertain where in the brain a concussion occurs, or the exact origin of the symptoms of acute concussion (Hynes and Dickey, 2006). It is now apparent that direct impact to the head is not required and a concussion can occur with a blow to the chest, for example, that causes a whiplash effect on the neck and brain (Hynes and Dickey, 2006). Whiplash of the neck and brain and the incidence of concussion frequently co-exist (Hynes and Dickey, 2006). What is also known is that the young brain is more susceptible to concussion than the adult brain and may require more time to recover (Baillargeon et al., 2012). Therefore, a better understanding of impact metrics may help the recognition and recovery of SRC.

The quantification of head impacts in sport has been documented in the literature using a variety of devices. For example, mouthguard or head-mounted sensors (XPatch; X2biosystems, USA) have documented head impacts in AF (Hecimovich et al., 2018), rugby union (King et al., 2015; 2016), and rugby league (King et al., 2017). These studies have enabled the development of analytical risk functions (Pellman et al., 2003; Rowson et al., 2011; 2012; 2013), concussion risk curves (Rowson et al., 2012), and risk weighted exposure metrics (Urban et al., 2013) further assisting in the identification of athletes at risk of SRC.

Hecimovich et al. (2018) measured the frequency, magnitude and distribution of head impacts in junior-league (aged 17-19) and senior-league (aged 20+) AF players, reporting that the resultant peak linear accelerations ranged from 10*g* to 158.8*g* with a median value of 15.3*g*. In the same study, the resultant peak rotational accelerations ranged from 2,996.6 to 1,286,748.6 deg/s^2 with a median value of 1,302,321.6 deg/s^2 (Hecimovich et al., 2018). There were no major differences observed between junior- and senior-league players, however there was only a small age gap between mean ± SD of cohorts (18.0 ± 0.7 yr. vs 21.0 ± 2.2 yr.).

Currently, there are no reported accelerations for AF players under the age of 17 yr. Therefore, the aims of this study were to: 1) Investigate the frequency, magnitude,

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and distribution of head impacts sustained by youth AF players on a single team over a season of games; and 2) compare the impact characteristics between players who self-reported sustaining a head impact during a game to those with no reported head impact.

Methods

A prospective observational cohort study was conducted on youth AF players on a single team competing during the 2017 competition season. All members of the team were invited to participate in the study. A total of 19 male youth AF players (age range 13-14 yr., mean ± SD 13.9 ± 0.3 yr.) were enrolled in the study. Consent was obtained from the players, parents and participating team before enrolling in the study. The researchers' University ethics committee approved all procedures (MUHREC 2016/012).

Over the course of the season (11 games) players were fitted with skin-mounted impact sensors to measure the impact frequency, magnitude and distribution of impacts and requested to respond to a post-game self-report logbook on recalling having a direct hit to their head with another player or striking their head to the ground.

Impact sensors and testing

All players enrolled in the study wore the XPatch impact-sensing skin patch (X2Biosystems Inc.) on the skin covering their right-side mastoid process for each game. The XPatch sensor, sampling at 1024 Hz, was placed behind the player's right ear just before participation in game activities and was removed immediately after completion of the game. The positioning of the XPatch over the mastoid process ensured that the sensor was not activated by enhanced soft-tissue effects when impacts occurred (Wu et al., 2016). The sensor contained a low-power, high-*g* triaxial accelerometer with 200*g* maximum per axis and a triaxial angular rate gyroscope to capture six degrees of freedom for linear and rotational time history accelerations of the heads center of gravity for all impacts that occurred during games. The time history incorporated three axes (x, y, z) of acceleration and velocity. While upright these planes describe the medial-lateral, anterior-posterior and vertical acceleration and deceleration. The Impact Management System (IMS) enabled the raw data to be transformed to the head center of gravity by using a rigid-body transformation for linear acceleration and a 5-point stencil for rotational acceleration (Wu et al., 2016). The biomechanical measures of head impact severity consisted of impact duration (ms), linear acceleration (*g*), and rotational head acceleration (deg/s^2). Resultant linear acceleration is the rate of change in velocity of the estimated center of gravity of the head attributable to an impact and the associated direction of motion of the head (Mihalik et al., 2010). Resultant rotational acceleration is the rate of change in rotational velocity of the head attributable to an impact, and its direction in a coordinate system with the origin at the estimated center of gravity of the head (Mihalik et al., 2010). False impacts were removed by the X2Biosystems proprietary 'de-clacking' algorithm (King et al., 2015). Impacts with a resultant linear acceleration of <10*g* were removed. The remaining impacts were downloaded and time-filtered to include only those impacts that occurred during match participation.

Head impact exposure including frequency, magnitude and location of impacts were quantified using previously established methods (Crisco et al., 2010; 2011). The impact variables were not normally distributed (Kolmogorov-Smirnov; $p < 0.001$). Two measures of impact frequency were computed for each player: *player impacts*, the total, median, 25th-75th interquartile range (IQR), and the 95th percentile of head impacts recorded for a player during all the matches observed, and *impacts per match*, the total, median [Interquartile Range (IQR)], and the 95th percentile of head impacts recorded for a player during all the matches observed.

Player head impacts exposure were assessed utilizing previously published levels for injury tolerance (linear >95 *g* and rotational acceleration >315,126.8 deg/s), impact (linear mild <66 *g*, moderate 66-106 *g*, severe >106 *g*) and rotational acceleration (mild <263,560.6 deg/s, moderate 263,560.6-452,636.7 deg/s, severe >452,636.7 deg/s) severity (Broglio et al., 2010; 2011a; Guskiewicz et al., 2007; Harpham et al., 2014; Ocwieja et al., 2012; Zhang et al., 2004). Two additional risk equations were included in the analysis of the head impact exposure data. The Head Impact Telemetry Severity profile (HIT_{SP}) (Greenwald et al., 2008) is weighted composite score including linear and rotational accelerations, impact duration, as well as impact location. The Risk Weighted Exposure Combined Probability (RWE_{CP}) (Urban et al., 2013) is a logistic regression equation and regression coefficient of injury risk prediction of an injury occurring based on previously published analytical risk functions. RWE_{CP} combines resultant linear and rotational accelerations to elucidate individual player and team-based head impact exposure. The HIT_{SP} and RWE_{CP} were analyzed by player-position impacts utilizing a Friedman repeated measures ANOVA on ranks. A Wilcoxon signed-rank test post-hoc analysis was conducted with a Bonferroni correction applied if any significant differences were observed.

Resultant peak linear (PRA[*g*]) and rotational (PLA[deg/s^2]) accelerations and impact locations (front, back, side and top) between player positions were assessed utilizing a Friedman repeated measures ANOVA on ranks. A post hoc analysis with a Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied if any significant differences were observed. A one sample chi-squared (χ^2) test and risk ratio (RR), with 95% confidence intervals (CI), were utilized to determine whether the observed impact frequency was significantly different from the expected impact frequency. Statistical significance was set at $p<0.05$.

Qualitative data (logbooks)

Over the course of the season, participants completed an individual post-game logbook (Figure 1). Items included written feedback responses on recalling having a direct hit to their head with another player (their head, knee, elbow etc) or striking their head to the ground. Further, the logbook listed nine common concussion signs and symptoms (Meehan et al., 2010) for participants to indicate if during, or after, the game the player experienced. The logbooks were collected after its completion during the first training session following the weekend game.

Impact analysis

Several steps were undertaken to exclude data identified as not representing on-field head impacts. First, the data contained on the XPatch were uploaded after each match onto the IMS provided by X2Biosystems. Next, the data were then downloaded and filtered through the IMS to remove any spurious linear acceleration that did not meet the proprietary algorithm for a head impact (Swartz et al., 2015). The data underwent a second filtering waveform parameter proprietary algorithm during data exporting to remove spurious linear acceleration data with additional layers of analysis (Swartz et al., 2015). This included the area under the curve, the number of points above threshold and filtered versus unfiltered peaks (Swartz et al., 2015). The remaining data were exported onto an Excel spreadsheet (version 2013; Microsoft Corporation, Redmond, WA) for visual examination. All data were reviewed and any impacts less than 10*g* were removed. The data on the spreadsheet were then adjusted to estimates of the Hybrid III headform criterion standard (Chrisman et al., 2016) and all impacts <10*g* were removed from the database following the completion of the adjusted calculations in line with previous results (Chrisman et al., 2016) that showed the XPatch over-estimates linear accelerations when compared with the centre of gravity of the headform criterion. Finally, a review was undertaken of all data to identify those impacts that occurred outside of the game times and these were removed. The resulting filtered data were analysed with SPSS V.25.0.0. (IBM Corp, Released 2017. IBM SPSS Statistics for Windows, Armonk, NY: IBM Corp).

Head impact location variables were computed as azimuth and elevation angles relative to the centre of gravity (CG) of the head centred on the mid-sagittal plane (Crisco et al., 2004; King et al., 2015; 2016). These were categorized as front, side, back and top. Impacts to the top of the head were defined as all impacts above an angle of 65° from a horizontal plane through the CG of the head (Greenwald et al., 2008). Additional analysis was undertaken to establish the RWE_{CP} (Urban et al., 2013) and HIT_{SP} (Greenwald et al., 2008). The RWE_{CP} is a logistic regression equation and regression coefficient of injury risk prediction of an injury occurring based on previously published analytical risk functions (Urban et al., 2013) and the HIT_{SP} is a weighted composite score including linear and rotational accelerations, impact duration, and impact location (Greenwald et al., 2008). The RWE_{CP} combines the linear and rotational accelerations to elucidate individual player and team-based exposure to head impacts

The data were further categorized into magnitude groups (Lynall et al., 2016) for linear (*g*) (10-19.9; 20-29.9; 30-39.9; 40+), rotational (deg/s^2) (<143,182; 143,239-426,661; 429,718-716,140; 716,197+), and RWE_{CP} (<0.2499; 0.2500-0.4999; 0.5000-0.7499; 0.7500+). As a value of 63 is a 75% indicator for a concussive injury (Broglio et al., 2011b; Greenwald et al., 2008) the HIT_{SP} values were evaluated by risk (< 21, 21-42, 43-63, >63). These were undertaken to provide greater information regarding the impact frequency of varying degrees of peak linear and rotational acceleration, severity profile and risk weighted exposure.

Upon visual inspection, the impact magnitudes were found to be positively skewed for PLA(*g*), PRA(deg/s^2), HIT_{SP} and RWE_{CP}. To control for this violation of normality the PLA(*g*), PRA(deg/s^2), HIT_{SP} and RWE_{CP} data were natural log transformed before analysis. Note, that for interpretability all magnitude results the data are presented in their original untransformed units. A one-way ANOVA test with a Tukey post-hoc test was used to test whether there were differences in the PLA(*g*),

Player ID # ___________________________
Todays' date: _____________________

1. Did you have a game on the weekend?
   Yes No
2. What is your primary position? _______________________
3. Do you recall having a direct hit to your head with another player (their head, knee, elbow etc) or did you strike your head to the ground?
   Yes No

   If yes, please explain

4. During or after the game did you experience any of the following (please circle)
   a. Headache
   b. Feel dizzy, sluggish or foggy
   c. Bothered by light or noise
   d. Have double or blurry vision
   e. Vomit or feel sick to your stomach
   f. Have trouble focusing or problems remembering
   g. Feel more emotional or "down"
   h. Feel confused
   i. Have problems with sleep

   If you answered yes to any of these can please provide a brief explanation

5. Did you sustain any injury to your body? If so please write down what is was

Figure 1. Logbook.

Table 1. Impacts to the head greater than 10g in youth Australian Football players for total impacts recorded, injured players and non-injured players by resultant peak and linear and rotational accelerations, head impact telemetry severity profile, risk weighted exposure combined (linear and rotational) probability for number of impacts recorded, impact duration and impact magnitude. Data are presented as mean (± standard deviation) and median [25th to 75th interquartile range].

		Impact to the head		Impact Duration (ms)	Peak Linear Acceleration (PLA(*g*))		Peak Rotational Acceleration (PRA(deg/s^2))		Head Impact Telemetry severity profile (HIT$_{SP}$)		Risk Weighted Exposure combined probability (RWE$_{CP}$)	
		Per Match	Per-player per match									
	n (%)	Mean ±SD	Mean ±SD	Mean ±SD	Median [IQR]	95%	Median [IQR]	95%	Median [IQR]	95%	Median [IQR]	95%
Total	453 (100)	41±30	5.3 ±4.8	10.0 ±7.7	15.2 [11.8-3.6]	45.8	183,152[104,307-288,828]	594,272	15.1 [12.4-21.6]	46.1	.0012 [.0003-.0083]	.71
Injured	26 (5.7)^b	3.8 ±2.9	3.8 ±2.9	9.3±6.7^b	13.5 [12.0-8.4]^b	49.9	164,851 [123,175-226,032]	519,593	13.8 [11.6-17.5]	58.6	.0013 [.0006-.0053]	.19
Non-Injured	427 (94.3)^a	39 ±29	5.1 ±4.3	10.1±7.8^a	15.4 [11.7-23.7]^a	45.8	182,613[98,260-293,131]	612,939	15.1 [12.3-21.9]	47.0	.0012 [.0003-.0093]	.75

SD = Standard Deviation; ms = milliseconds; IQR = interquartile [25th-75th] percentile; 95th = 95th percentile; Significant difference ($p < 0.05$) than (a) = Injured; (b) = Non-Injured

PRA(deg/s^2), HIT$_{SP}$ and RWE$_{CP}$ between players who reported a head impact and those players who did not report a head impact. A post hoc *t*-test was utilized for any significant ANOVA result. Impact durations were assessed using a paired-sample *t*-test. A one sample chi-squared (χ^2) test were used to determine whether the observed impact frequency was significantly different from the expected impact frequency. Statistical significance was set at $p < 0.05$. Cohen's effect size (*d*) were utilised to calculate practically meaningful differences. Effect sizes of <0.19, 0.20-0.60, 0.61-1.20 and >1.20 were considered trivial, small, moderate, and large, respectively (Hopkins et al., 2009).

Logbook analysis

Individual logbook entries were placed into two group, 1) the 'yes' group comprised participants reporting a direct hit to their head with another player or striking their head to the ground, and 2) the 'no' group comprised participants reporting no direct hit to their head with another player or striking their head to the ground. Responses on symptoms experienced and mechanism of injury were not analyzed and used for this manuscript.

Results

Collective impacts

Over the 11 rounds there were 453 impacts recorded resulting in an average of 41 ±30 impacts per-game resulting in an average of 5 ±4 impacts per-player per-game (Table 1). Players (n=12) who self-reported having sustained a head impact during a game recorded PLA(g) of 13.5 [12.0 to 18.4]g, PRA(deg/s^2) of 164,851 [123,175 to 226,032] deg/s, HIT$_{SP}$ 13.8 [11.6-17.5] and RWE$_{CP}$ of 0.0013 [0.0006 to 0.0053]. Players reporting a head impact had a faster mean impact duration ($t_{(25)} = 2.4$; $p = 0.0025$) but a lower median PLA(g) ($F_{(23,2)} = 845.5$; $p = 0.0012$) when compared with those players who did not report a head impact.

The side of the head (44.4%) sustained more impacts than the back (25.8%), top (5.1%) or front (24.7%) of the head (see Table 2). The front of the head recorded a higher median resultant PLA(g) (17.9 [13.6-25.9] g) than the side ($F_{(93,18)} = 5.1$; $p = 0.0001$; $t_{(111)} = 13.2$; $p < 0.0001$) and top ($F_{(15,7)} = 74.4$; $p < 0.0001$; $t_{(22)} = -6.1$; $p < 0.0001$) of the head. Interestingly the front of the head recorded a lower RWE$_{CP}$ to the front of the head than the back ($F_{(76,35)} = 4.8$; $p = 0.0001$; $t_{(111)} = 2.1$; $p = 0.0349$) and side ($F_{(76,35)} = 2.2$; $p = 0.0057$; $t_{(111)} = 10.5$; $p < 0.0001$) of the head.

Tables 3 and 4 report the differences in the magnitudes by PLA(g), PRA(deg/s^2), HIT$_{SP}$ and RWE$_{CP}$ for those players who reported a head impact and those who did not. Although there were notable differences in median impact duration at the HIT$_{SP}$ less than 21 ($t_{(22)} = 2.8$; $p = 0.0106$) and the RWE$_{CP}$ at the less than <0.2500 ($t_{(24)} = 3.5$; $p = 0.0017$) there were no other notable differences observed when comparing the other different magnitudes.

Logbooks

Over the course of the season, 12 participants reported having experienced either a direct or indirect hit to their head in one or more games with all of them reporting at least one symptom.

Discussion

To the authors knowledge this is the first study to measure the frequency, magnitude, and distribution of head impacts sustained by youth AF players over a season of games.

Table 2. **Impacts to the head greater than 10*g* in youth Australian Football players by impact location for resultant peak linear and rotational accelerations, head impact telemetry severity profile and risk weighted exposure combined (linear and rotational) probability for number of impacts recorded, impact duration and impact magnitude. Data are presented as mean (± standard deviation) and median [25th to 75th interquartile range].**

Impact Location		Impact to the head	Impact Duration (ms)	Peak Linear Acceleration (PLA(*g*))		Peak Rotational Acceleration (PRA(deg/s^2))		Head Impact Telemetry severity profile (HIT_{SP})		Risk Weighted Exposure combined probability (RWE_{CP})	
		N = (%)	Mean ±SD	Median [IQR]	95%	Median [IQR]	95%	Median [IQR]	95%	Median [IQR]	95%
Total	Front	112 (24.7)	11.0 ±7.5^{bcd}	17.9 [13.6-25.9]^{cd}	46.3	220,635 [141,624-360,729]	664,929	17.2 [13.6-23.3]^{c}	48.7	.0003 [.0006-.0180]^{bc}	.82
	Back	117 (25.8)	8.5 ±6.2^{ad}	14.6 [11.4-24.9]^{cd}	48.6	192,909 [77,229-313,877.7]	889,294	14.1 [11.4-22.2]^{c}	46.5	.0014 [.0002-.0166]^{a}	.93
	Side	201 (44.4)	10.2 ±8.4^{a}	14.2 [11.6-22.6]^{abd}	44.1	155,650 [86,557-242,642]	514,356	14.2 [12.3-20.1]^{ab}	49.8	.0007 [.0002-.0038]^{a}	.31
	Top	23 (5.1)	11.5±9.1^{ab}	14.1 [13.1-19.1]^{abc}	40.8	206,053 [122,017-315,648]	600,477	14.3 [13.3-19.7]	46.4	.0015 [.0005-.0112]	.53
Injured	Front	8 (30.8	11.1 ±9.7	15.3 [11.1-18.4	-	151,926 [131,924-201,292]	-	14.5 [11.3-16.4]	-	.0006 [.0006-.0016]	-
	Back	6 (23.1)	4.8 ±3.1	12.4 [12.1-13.4]	-	222,606 [211,341-272,682]	-	12.6 [11.3-13.9]	-	.0019 [.0014-.0046]	-
	Side	10 (38.5)	10.3 ±5.3	15.4 [12.3-25.1]	-	166,261 [82,552-346,628]	-	13.8 [12.1-23.7]	-	.0009 [.0003-.0097]	-
	Top	2 (7.7)	9.0 ±5.7	15.0 [14.2-15.9]	-	350,198 [278,125-422,270]	-	17.5 [15.9-19.1]	-	.0565 [.0290-.0840]	-
Non-Injured	Front	104 (24.4)	11.0 ±7.3^{bcd}	18.4 [13.7-26.9]^{bcd}	45.9	226,846 [144,723-368,859]	669,186	17.5 [13.7-25.1]^{bc}	49.8	.0032 [.0006-.0224]^{bc}	.83
	Back	111 (26.0)	8.7 ±6.2^{ad}	15.1 [11.3-26.0]^{acd}	49.2	184,664 [76,152-328,884]	739,763	14.6 [11.4-22.3]^{ac}	47.9	.0012 [.0002-.0168]^{a}	.92
	Side	191 (44.7)	10.2 ±8.5^{ad}	14.2 [11.6-22.1]^{adb}	43.3	155,174 [87,496-242,132]	500,502	14.2 [12.3-20.0]^{ab}	47.6	.0007 [.0002-.0037]^{ad}	.44
	Top	21 (4.9)	11.7 ±9.4^{abc}	14.1 [13.0-19.9]^{abc}	41.5	201,171 [118,608-303,324]	621,762	14.3 [13.3-18.7]	47.9	.0014 [.0005-.0082]^{c}	.55

SD = Standard Deviation; ms = milliseconds; IQR = interquartile [25th-75th] percentile; 95th = 95th percentile; Significant difference ($p < 0.05$) than (a) = Front, (b) = Back; (c) = Side; (d) = Top

Furthermore, this study compared the impact characteristics between players who reported sustaining a head impact during the course of a game to those who did not.

The frequency, magnitude, and distribution of head impacts were recently reported by Hecimovich et al. (2018) at the junior-level (aged 17-19) and senior-level (aged 20+) AF level. Although comparison of impact data from study to study can be difficult due to the different thresholds utilised in recording an impact, and the different sporting activities involved (King et al., 2017), the Hecimovich et al. (2018) study used the same equipment and analysis as the current study. In that study (Hecimovich et al, 2018), players sustained similar impacts per-player per-game (junior, 7 ±9 [d = 0.287]; senior, 8 ±7 [d = 0.526]) to those of the current study (5 ±4). The PLA(*g*) median and 95th percentiles in the current study (15.2*g*; 45.8*g*) are also similar to the aforementioned study (Hecimovich et al., 2018) with junior-league players experiencing 15.1*g* (d = 0.038) and 45.7*g*, and senior-league players at 15.7*g* (d = 0.057) and 46.8*g*, respectively. The median and 95th percentile PRA(deg/s^2) in the current study (183,117 deg/s^2; 594,272 deg/s^2) and those from the Hecimovich et al. (2018) study revealed junior- (157,048 deg/s^2 (d = 0.003); 552,560 deg/s^2) and senior-league (157,964 deg/s^2 [d = 0.001]; 547,518 deg/s^2) players sustaining similar levels. The linear and rotational totals across the age groups resulted in similar median and 95th percentile HIT_{SP} (15.3, 46.8 for junior; 15.4 [d = 0.000], 39 for senior; 15.1 [d = 0.016], 46.1 for youth) and slightly higher RWE_{CP} for the youth players (0.0012, 0.7062) in comparison to junior- (0.0008 [d = 0.002]; 0.3969) and senior-league (0.0008 [d = 0.003]; 0.3862) players. As can be seen, the effect size in all the head impact kinematics between the current study (age 13-14), and the aforementioned study (Hecimovich et al., 2018) were trivial indicating that they were all recording similar head impact kinematics despite recording fewer impacts to the head as a result of participating in AF.

The comparison results show that the youth players are sustaining similar impact levels to older players. This is problematic and can potentially place the younger cohort at an increased risk of SRC, as the developing brain is more vulnerable to the effects of widespread damage associated with traumatic brain injury (Levin et al., 2001). This is further enhanced because children have less developed neck and shoulder musculature (Ommaya et al., 2002; Vopat and Micheli, 2015). Although the participants in this study would be less effected, younger players (< aged 10) are at even greater risk due to them having an increased head-to-body ratio compared with adults (Ommaya et al., 2002; Vopat and Micheli, 2015) that may result in a higher centre of gravity, and greater head momentum (Vopat and Micheli, 2015). Consequently, children are less able to dissipate impact forces that occur from game participation with lesser forces required to cause similar concussive injuries in smaller brains than larger brains with greater mass (Goldsmith et al., 2004; Ommaya et al, 2002). Crucially, this leads to signs and symptoms of concussion reported in children resulting from equal or lesser impact forces than if an adult presents with similar signs and symptoms of a concussive injury (Meehan et al., 2011).

The comparable levels, and notably the RWE_{CP}, across youth, junior and senior players may justify increased efforts for safety at the youth level with attention to SRC. The Australian Football League (AFL) has been proactive in SRC and first developed its community-AF concussion guidelines in 2011 based on the 2008 International Consensus Statement on Concussion in Sport (McCrory et al., 2009). However, the results of the current study indicate that current guidelines on appropriate medical cover for AF do not reflect the risks seen in previous, and this research on SRC, where senior games have higher levels of medical cover than youth levels. The key to community-based concussion programs may be greater awareness of concussion as this is an essential step in increasing the number of athletes or parents who report on concussion and proper clinical assessment and management (Yang et al., 2008). This awareness is important in youth sports such as AF where medical care at games and training may be limited. In this circumstance, aside from the coach, it is the player and their parent who need to aware of any head impacts that occurred during a game and possible signs and symptoms of concussion (Hecimovich et al., 2016). Therefore, an increased player and parent awareness is an important step toward progress in this area (McCrory et al., 2009).

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Table 3. Impacts to the head greater than 10*g* in youth Australian Football players for magnitude groups and impact location for resultant peak linear and rotational accelerations, for number of impacts recorded, impact duration and impact magnitude. Data are presented as mean (± standard deviation) and median [25^{th} to 75^{th} interquartile range].

		Players not reporting a notable head impact						Players reporting a notable head impact					
			Impact Duration (ms)	Peak Linear Acceleration (PLA(*g*))		Peak Rotational Acceleration (PRA(deg/ s^2))			Impact Duration (ms)	Peak Linear Acceleration (PLA(*g*))		Peak Rotational Acceleration (PRA(deg/ s^2))	
		n (%)	Mean ±SD	Median [IQR]	95th	Median [IQR]	95th	n (%)	Mean ±SD	Median [IQR]	95th	Median [IQR]	95th
PLA(*g*)	10.0-19.9	302 (66.7)	13.6 ±2.3	12.9 [11.0-15.3]	19.2	131,156 [77,739-195,780]	288,198	21 (80.8)	9.2 ±6.9	12.7 [11.5-16.5]	19.7	158,979 [123,524-202,535]	482,706
	20.0-29.9	76 (16.8)	13.0 ±6.3	23.7 [21.5-26.0]	29.3	307,403 [235,434-394,894]	643,260	4 (15.4)	14.8 ±4.1	21.8 [21.6-25.8]	-	230,306 [129,357-479,778]	-
	30.0-39.9	42 (9.3)	17.0 ±6.9	33.8 [32.4-36.3]	39.2	372,211 [253,093-498,995]	821,965	-	-	-	-	-	-
	40+	33 (7.3)	17.3 ±8.6	49.4 [43.0-64.2]	113.6	539,205 [398,481-694,505]	902,930	1 (3.8)	10-	62.8	-	220,503	-
PRA (deg/s^2)	<143,182	175 (38.6)	12.7 ±2.5	11.7 [10.5-13.8]	19.6	83,795 [59,095-116,517]	138,226	7 (26.9)	8.3 ±6.6	11.7 [10.9-20.7]	-	100,170 [52,231-118,364]	-
	143,239-429,661	225 (49.7)	10.7 ±6.2	18.0 [13.7-24.4]	37.3	231,538 [188,263-298041]	391,726	17 (65.4)	9.2 ±7.6	13.6 [12.1-17.7]	59.8	186,400 [147,474-231,567]	373,282
	429,718-716,140	40 (8.8)	16.8 ±8.3	37.8 [27.8-48.9]	106.5	539,033 [481,113-605,250]	698,974	2 (7.7)	12.5 ±0.7	20.5	-	454,189	-
	716,197+	13 (2.9)	17.0 ±8.9	37.8 [28.0-54.8]	-	846,219 [775,716-910.969]	-	0	-	-	-	-	-
HIT_{SP}	<21	333 (73.5)	7.8 ±6.5	13.3 [11.1-16.7]	21.6	140,610 [81,744-209,519]	323,228	23 (88.5)	9.4 ±6.9	13.2 [11.7-17.0]	24.9	154,750 [118,637-199,607]	471,063
	21-43	92 (20.3)	15.0 ±6.6	30.3 [25.2-34.8]	44.9	350,272 [264,827-469,338]	776,879	2 (7.7)	16.0 ±5.7	24.8	-	376,932	-
	43-63	19 (4.2)	20.7 ±8.3	47.3 [40.5-54.5]	62.1	661,199 [459,163-709,958]	895,894	-	-	-	-	-	-
	>63	9 (2.0)	20.4 ±9.4	81.6 [66.0-109.3]	-	584,670 [463,523-768,783]	-	1 (3.8)	10-	62.8	-	220,503	-
RWE_{CP}	<.2499	414 (91.4)	9.3 ±7.2[b]	14.2 [11.6-20.3]	35.8	163,883 [93,770-258,983]	398,051	26 (100)	9.3 ±7.0[a]	13.5 [12.0-18.4]	49.9	164,851 [123,175-226,032]	519,593
	.2500-.4999	12 (2.6)	17.5 ±8.4	37.0 [28.1-40.5]	-	552,939 [536,873-564,398]	-	-	-	-	-	-	-
	.5000-.7499	7 (1.5)	19.8 ±8.3	35.1 [32.2-87.1]	-	612,108 [517,994-634,648]	-	-	-	-	-	-	-
	.7500+	21 (4.6)	17.7 ±9.1	48.5 [34.2-63.3]	116.4	765,357 [668,298-868,335]	1,228,055	-	-	-	-	-	-

SD = Standard Deviation; ms = milliseconds; IQR = interquartile [25^{th}-75^{th}] percentile; 95^{th} = 95^{th} percentile; Significant difference ($p < 0.05$) than (a) = Injured; (b) = Non-Injured

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A total of 12 players reported sustaining an impact to the head, either direct or indirect, at least once during the season. The data from these players during those particular games was established. Interestingly, those players who reported sustaining an impact recorded a lower resultant median PLA(g), PRA(deg/s^2) and HITSP. Furthermore, they recorded a higher percentage (80% to 66%) of impacts at the 10-19.9g for peak linear acceleration, HITSP and RWECP. However, the differences between the two groups is not significant, notwithstanding the faster mean impact duration ($p = 0.0025$) for the impact group that also had lower median PLA(g) ($p = 0.0012$). All players who reported sustaining an impact to the head also reported experiencing at least one of the symptoms listed on the logbook despite experiencing very little differences in head impact characteristics. The reliance on concussion symptoms reported by players is questionable as the nature of concussion is a functional, more so than a structural, injury (Broglio et al., 2011b). Furthermore, concussion probably depends upon many intrinsic factors, which may vary more between individuals than do the type and magnitude of forces experienced by the brain, and may further explain the lack of relationship between biomechanical factors and clinical outcomes (Broglio et al., 2011b).

Table 4. Impacts to the head greater than 10*g* in youth Australian Football players by magnitude groups and impact location for head impact telemetry severity profile and risk weighted exposure combined (linear and rotational) probability for number of impacts recorded, impact duration and impact magnitude. Data are presented as mean (± standard deviation) and median [25th to 75th interquartile range].

		Players not reporting a notable head impact						Players reporting a notable head impact					
			Impact Duration (ms)	Head Impact Telemetry severity profile (HIT_{SP})		Risk Weighted Exposure combined probability (RWE_{CP})			Impact Duration (ms)	Head Impact Telemetry severity profile (HIT_{SP})		Risk Weighted Exposure combined probability (RWE_{CP})	
		n (%)	Mean ±SD	Median [IQR]	95th	Median [IQR]	95th	n (%)	Mean ±SD	Median [IQR]	95th	Median [IQR]	95th
PLA(*g*)	10.0-19.9	302 (66.7)	13.6 ±2.3[b]	13.2 [11.7-15.2]	18.1	.005 [.0002-.0013]	.006	21 (80.8)	9.2 ±6.9[a]	13.1 [10.9-14.9]	20.5	.0012 [.0005-.0026]	.102
	20.0-29.9	76 (16.8)	13.0 ±6.3	21.7 [19.7-24.5]	28.3	.0108 [.0032-.0374]	.615	4 (15.4)	14.8 ±4.1	22.5 [17.9-25.6]	-	.0067 [.0007-.1726]	-
	30.0-39.9	42 (9.3)	17.0 ±6.9	30.8 [26.7-36.3]	43.8	.0413 [.0064-.1995]	.965	0	-	-	-	-	-
	40+	33 (7.3)	17.3 ±8.6	51.4 [42.0-72.1]	133.7	.6795[.1346-.9058]	.997	1 (3.8)	10-	76.3		0	
PRA (deg/s^2)	<143,182	175 (38.6)	12.7 ±2.5	11.9 [11.2-13.4]	16.3	.0002 [.002-.0004]	.0006	7 (26.9)	8.3 ±6.6	11.7 [10.0-17.1]	-	.0003 [.0002-.0006]	-
	143,239-429,661	225 (49.7)	10.7 ±6.2	17.3 [14.4-22.0]	34.7	.0030[.0012-.0107]	.0456	17 (65.4)	9.2 ±7.6	14.1 [12.0-15.8]	64.6	.0015 [.0008-.0053]	.019
	429,718-716,140	40 (8.8)	16.8 ±8.3	38.7 [27.1-51.8]	98.6	.3461 [.2043-.7210]	.918	2 (7.7)	12.5 ±.7	23.3	-	.1687	-
	716,197+	13 (2.9)	17.0 ±8.9	44.9 [33.0-60.2]	-	.9814 [.9250-.9967]	-	0	-	-	-	-	-
HIT_{SP}	<21	333 (73.5)	7.8 ±6.5	13.5 [11.9-15.9][b]	19.4	.0006 [.0002-.0018]	.011	23 (88.5)	9.4 ±6.9	13.2 [11.0-15.4][a]	20.6	.0009 [.0006-.0022]	.093
	21-43	92 (20.3)	15.0 ±6.6	27.0 [23.1-31.4]	39.8	.0254 [.0080-.1232]	.922	2 (7.7)	16.0 ±5.7	25.4	-	.1193	-
	43-63	19 (4.2)	20.7 ±8.3	51.1 [46.0-54.4]	63.3	.7890 [.2232-.9210]	.990	0	-	-	-	-	-
	>63	9 (2.0)	20.4 ±9.4	93.0 [76.1-111.5]	-	.7890 [.6795-.9318]	-	1 (3.8)	10-	76.3	-	.0192	-
RWE_{CP}	<.2499	414 (91.4)	9.3 ±7.2[b]	14.4 [12.3-18.8]	31.5	.0009 [.0003-.0045]	.048	26 (100)	9.3 ±7.0[a]	13.8 [11.5-17.5]	58.7	.0013 [.0006-.0053	
	.2500-.4999	12 (2.6)	17.5 ±8.4	35.2 [27.5-43.8	-	.3461 [.3065-.3908]	-	-	-	-	-	-	-
	.5000-.7499	7 (1.5)	19.8 ±8.3	37.8 [31.1-84.7]	-	.6287 [.5690-.7117]	-	-	-	-	-	-	-
	.7500+	21 (4.6)	17.7 ±9.1	52.0 [37.6-69.2]	152.7	.9210 [.8408-.9904]	.999	-	-	-	-	-	-

SD = Standard Deviation; ms = milliseconds; IQR = interquartile [25th-75th] percentile; 95th = 95th percentile; Significant difference ($p<0.05$) than (a) = Injured; (b) = Non-Injured

Therefore, the results of this study highlight the difficulty of concussion recognition, at least with youth and reported symptoms, thus supporting the need for evaluation tests such as the King-Devick and the Sport Concussion Assessment Tool (SCAT). Future studies may want to include head injury incidence; head impact frequency; acceleration magnitude; impact location, signs and symptoms and concussion assessment evaluations.

Limitations

A health care provider was not present at the games, therefore concussion evaluations were not conducted and the two groups were established based on self-report incidences without a clear diagnosis of SRC. A further limitation to this study was not having multi-angled video footage of the game to enable correlation between the head impacts recorded and physical contacts that occurred during game participation. As such, it was not established whether the impacts were from body contact or from contact with the ground and hence, the results must be interpreted accordingly. Future head impact studies should use high quality multiple angled cameras in an elevated position to enable verification of the impacts recorded.

The XPatch has been reported to have several noteworthy limitations. The risk of device malfunction, premature battery discharge and time stamp malfunction can lead to some degree of data loss (Eckner, et al., 2018). No XPatch sensors utilised in this study were identified to have had a malfunction but the possibility does exist and thus poses a limitation on the data reported. Moreover, the accuracy of the linear and rotational acceleration measurements has been reported to vary widely under different testing environments (Nevins et al., 2015; Siegmund et al., 2015; Wu et al., 2016). The PRA was found to underestimate in a study utilising a non-helmeted anthropometric test device but, when utilising cadaveric model with a helmet, it was reported that the XPatch overestimated PLA(g) and PRA(deg/s^2) when compared with a reference device mounted at the foramen magnum (Siegmund et al., 2015). In addition, the cadaveric model also reported a significant difference in impact location between the XPatch and the reference sensor for forehead impacts but when tested on side and rear impacts the agreement was better (Siegmund et al., 2015). As the XPatch is adhered to the side of the head over the mastoid process there is the potential problem of dermal artifact that can occur with imperfect coupling between the skin patches and the skull causing inaccuracy (Wu et al., 2016). As well there may have been some measurement error resulting from relative motion between the skin at the mastoid process and the skull which may have amplified the resultant head impact accelerations.

Another concern that has been reported for the XPatch is the proprietary algorithm utilised to remove errant events from the recorded data set. If these erroneous events are not appropriately identified and removed this can lead to an elevated false-positive rate for the XPatch dataset (Cortes et al., 2017; Press and Rowson, 2017). As the XPatch do not have the ability to detect when they are worn by the athlete there is the risk that the algorithm may include false-positive impacts in the data set recorded from any time the device is turned on until they are switched off (Eckner, et al., 2018). Conversely, there is the potential for the algorithm to identify valid impacts as false negative and exclude these from the data set (Eckner, et al., 2018). The classification of false-positive and false-negative impacts has the potential to influence impact counts and impact magnitude calculations, especially if the rate of false-positive and/or false-negative rates vary over the range of impact magnitudes (Eckner, et al., 2018). As a result, the number of impacts, impact magnitudes and impact locations reported in this study may vary when compared with studies recorded by other impact-sensing devices (Eckner, et al., 2018). Therefore the results of this study should be interpreted cautiously. In an endeavour to reduce the risk of false-positive impacts, all the XPatches were calibrated to the correct time and following the downloading of the dataset, these were manually reviewed and any impacts outside of the game start and stop times were removed from the data set.

Conclusion

This study established the frequency, magnitude, and distribution of head impacts sustained by youth AF players over a season of games. The results showed similar measurements to players in the older junior- (aged 17-19) and senior-leagues (20+). Furthermore, players who reported sustaining a direct or indirect impact during a games had similar measurements to those who did not, thus highlighting the difficulty of concussion recognition, at least with youth. Future research may need to establish the relationship between concussion-like symptoms in the absence of an impact and in relation to concussion evaluation assessments such as the King-Devick and the SCAT.

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Key points

- 13- 14 year old Australian Football players experience approximately 5 head impacts per-player per-game.
- The magnitude, peak linear rotation and peak rotational acceleration of these head impacts are comparable to those of Australian football players 17 years and older.
- Given the age of these players this study highlights the need for increased awareness of head impacts and concussion in youth, community level Australian football

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