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

Mark Hecimovich 1,2,*, Doug King 3,4, Alasdair Dempsey 2, Mason Gittins 2 and Myles Murphy 5,6,7

1 Division of Athletic Training, University of Northern Iowa, Cedar Falls, Iowa, USA; 2 School of Psychology and Exercise Science, Murdoch University, Murdoch, Western Australia, Australia; 3 School of Psychology and Exercise Science Murdoch University, Murdoch, Western Australia, Australia; 4 Department of Science and Technology, University of New England, Sydney, Australia; 5 School of Physiotherapy, The University of Notre Dame Australia, Fremantle, Australia; 6 SportsMed Subiaco, St John of God Health Care, Subiaco, Australia; 7 Sports Science Sports Medicine Department, The Western Australian Cricket Association, East Perth, Australia

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 15.2g (45.8g). The median (95th percentile) peak rotational acceleration (PRA) were 183,117 deg/s² (594,272 deg/s²). 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) 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 (McCrorry 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 (Pullman 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 10g to 158.8g with a median value of 15.3g. In the same study, the resultant peak rotational accelerations ranged from 2,996.6 to 1,286,748.6 deg/s² with a median value of 1,302,321.6 deg/s² (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,
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 200g maximum per axis and a triaxial angular rate gyroscope to capture six degrees of freedom for linear and rotational time history accelerations of the head's 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/s²). 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 <10g 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 (HITSP) (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 (RWECP) (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. RWECP combines resultant linear and rotational accelerations to elucidate individual player and team-based head impact exposure. The HITSP and RWECP 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/s²)) 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 (χ²) 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 10g 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 <10g 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 RWECP (Urban et al., 2013) and HITSP (Greenwald et al., 2008). The RWECP 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 HITSP is a weighted composite score including linear and rotational accelerations, impact duration, and impact location (Greenwald et al., 2008). The RWECP 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/s²) (<143,182; 143,239-426,661; 429,718-716,140; 716,197+), and RWECP (<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 HITSP 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/s²), HITSP and RWECP. To control for this violation of normality the PLA(g), PRA(deg/s²), HITSP and RWECP 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),

![Figure 1. Logbook.](image-url)
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].

<table>
<thead>
<tr>
<th>Impact to the head</th>
<th>Per Match</th>
<th>Per-player per match</th>
<th>Impact Duration (ms)</th>
<th>Peak Linear Acceleration (PLA(g))</th>
<th>Peak Rotational Acceleration (PRA(deg/s²))</th>
<th>Head Impact Telemetry severity profile (HITSP)</th>
<th>Risk Weighted Exposure combined probability (RWECP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n (%)</td>
<td>Mean ±SD</td>
<td>Mean ±SD Median [IQR] 95%</td>
<td>95% Median [IQR] 95%</td>
<td>95% Median [IQR] 95%</td>
<td>95% Median [IQR] 95%</td>
<td>95% Median [IQR] 95%</td>
</tr>
<tr>
<td>Non-Injured</td>
<td>427 (94.3)a</td>
<td>39 ±29</td>
<td>5.1 ±4.3</td>
<td>10.1±7.8a</td>
<td>15.4 [11.7-23.7]</td>
<td>45.8</td>
<td>182,613 [98,260-293,131]</td>
</tr>
</tbody>
</table>

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/s²), HITSP and RWECP 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 (χ²) 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/s²) of 164,851 [123,175 to 226,032] deg/s, HITSP 13.8 [11.6-17.5] and RWECP of 0.0013 [0.0006 to 0.0053]. Players reporting a head impact had a faster mean impact duration (t(22) = 2.4; p = 0.0025) but a lower median PLA(g) (F(21,2) = 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 RWECP 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/s²), HITSP and RWECP for those players who reported a head impact and those who did not. Although there were notable differences in median impact duration at the HITSP less than 21 (t(22) = 2.8; p = 0.0106) and the RWECP 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 10g 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].

<table>
<thead>
<tr>
<th>Impact Location</th>
<th>Impact to the head</th>
<th>Peak Linear Acceleration (PLA(g))</th>
<th>Peak Rotational Acceleration (PRA(deg/s²))</th>
<th>Head Impact Telemetry</th>
<th>Risk Weighted Exposure combined probability (RWEcp)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (%)</td>
<td>Mean ±SD</td>
<td>Median [IQR]</td>
<td>95% Median [IQR]</td>
<td>95% Median [IQR]</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td>112 (24.7)</td>
<td>11.0 ±7.5&lt;sup&gt;bd&lt;/sup&gt;</td>
<td>17.9 [13.6-25.9]&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>46.3</td>
<td>220,635 [141,624-360,729]</td>
</tr>
<tr>
<td>Back</td>
<td>117 (25.8)</td>
<td>8.5 ±6.2&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>14.6 [11.4-24.9]&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>48.6</td>
<td>192,909 [77,229-313,877]</td>
</tr>
<tr>
<td>Side</td>
<td>201 (44.4)</td>
<td>10.2 ±8.4&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>14.2 [11.6-22.6]&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>44.1</td>
<td>155,650 [86,557-242,642]</td>
</tr>
<tr>
<td>Top</td>
<td>23 (5.1)</td>
<td>11.5±9.1&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>14.1 [13.1-19.1]&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>40.8</td>
<td>206,053 [122,017-315,648]</td>
</tr>
<tr>
<td><strong>Injured</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side</td>
<td>10 (38.5)</td>
<td>10.3±5.3</td>
<td>15.4 [12.3-25.1]</td>
<td>-</td>
<td>166,261 [82,552-346,628]</td>
</tr>
<tr>
<td>Top</td>
<td>2 (7.7)</td>
<td>9.0±5.7</td>
<td>15.0 [14.2-15.9]</td>
<td>-</td>
<td>350,198 [278,125-422,270]</td>
</tr>
<tr>
<td><strong>Non-Injured</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td>104 (24.4)</td>
<td>11.0±7.3&lt;sup&gt;bd&lt;/sup&gt;</td>
<td>18.4 [13.7-26.9]&lt;sup&gt;bd&lt;/sup&gt;</td>
<td>45.9</td>
<td>226,846 [144,723-368,859]</td>
</tr>
<tr>
<td>Back</td>
<td>111 (26.0)</td>
<td>8.7±6.2&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>15.1 [11.3-26.0]&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>49.2</td>
<td>184,664 [76,152-328,884]</td>
</tr>
<tr>
<td>Side</td>
<td>191 (44.7)</td>
<td>10.2±8.5&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>14.2 [11.6-22.1]&lt;sup&gt;ad&lt;/sup&gt;</td>
<td>43.3</td>
<td>155,174 [87,496-242,132]</td>
</tr>
<tr>
<td>Top</td>
<td>21 (4.9)</td>
<td>11.7±4.9&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>14.1 [13.0-19.9]&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>41.5</td>
<td>201,171 [118,608-303,324]</td>
</tr>
</tbody>
</table>

SD = Standard Deviation; ms = milliseconds; IQR = interquartile [25th-75th] percentile; 95<sup>th</sup> 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 95<sup>th</sup> percentiles in the current study (15.2g; 45.8g) are also similar to the aforementioned study (Hecimovich et al., 2018) with junior-league players experiencing 15.1g (d = 0.038) and 45.7g, and senior-league players at 15.7g (d = 0.057) and 46.8g, respectively. The median and 95<sup>th</sup> percentile PRA(deg/s²) in the current study (183,117 deg/s²; 594,272 deg/s²) and those from the Hecimovich et al. (2018) study revealed junior- (157,048 deg/s² (d = 0.003); 552,560 deg/s²) and senior-league (157,964 deg/s² [d = 0.001]; 547,518 deg/s²) players sustaining similar levels. The linear and rotational totals across the age groups resulted in similar median and 95<sup>th</sup> percentile HITSP (15.3, 46.8 for junior; 15.4 [d = 0.000], 46.1 for senior; 15.1 [d = 0.016]).
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 training partners who need to be 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).

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., 2002; 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).

### Table 3. Impacts to the head greater than 10 g

<table>
<thead>
<tr>
<th>Players not reporting a notable head impact</th>
<th>Players reporting a notable head impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Impact (ms)</strong></td>
<td><strong>Peak Linear Acceleration (PLA(g))</strong></td>
</tr>
<tr>
<td>Duration (ms)</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>PLA(g)</td>
<td></td>
</tr>
<tr>
<td>30.0-39.9</td>
<td>42 (9.3)</td>
</tr>
<tr>
<td>40+</td>
<td>33 (7.3)</td>
</tr>
<tr>
<td>PRA (deg/s²)</td>
<td></td>
</tr>
<tr>
<td>429,718-716,140</td>
<td>40 (8.8)</td>
</tr>
<tr>
<td>716,197+</td>
<td>13 (2.9)</td>
</tr>
<tr>
<td>HItSp</td>
<td></td>
</tr>
<tr>
<td>21-43</td>
<td>92 (20.3)</td>
</tr>
<tr>
<td>43-63</td>
<td>19 (4.2)</td>
</tr>
<tr>
<td>&gt;63</td>
<td>9 (2.0)</td>
</tr>
<tr>
<td>RWECP</td>
<td></td>
</tr>
<tr>
<td>.2500-4999</td>
<td>12 (2.6)</td>
</tr>
<tr>
<td>.5000-7499</td>
<td>7 (1.5)</td>
</tr>
<tr>
<td>.7500+</td>
<td>21 (4.6)</td>
</tr>
</tbody>
</table>

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

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The comparable levels, and notably the RWECP, 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). Interestingly, those players who reported sustaining an impact recorded a lower resultant median PLA(g), PRA(deg/s²) and HITSP. Furthermore, they 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). Therefore, an increased player and parent awareness is an important step toward progress in this area (McCorry et al., 2009).

Table 4. Impacts to the head greater than 10g 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].

<table>
<thead>
<tr>
<th>Impact Duration (ms)</th>
<th>Head Impact Telemetry severity profile (HITSP)</th>
<th>Risk Weighted Exposure combined probability (RWECP)</th>
<th>Impact Duration (ms)</th>
<th>Head Impact Telemetry severity profile (HITSP)</th>
<th>Risk Weighted Exposure combined probability (RWECP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (%)</td>
<td>Mean ±SD</td>
<td>Median [IQR]</td>
<td>95th Median [IQR]</td>
<td>n (%)</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>PLA(g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;143,182</td>
<td>302 (66.7)</td>
<td>13.6 ±2.3a</td>
<td>13.2 [11.7-15.2]</td>
<td>18.1</td>
<td>.005 [0.002-0.013]</td>
</tr>
<tr>
<td>143,182-428,661</td>
<td>76 (16.8)</td>
<td>13.0 ±6.3</td>
<td>21.7 [19.7-24.5]</td>
<td>28.3</td>
<td>.0108 [0.0032-0.0374]</td>
</tr>
<tr>
<td>429,718-716,140</td>
<td>42 (9.3)</td>
<td>17.0 ±6.9</td>
<td>30.8 [26.7-36.3]</td>
<td>43.8</td>
<td>.0413 [0.0064-1995]</td>
</tr>
<tr>
<td>716,197+</td>
<td>33 (7.3)</td>
<td>17.3 ±8.6</td>
<td>51.4 [42.0-72.1]</td>
<td>133.7</td>
<td>.6795 [1346-9058]</td>
</tr>
<tr>
<td>PRA (deg/s²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;21</td>
<td>333 (73.5)</td>
<td>7.8 ±6.5</td>
<td>12.5 [11.9-15.9b]</td>
<td>19.4</td>
<td>.0006 [0.0002-0.018]</td>
</tr>
<tr>
<td>21-43</td>
<td>92 (20.3)</td>
<td>15.0 ±6.6</td>
<td>27.0 [23.1-31.4]</td>
<td>39.8</td>
<td>.0254 [0.0080-1207]</td>
</tr>
<tr>
<td>43-63</td>
<td>19 (4.2)</td>
<td>20.7 ±8.3</td>
<td>51.1 [46.0-54.4]</td>
<td>63.3</td>
<td>.7890 [2232-9210]</td>
</tr>
<tr>
<td>&gt;63</td>
<td>9 (2.0)</td>
<td>20.4 ±9.4</td>
<td>93.0 [76.1-111.5]</td>
<td>-</td>
<td>.7890 [6795-9318]</td>
</tr>
<tr>
<td>HITSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;.2499</td>
<td>414 (91.4)</td>
<td>9.3 ±7.2b</td>
<td>14.4 [12.3-18.8]</td>
<td>31.5</td>
<td>.0009 [0.003-0.045]</td>
</tr>
<tr>
<td>.2500-4999</td>
<td>12 (2.6)</td>
<td>17.5 ±8.4</td>
<td>35.2 [27.5-43.8]</td>
<td>-</td>
<td>.3461 [3065-3908]</td>
</tr>
<tr>
<td>.5000-7499</td>
<td>7 (1.5)</td>
<td>19.8 ±8.3</td>
<td>37.8 [31.8-84.7]</td>
<td>-</td>
<td>.6287 [5690-7117]</td>
</tr>
<tr>
<td>.7500+</td>
<td>21 (4.6)</td>
<td>17.7 ±9.1</td>
<td>52.0 [37.6-69.2]</td>
<td>152.7</td>
<td>.9210 [8408-9904]</td>
</tr>
<tr>
<td>RWECP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 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(ɡ) and PRA(deg/s²) 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.

**Acknowledgements**

The authors have no conflicts of interest to declare. All experiments comply with the current laws of the country.

**References**


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.

Mark Hecimovich
Division of Athletic Training, 003C Human Performance Center
University of Northern Iowa, Cedar Falls, Iowa, USA

AUTHOR BIOGRAPHY

Mark HECIMOVICH
Employment
Associate Professor, University of Northern Iowa, Division of Athletic Training, Cedar Falls, Iowa, USA.
Degree
BS, MS, PhD, ATC
Research interests
Concussion and head impact, assessment (King-Devick, VOMS), surveillance and knowledge with current projects involving youth athletes in American and Australian football, wrestling and soccer.
E-mail: mark.hecimovich@uni.edu

Doug KING
Employment
Adjunct Research Fellow, School of science and technology, University of New England, Armidale, NSW, Australia.
Degree
Dip Nurs, BNurs, PGCertHSc (SportsMed), PGCertHealthSc(Resus), PDipSportsMed, DipFootball(FIFA), MHealthSc, PhD, PhD
Research interests
Injury epidemiology in rugby, including concussion and head impact biomechanics, as well as mTBI IPV and NAI.
E-mail: dking30@une.edu.au

Alasdair DEMPSEY
Employment
Senior lecturer, Murdoch University, School of Psychology and Exercise Science, Murdoch, Western Australia
Degree
BSc (Hons), PhD
Research interests
Sports injury prevention, and biomechanics of injury
E-mail: a.dempsey@murdoch.edu.au

Mason GITTINS
Employment
PhD candidate, Murdoch University, Murdoch, Western Australia
Degree
BSc (Hons)
Research interests
Injury epidemiology with a focus on concussion recognition and management
E-mail: m.gittins@murdoch.edu.au

Myles MURPHY
Employment
PhD candidate, School of Physiotherapy, The University of Notre Dame Australia, Fremantle, Western Australia
Degree
B. Physio, GradCert Sports Physio, M. ClinPhys (Sports)
Research interests
Sports-related concussion recognition and management; lower limb tendinopathy
E-mail: myles.murphy1@my.nd.edu.au