Video Analysis and Verification of Direct Head Impacts Recorded by Wearable Sensors in Junior Rugby League Players

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Abstract

Background: Rugby League is a high-intensity collision sport that carries a risk of concussion. Youth athletes are considered to be more vulnerable and take longer to recover from concussion than adult athletes.

Purpose: To review head impact events in elite level junior representative rugby league and to verify and analyze x-patch™ recorded impacts via video analysis.

Study Design: Observational case series.

Methods: The x-patch™ was used on twenty-one adolescent players (thirteen forwards and eight backs) during a 2017 junior representative rugby league competition. Game day footage, recorded by a trained videographer from a single camera, was synchronized with accelerometer timestamps. Impacts were double verified by video review. Impact rates, playing characteristics, and game play situations were described.

Results: The x-patch™ recorded 624 impacts 20g between game start and finish, of which 564 (90.4%) were verified on video. Upon video review, 413 (73.2%) of all verified impacts 20g where determined to be direct head impacts. Direct head impacts 20g occurred at a rate of 5.2 impacts per game hour; 7.6 for forwards and 3.0 for backs (range=0-18.2). A defender’s arm directly impacting the head of the ball carrier was the most common event, accounting for 21.3% (n=120) of all impacts, and 46.7% of all “hit-up” impacts. There were no medically diagnosed concussions during the competition.

Conclusion: The majority (90.4%) of impacts 20g recorded by the x-patch™ sensor were verified by video. Double verification of direct head impacts in addition to cross-verification of sensor recorded impacts using a secondary source such as synchronized video review can be used to ensure accuracy and validation of data.

Key Points

1. There was a substantial number of false-positive high acceleration impacts recorded that occurred before, during, or after the games. Wearable instrumented technology has limitations as a primary data source and should be used in conjunction with video review.
2. The vast majority of high acceleration impacts (20g) that occurred during game time were verified on video review.
3. Careful synchronization of impacts sensors timestamps to video footage is vital to help cross-validation and to reduce over-estimation of athlete’s direct head impact exposure.

1. Background

Rugby League carries a risk of concussion due to its high intensity and frequency of collisions [1]. Youth athletes may be more vulnerable to sustaining a concussion [2–4] and may also take longer to recover from a concussion than adult athletes [5–8]. Recently, various technology has been introduced to assist in the identification of head impacts and suspected concussions during athlete competitions. For instance, sideline video review [9, 10], and to a lesser extent, impact sensors in helmeted and non-helmeted sports have been introduced to measure kinematic forces to the head [11].

Sideline video review has become increasingly common in professional sports for identifying head impact events and potential concussions. Recently, multiple experts from seven national and international professional sporting codes developed international consensus definitions of video signs of possible concussion, agreeing on six video signs: (i) lying motionless (for > 2 seconds); (ii) motor incoordination (e.g., losing balance); (iii) impact seizure; (iv) tonic posturing (involuntary sustained contraction of one or more limbs); (v) no protective action/floppy; and (vi) blank/vacant look [9]. The National Rugby League (NRL) has incorporated a Head Injury Assessment (HIA) process that uses sideline video review as a method to identify direct head impacts and potential signs of concussion in players. The identification of a player displaying potential signs of concussion evokes the HIA process, which includes mandatory immediate removal from play and subsequent assessment [12]. During the 2014 season, the incidence of suspected concussions based on the use of this process was 24.0 per 1,000 NRL player game hours [12]. In the same season the incidence of medically diagnosed concussions following the use of this process was 8.9 per 1,000 player game hours [13].

Another proposed method for ascertaining whether a possible concussion occurred during game play has been measuring the forces exerted to a player’s head through wearable sensor technology. The X2 x-patch™ is an impact sensor designed for non-helmeted athletes that has been used in three previous Rugby League studies in junior, women’s, and semi-professional competitions [14–16]. Worn behind the ear, the x-patch™ uses a triaxial gyroscope and accelerometer to calculate linear and angular accelerations experienced by the head during collisions [17]. Previous x-patch™ studies in under 10-year old rugby league [14] and under 9-year old rugby union [18] reported on impact magnitudes comparable to studies on young adults. However, given that the x-patch recorded impacts were not verified on video, the reliability of these findings are questionable [14, 18]. Some studies have examined helmeted impacts in 15 to 17-year-old athletes (e.g., American Football [19–22], Lacrosse [17]) using wearable sensors, but no studies have examined impacts in similarly aged rugby league players. The purpose of this study is to (i) determine the rate at which sensor recorded impacts using the x-patch™ are verified on video review of game footage, (ii) document the number of video verified head impacts that are
not recorded on the sensors, and (iii) describe playing characteristics and game play situations of video-verified direct head impacts over a full season of play in a squad of elite-level youth (under 16 s) rugby league players.

2. Methods

Participants

A prospective cohort study was performed on a junior representative Rugby League team during the 2017 New South Wales (NSW) Rugby League Harold Matthews Competition. The Harold Matthews competition is an elite-level, state-based season of games for under 16-year old rugby league players. It forms one of the first stages of the elite-level pathway. The competition consists of 16 clubs from the NRL and Canterbury (NSW) Cup competitions. The Harold Matthews competition is played over 9 weeks, with the top five teams qualifying for the post-season (i.e., a three-week finals series). A total of 21 adolescent players (age range: 15–16 years, mean = 15.5 years, SD = 0.5 years) including 13 forwards and 8 backs from one club participated in the study. Written consent was obtained by a legal parent or guardian for each player, and verbal assent was obtained by each individual player. A rugby league team consists of 13 players (6 forwards and 7 backs) on the field at any one time with 4 interchange players. On average, data were collected from 13 participants per week (range: 9–15 players per week).

The research protocol was approved by the University of Newcastle Human Research Ethics Committee. The study was also endorsed by the participating club. The methods for data collection were identical to our previous study on a semi-professional men’s rugby league team [16].

Measures

Impact Sensors

All players wore x-patch™ sensors (X2 Biosystems) that were attached to the skin covering the right mastoid process by an experienced member of the research team. Positioning of the sensor is crucial to ensure it is not activated by soft tissue muscles in the neck [23]. Each sensor was uniquely labelled and attached before the warm-up using a double-sided adhesive patch. Each impact recorded detailed “time-stamped” information on Peak Linear Acceleration (PLA), Peak Rotational Acceleration (PRA), Peak Rotational Velocity (PRV) and other variables to estimate head kinematic responses. The x-patch™ contains a low-power, high-g triaxial accelerometer and gyroscope that measures linear and angular accelerations and decelerations to provide 6 degrees of freedom kinematic head impact data. The x-patch™ is triggered when linear acceleration exceeds 10 g and records data for 90 ms after impact and 10 ms before impact equalling one tenth of a second of data (100 ms) to its on-board memory.

Sensors were collected from players immediately after the game. Data from the sensors were downloaded to the Injury Management Software (IMS; X2 Biosystems), which automatically filters out impacts with a PLA under 10 g. All recorded impacts were displayed in the form of a Microsoft excel spreadsheet and sorted into individual player cross-tabulations. Each sensor was then cleared of all impacts and charged in preparation for the following game.

Video Review and Synchronizing with Sensors’ Time Stamp

Each game was recorded with a single high-definition camera by a trained videographer. The video closely followed the play, including both the ball carrier and engaged defenders, and therefore captured competition-related collisions. The best possible vantage point was obtained on the midline of the field with close up shots panning left and right to follow the play. Each game was reviewed from start to finish using QuickTime X (Apple Inc.) by one reviewer (LC). Video was synchronized with the time-stamps of each sensor before the verification review was conducted. The first impact seen on video review was checked against the first impact after the game start time on the sensors timestamp, the same synchronization method used previously on collegiate Lacrosse athletes by Kindschi and colleagues [24]. Subsequent video recorded impacts were then checked against timestamps at corresponding intervals. To synchronize the timestamp from the x-patch™ with the video footage time, multiple impacts were reviewed on video and aligned to the sensor timestamp. Major emphasis was placed on impacts ≥20 g to avoid confusion with a large number of low acceleration events. Each impact was checked multiple times with both the timestamp and video to establish they were precisely synchronized before conducting the video verification process from start to finish of game play.

Upon video review of impacts, the plays were classified in a variety of ways. Each impact was deemed to be a “Hit-Up” (attacking player carrying the ball), “Tackle” (defending player attempting to stop the ball carrier), or “Off-The-Ball” incident (contact without the ball). Impacts that did not correlate with a collision on video review were documented. Similarly, collisions on video review that involved a player with a working sensor attached were documented. Video verified impacts were then sorted into a number of sub-categories including: (i) direct (impact to head) vs. non-direct, (ii) number of tacklers involved (i.e., 1–4), (iii) point of impact on player with sensor (i.e., head, shoulder, chest, arm, waist and below), (iv) side of impact (i.e., right, left, front, back, top), (v) point of contact from opposition player (i.e., head, shoulder, chest, arm, waist and below), and (vi) wrestling impacts happening after first initial contact from tackle. A second reviewer (AG) then independently reviewed impacts during game time that were not verified on video. The process of double verification of these “false-positive” impacts helped clarify the accuracy of each ‘impact’ included in the video verified data. Using the synchronized data set, the timestamps of non-verified impacts were double checked with the corresponding video time. Video for approximately 20 seconds before and after the recorded impact was reviewed with a focus on the relevant player. The results of this review process were then coded into categories (e.g., ‘not fully visualized in the available footage’, or ‘fully visualized with
no contact identified). All data that were not verified as involving an impact were excluded from the analyses. This double verification process was conducted independently by the two reviewers.

### Statistical Analyses

To remove low acceleration events commonly associated with normal game play (e.g., sharp changing of directions, jumping, running) all video-verified impacts were filtered to only include impacts ≥20 g as suggested in previous studies [16, 25, 26]. Descriptive statistics of PLA and PRV were calculated and included frequencies, percentages, medians, and standard deviations. Verified impacts per player game hours rates were calculated for all players and positions using the number of video verified impacts ≥20 g divided by the number of game hours. The formula for calculating the impact rate is provided below.

\[
\text{Impact Rate} = \frac{\sum \text{verified impacts} \geq 20 \text{ g}}{\sum \text{Player Game Hours}}
\]

#### Percentages of video verified and non-verified sensor recorded impacts ≥20 g were calculated to determine the accuracy of the x-patch™ and to remove any “false positives” from the analyzed data set. This was calculated as the number of video verified impacts ≥20 g divided by the number of total recorded impacts during game play, times one hundred. The formula for calculating percentage of verified impacts is provided below.

\[
\% \text{ Video Verified Impacts} = \frac{\sum \text{verified impacts}}{\sum \text{total impacts}} \times 100
\]

#### Location accuracy of direct and indirect impacts was analyzed and the accuracy percentage was calculated to show the agreement between the sensors impact location (i.e., front, back, side, top) and video review. Location accuracy percentages were calculated as the number of times the sensor and the video review agreed on location divided by the total number of impacts per location on video review, times one hundred. The formula for location accuracy is provided below.

\[
\text{Location Accuracy} = \frac{\sum \text{location agreement}}{\sum \text{total video locations}} \times 100
\]

#### Data were reviewed for playing positions (i.e., forward versus back) and characteristics (i.e., attacking, defending, off-the-ball). An identical approach to our previous video verification study [16] for the analysis of this data was conducted. Rates of verified impacts for forwards and backs were compared using an exploratory t test. Exploratory Mann-Whitney U tests compared impact magnitude (i.e., PLA, PRV) between verified/non-verified impacts, direct/indirect impacts, first/second half impacts, and forward/back position impacts because these variables were not normally distributed. All analyses were performed using SPSS 23 (IBM Corp).

### 3. Results

#### Game Hours and Sensor Recording

Data were collected from 21 different players during nine games in the 2017 New South Wales Rugby League Harold Matthews competition, with an average of 12.9 players per game. This equated to 79.4 player game hours (4,762 minutes) with backs accounting for 52.1% (2,479 minutes) and forwards accounting for 47.9% (2,283 minutes) of the hours. A total of 15 x-patch™ sensors were available and deployed at the beginning of the season. Throughout the season, the number of available and working sensors was reduced to eleven due to deteriorating battery life (i.e., the sensor did not recharge), or the sensor was permanently lost during a game. The x-patch™ became detached 16 times throughout the season from eight different players (2 players once, 5 players twice, and 1 player 4 times), for a total of 456 minutes of lost data due to detached sensors for the season (backs: n = 4, Total = 148 min, Mean = 37 min, Median = 33 min, SD = 11.11, Range = 29–53; Forwards: n = 12, Total = 308, Mean = 25.7 min, Median = 28.5 min, SD = 9.94, range = 11–45). In addition, there were 121 minutes of game time lost due to 3 faulty sensors (all forwards).

#### Sensor Recorded Impacts

There were 3,835 impacts recorded by the x-patch™ as 10 g or greater. The distribution of sensor impacts was as follows: 10<20g = 66.3% (n = 2,544), 20<30g = 17.3% (n = 664), 30<40g = 7.0% (n = 268), 40<50g = 4.2% (n = 160), 50<60g = 2.0% (n = 75), 60<70g = 1.1% (n = 43), 70<80g = 0.9% (n = 35), 80<90g = 0.5% (n = 18), 90<100g = 0.3% (n = 11), and 100 g or greater = 0.4% (n = 17). Impacts outside of game time (i.e., in warm-up, cooldown, during application/removal of sensors) accounted for 1,199 impacts (31.3%; 678 before game, 521 after game). On video review 34 impacts were removed due to occurring in the process of, or after, the sensor becoming detached in a tackle. A further 636 impacts were removed due to two players placing the sensor in their sock after it became dislodged. This yielded a total of 1,966 impacts greater than 10 g during game play.

#### Video Verification of Sensor Recorded Impacts

Data were verified for playing positions (i.e., forward versus back) and characteristics (i.e., attacking, defending, off-the-ball). An identical approach to our previous video verification study [16] for the analysis of this data was conducted. Rates of verified impacts for forwards and backs were compared using an exploratory t test. Exploratory Mann-Whitney U tests compared impact magnitude (i.e., PLA, PRV) between verified/non-verified impacts, direct/indirect impacts, first/second half impacts, and forward/back position impacts because these variables were not normally distributed. All analyses were performed using SPSS 23 (IBM Corp).
Of the 1,966 sensor recorded impacts during game play, 1,541 (78.3%) were verified on video. The distribution of sensor impacts verified during game play was as follows: 10–<20g = 63.4% (n = 977), 20–<30g = 20.3% (n = 313), 30–<40g = 7.4% (n = 114), 40–<50g = 4.2% (n = 65), 50–<60g = 2.3% (n = 35), 60–<70g = 0.8% (n = 12), 70–<80g = 0.6% (n = 9), 80–<90g = 0.5% (n = 7), 90–<100g = 0.1% (n = 2), and 100 g or greater = 0.5% (n = 7). During game play there were 624 total impacts ≥ 20 g, with 564 (90.4%) verified on video (i.e., 257 as a result of a hit-up, 278 from a tackle, and 29 off-the-ball incidents; see Fig. 1). Of the 564 video verified impacts ≥ 20 g, 413 (73.2%) were identified as direct head impacts and 151 (26.9%) as non-direct impacts occurring to either the shoulder, chest, arm, or waist. Of the 413 video verified direct head impacts ≥ 20 g, the tackler (defender) recorded 204 (49.4%), the ball carrier (attacker) recorded 186 (45.0%), while 23 were recorded during off-the-ball incidents (5.6%; incidental contact n = 4; melee/scuffle or fighting n = 1; contact celebrating tries n = 10; contact celebrating penalty n = 1; contact packing scrums n = 5; clutching at own head after tackle n = 2). Direct impacts (as determined by video review) had a greater PLA compared to indirect impacts [direct n = 413, mean = 37.3, median = 31.3, SD = 17.5, range 20–113.3; indirect n = 151, mean = 25.5, median = 24.0, SD = 5.4, range 20–45.7; U = 15,728.00, p < .001; Cohen's d = 0.83] as well as greater PRV compared to indirect impacts [direct n = 413, mean = 29.9, median = 28.5, SD = 11.3, range 6.8–56.6; indirect n = 151, mean = 24.8, median = 23.4, SD = 8.7, range 6.2–54.9; U = 23,162.00, p < .001; d = 0.48] (Fig. 2). The individual player data by position, playing time, video-verified impacts, and impacts per game hour are provided in Table 1.
Table 1
Cross-tabulation of Frequency of Verified In-Game Impacts ≥20 g Measured by the X-patch™

<table>
<thead>
<tr>
<th>Playing Position</th>
<th>Player Time in Game (Mins)</th>
<th>Sensor-Recorded In-Game Impacts</th>
<th>Video Verified Game Impacts</th>
<th>Percentage of Impacts Verified (%)</th>
<th>Video Verified Impacts per Game Hour</th>
<th>Video Verified Direct Impacts</th>
<th>Video Verified Direct Impacts per Game Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Player 1 Back</td>
<td>211</td>
<td>17</td>
<td>16</td>
<td>94.1</td>
<td>4.5</td>
<td>12</td>
<td>3.4</td>
</tr>
<tr>
<td>Player 2 Back</td>
<td>337</td>
<td>22</td>
<td>22</td>
<td>100</td>
<td>3.9</td>
<td>17</td>
<td>3.0</td>
</tr>
<tr>
<td>Player 3 Back</td>
<td>490</td>
<td>46</td>
<td>44</td>
<td>95.7</td>
<td>5.4</td>
<td>30</td>
<td>3.7</td>
</tr>
<tr>
<td>Player 4 Back</td>
<td>463</td>
<td>36</td>
<td>36</td>
<td>100</td>
<td>4.7</td>
<td>24</td>
<td>3.1</td>
</tr>
<tr>
<td>Player 5 Back</td>
<td>300</td>
<td>14</td>
<td>14</td>
<td>100</td>
<td>2.8</td>
<td>9</td>
<td>1.8</td>
</tr>
<tr>
<td>Player 6 Back</td>
<td>390</td>
<td>15</td>
<td>15</td>
<td>100</td>
<td>2.3</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>Player 7 Forward</td>
<td>259</td>
<td>26</td>
<td>25</td>
<td>96.2</td>
<td>5.8</td>
<td>14</td>
<td>3.2</td>
</tr>
<tr>
<td>Player 8 Forward</td>
<td>192</td>
<td>39</td>
<td>35</td>
<td>89.7</td>
<td>10.9</td>
<td>22</td>
<td>6.9</td>
</tr>
<tr>
<td>Player 9 Forward</td>
<td>204</td>
<td>67</td>
<td>56</td>
<td>83.6</td>
<td>16.5</td>
<td>44</td>
<td>12.9</td>
</tr>
<tr>
<td>Player 10 Forward</td>
<td>398</td>
<td>37</td>
<td>37</td>
<td>100</td>
<td>5.6</td>
<td>31</td>
<td>4.7</td>
</tr>
<tr>
<td>Player 11 Forward</td>
<td>272</td>
<td>25</td>
<td>25</td>
<td>100</td>
<td>5.5</td>
<td>20</td>
<td>4.4</td>
</tr>
<tr>
<td>Player 12 Forward</td>
<td>247</td>
<td>63</td>
<td>63</td>
<td>100</td>
<td>15.3</td>
<td>45</td>
<td>10.9</td>
</tr>
<tr>
<td>Player 13 Back</td>
<td>87</td>
<td>12</td>
<td>11</td>
<td>91.7</td>
<td>7.6</td>
<td>8</td>
<td>5.5</td>
</tr>
<tr>
<td>Player 14 Forward</td>
<td>63</td>
<td>10</td>
<td>8</td>
<td>80</td>
<td>7.6</td>
<td>7</td>
<td>6.7</td>
</tr>
<tr>
<td>Player 15 Forward</td>
<td>118</td>
<td>24</td>
<td>16</td>
<td>66.7</td>
<td>8.1</td>
<td>13</td>
<td>6.6</td>
</tr>
<tr>
<td>Player 16 Forward</td>
<td>91</td>
<td>30</td>
<td>26</td>
<td>86.7</td>
<td>17.1</td>
<td>20</td>
<td>13.2</td>
</tr>
<tr>
<td>Player 17 Back</td>
<td>180</td>
<td>20</td>
<td>18</td>
<td>90</td>
<td>6</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>Player 18 Forward</td>
<td>36</td>
<td>9</td>
<td>8</td>
<td>88.9</td>
<td>13.3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Player 19 Forward</td>
<td>72</td>
<td>12</td>
<td>11</td>
<td>91.7</td>
<td>9.2</td>
<td>9</td>
<td>7.5</td>
</tr>
<tr>
<td>Player 20 Forward</td>
<td>56</td>
<td>26</td>
<td>21</td>
<td>80.8</td>
<td>22.5</td>
<td>17</td>
<td>18.2</td>
</tr>
<tr>
<td>Player 21 Back</td>
<td>21</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Player 21 Forward</td>
<td>60</td>
<td>9</td>
<td>8</td>
<td>88.9</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

Note. Season Totals. Players 6, 13 & 21 played in both forward and back positions during the season. Sensor recorded impacts were ≥ 20gs.
### All X-patch™ Recorded Impacts During Game Time

<table>
<thead>
<tr>
<th>Total</th>
<th>Game Time</th>
<th>Total</th>
<th>Game Time</th>
<th>Total</th>
<th>Game Time</th>
<th>Total</th>
<th>Game Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,762</td>
<td>624</td>
<td>564</td>
<td>90.4</td>
<td>7.1</td>
<td>413</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>

Note. Season Totals. Players 6, 13 & 21 played in both forward and back positions during the season. Sensor recorded impacts were ≥ 20gs.

### Impacts Seen on Video and Not Recorded on the Sensors

There were 858 video witnessed impacts, including 28 direct head impacts, that did not result in any reading from the x-patch™, either because the sensors did not activate (despite other impacts being recorded on those sensors in close temporal proximity) or because the impact did not reach the 10 g threshold (see Fig. 3).

### Sensor Recorded Impacts Not Verified on Video

There were 1,199 sensor recorded impacts that occurred before or after the game (Fig. 1). The distribution of those sensor impacts was as follows:

- 10-<20g = 62.8% (n = 753), 20-<30g = 13.2% (n = 158), 30-<40g = 9.3% (n = 111), 40-<50g = 6.1% (n = 73), 50-<60g = 2.7% (n = 32), 60-<70g = 2.2% (n = 26), 70-<80g = 1.8% (n = 21), 80-<90g = 0.8% (n = 10), 90-<100g = 0.7% (n = 8), and 100 g or greater = 0.6% (n = 7). There were 506 impacts registered as ≥ 20 g that were not seen on video, and of those 185 occurred before the game (36.6%, presumably during warm up), 60 occurred during the game (11.9%), and 261 occurred after the game (51.6%). It seems particularly unusual that there would be 261 ≥ 20 g impacts (as well as 260 impacts between 10 to 20 g) occurring after the game had ended.

A total of 60 impacts ≥ 20 g occurring during game time were not verified on video review. Of these, 33 impacts were recorded when the player was on the bench, 15 were not visualized (including 12 impacts while the player was not involved or was “behind” the play and 3 impacts when the game was halted after the awarding of a penalty), 1 was partially visualized on video but was indeterminant, and 11 recorded impacts had complete visualization but with no identified contact (including 7 during a sharp change of direction from the player, 3 during change of speed while running, and 1 with no visible correlate). In all of these instances there was clearly no contact from another player. Each of these recorded impacts were verified by two reviewers to confirm them as “false-positive” impacts. There was no significant difference in the PLA of video-verified versus non-video verified impacts ≥ 20 g (verified n = 564, mean = 34.1 g, median = 28.4 g, SD = 16.1, range = 20.0 g-113.3 g; non-verified n = 60, mean = 30.9 g, median = 26.1 g, SD = 13.3, range = 20.0 g-76.6 g; U = 14,706.00, p = .10; d = 0.20) but a difference in PRV (verified mean = 28.5 rad/s, median = 26.9 rad/s, SD = 10.9, range = 6.2 rad/s-56.6 rad/s; non-verified mean = 25.2 rad/s, median = 22.4 rad/s, SD = 13.0, range = 6.3 rad/s-55.4 rad/s; U = 13,727.00, p = .02, d = 0.30).

There were 45 impacts recorded on the sensors that had a PLA of 80gs or greater. Of those, 16 (35.6%) were during the game, 25 (55.6%) were outside game time, and 4 (8.9%) were recorded while the sensor was known to be detached. Individual impacts during the game, outside game time, and while the sensor was detached are illustrated in Fig. 4.

### Situational Characteristics of Video Verified and Sensor Recorded Impacts

Of the 413 sensor recorded and video verified direct head impacts ≥ 20 g, players sustained an average of 5.2 impacts per hour of game play, with a slightly higher average of impacts during the second half of the game [first half 4.6 impacts/hr, n = 192; second half 5.8 impacts/hr, n = 221]. The magnitude of these impacts did not statistically differ between the first and second half (PLA: U = 20,211.00, p = .41; PRV: U = 21,088.00, p = .92). Forwards had a higher rate of direct head impacts ≥ 20 g than backs [forwards M = 8.08 impacts/hr, SD = 4.46; backs M = 2.90 impacts/hr, SD = 1.60; t(22) = 7.58 p = .001, d = 1.29]. However, the intensity of impacts did not statistically differ between forwards and backs (PLA: U = 17,047.00, p = .53; PRV: U = 17,656.00, p = .93).

The most common event that caused a sensor recorded, and video-verified, impact ≥ 20 g was from a defender’s arm directly impacting the head of a ball carrier (n = 120). This type of game play accounted for 21.3% of all impacts and 46.7% of all hit-up impacts. The most common event for a tackler was an attacker’s arm (n = 60) or waist (n = 60) directly impacting the head of the tackler. Each of these accounted for 10.6% of all impacts and 21.6% of tackler impacts. Contact with the playing surface accounted for 44 impacts ≥ 20 g (7.8%; hit-up n = 32, tackle n = 9, off-the-ball n = 3).

Of the 151 indirect impacts, a ball carrier’s shoulder impacting with a defender’s shoulder (11.9%, n = 18, 3.2% of all impacts) or the defender’s chest impacting a ball carrier’s shoulder (10.6%, n = 16, 2.9% of all impacts) were the most common. A detailed overview of all impact events for a hit-up, tackle, and off-the-ball event is provided in Table 2.
Table 2
Sensor Recorded and Video Verified Impact Locations ≥20 g

<table>
<thead>
<tr>
<th>Point of Impact</th>
<th>Head</th>
<th>Shoulder</th>
<th>Chest</th>
<th>Arm</th>
<th>Waist</th>
<th>Leg/knee</th>
<th>Ground</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>13a</td>
<td>64b</td>
<td>34c</td>
<td>199d</td>
<td>66e</td>
<td>26f</td>
<td>11g</td>
<td>413</td>
</tr>
<tr>
<td></td>
<td>(4,7,2)</td>
<td>(26,37,1)</td>
<td>(12,22,0)</td>
<td>(120,60,19)</td>
<td>(5,60,1)</td>
<td>(13,13,0)</td>
<td>(6,5,0)</td>
<td>(186,204,23)</td>
</tr>
<tr>
<td>Shoulder</td>
<td>0 (0,0,0)</td>
<td>30 (11,18,1)</td>
<td>29 (16,13,0)</td>
<td>2 (2,0,0)</td>
<td>13 (1,12,0)</td>
<td>0 (0,0,0)</td>
<td>10 (8,1,1)</td>
<td>84 (38,44,2)</td>
</tr>
<tr>
<td>Chest</td>
<td>0 (0,0,0)</td>
<td>26 (10,16,0)</td>
<td>10 (2,8,0)</td>
<td>5g (0,3,2)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>18 (14,2,2)</td>
<td>59 (26,29,4)</td>
</tr>
<tr>
<td>Arm</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>1 (1,0,0)</td>
<td>1 (1,0,0)</td>
</tr>
<tr>
<td>Waist</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>0 (0,0,0)</td>
<td>4 (3,1,0)</td>
<td>7 (6,1,0)</td>
</tr>
<tr>
<td>Total</td>
<td>13 (4,7,2)</td>
<td>123 (50,71,2)</td>
<td>73 (30,43,0)</td>
<td>206 (122,63,21)</td>
<td>79 (6,72,1)</td>
<td>26 (13,13,0)</td>
<td>44 (32,9,3)</td>
<td>564 (257,278,29)</td>
</tr>
</tbody>
</table>

Note. Data in the parentheses are for a hit-up, tackle and off-the-ball incident, as follows: (hit-up, tackle, off-the-ball)

a 4 impacts from teammate’s head (3 tackle, 1 off-the-ball)

b 7 impacts from teammate’s shoulder (tackle), 1 impact from player’s own shoulder (hit-up)

c 6 impacts from teammate’s chest (6 tackle)

d 32 impacts from teammate’s arm (20 tackle, 12 off-the-ball), 2 impacts from player’s own arm (2 off-the-ball)

e 5 impacts from teammate’s waist (4 tackle, 1 off-the-ball)

f 2 impacts from teammate’s leg/knee (2 tackle)

g 1 impacts from teammate’s arm (off-the-ball)

Direction of Sensor Recorded and Video Verified Head Impacts

When looking at the direction of all video verified direct head impacts (n = 413) as recorded by the x-patch™, the most occurred to the front (n = 198; 47.9%), followed by the side (n = 111; 26.9%), back (n = 83; 20.1%), and top (n = 21; 5.1%) of the head. When examining the location via video review we found most impacts occurred from the side (n = 357, 86.4%) with fewer to the front (n = 14, 3.4%), back (n = 34, 8.2%), and top (n = 8, 1.9%) of the head. The x-patch™ accurately recorded the location in 24.9% of all video verified direct head impacts: 42.9% (n = 6) to the front of the head, 25.2% (n = 90) of video verified impacts to the side of the head, 17.6% (n = 6) of video verified impacts to the back of the head, and 12.5% (n = 1) of video verified impacts to the top of the head. The sensor greatly underestimated side-on direct head impacts visualized on video, and as such overestimated impacts in all other directions, particularly front-on impacts. A detailed description of the location accuracy for direct and indirect impacts is provided in Table 3.

Table 3
Video Verified Impacts: Location Accuracy of Direct and Indirect Impacts ≥20 g

<table>
<thead>
<tr>
<th>Total</th>
<th>Direct Impact</th>
<th>Indirect Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-patch™ (n)</td>
<td>Video (n)</td>
<td>Agreement (n)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td>269</td>
<td>68</td>
</tr>
<tr>
<td>Side</td>
<td>150</td>
<td>447</td>
</tr>
<tr>
<td>Back</td>
<td>116</td>
<td>41</td>
</tr>
<tr>
<td>Top</td>
<td>29</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>564</td>
<td>564</td>
</tr>
</tbody>
</table>

Insert Table 2 About Here

Insert Table 3 About Here
Tackles and Secondary Impacts

Secondary impacts during a tackle (i.e., impacts after the initial contact) accounted for 53.5% (n = 221) of all direct head impacts and 46.1% (n = 260) of total impacts ≥20 g. For 260 secondary impacts, 16.2% (n = 42) were accompanied by a video verified primary impact ≥20 g, with 83.8% (n = 218) of all secondary impacts occurring after the primary impact was less than 20 g. There were 456 tackles that resulted in the 535 video verified impacts ≥20 g, excluding impacts that occurred “off the ball.” For 388 tackles there was one impact recorded, for 60 there were two impacts recorded, for 7 there were three impacts recorded, and for 1 there were six impacts recorded. There were an additional 27 incidents occurring off the ball that resulted in 29 video verified impacts (25 with one impact recorded and 2 with two impacts). The hit-up was a play that accounted for approximately 47.1% (n = 215) of all x-patch™ recorded events. Of the hit-up plays, the forward positions accounted for 62.8% (n = 135) of those impacts, while the back positions accounted for approximately 37.2% (n = 80) of impacts. The tackle accounted for approximately 52.9% (n = 241) of all x-patch™ recorded events. Of the tackles, the forward positions accounted for 73% (n = 175) of those impacts, while the back positions accounted for approximately 27% (n = 66) of impacts.

Insert Figs. 3 and 4 About Here

4. Discussion

This study is the first to analyze video game footage and verify x-patch™ recorded data in elite youth rugby league players. Over the course of nine games (79.4 player game hours) involving 21 players, we recorded a total of 624 impacts ≥20 g between game start and finish with 90.4% (n = 564) verified on video review (see Fig. 1 and Table 1). The percentage of video verified impacts in elite junior rugby league is similar to that previously recorded in men's semi-professional rugby league (94%) [16]. We recorded 5.2 video verified direct head impacts ≥20 g per game hour which is similar to that recorded previously in men's semi-professional rugby (6.0 direct head impacts/hr) [16]. Upon video review we discovered not all recorded “head impacts” occurred as a result of a direct impact to the head. Although the majority of impacts occurred as a result of a direct force to the head (73.2%), the x-patch™ recorded impacts confirmed by video to be caused by an impulsive force to the head after an impact elsewhere on the body (i.e., chest/torso, shoulder, arm, etc.). The rate of video verified direct head impacts was not significantly different between the first and second half, but showed a greater exposure experienced by forwards when compared to backs, consistent with previous literature [16, 27, 28] (Table 4). There was poor agreement in the location and direction of video verified impacts between the x-patch™ and video review. For 413 direct head impacts ≥20 g, the x-patch™ accurately recorded the location in 24.9% (n = 103) of impacts, see Table 4. Previously Kuo and colleagues, using a similar tri-axial linear accelerometer embedded into a mouthguard, reported similarly poor rates of agreement between sensor recorded and video identified impacts (37.3%), with impact locations that did not match the direction of motion [29].

Table 4 Frequency of Video Verified Direct Head Impacts by Game Time and Playing Position

<table>
<thead>
<tr>
<th>Playing hours (mins)</th>
<th>Game Impacts (n)</th>
<th>Impacts per game hour (n)</th>
<th>Game Impacts (n)</th>
<th>Impacts per game hour (n)</th>
<th>Game Impacts (n)</th>
<th>Impacts per game hour (n)</th>
<th>Game Impacts (n)</th>
<th>Impacts per game hour (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Half</td>
<td>41.3 (2,479)</td>
<td>956</td>
<td>23.1</td>
<td>271</td>
<td>6.6</td>
<td>192</td>
<td>4.6</td>
<td>506</td>
</tr>
<tr>
<td>2nd Half</td>
<td>38.1 (2,283)</td>
<td>1,010</td>
<td>26.5</td>
<td>293</td>
<td>7.7</td>
<td>221</td>
<td>5.8</td>
<td>471</td>
</tr>
<tr>
<td>Forwards</td>
<td>38.1 (2,283)</td>
<td>1,305</td>
<td>34.3</td>
<td>388</td>
<td>10.2</td>
<td>291</td>
<td>7.6</td>
<td>643</td>
</tr>
<tr>
<td>Backs</td>
<td>41.3 (2,479)</td>
<td>661</td>
<td>16.0</td>
<td>176</td>
<td>4.3</td>
<td>122</td>
<td>3.0</td>
<td>334</td>
</tr>
<tr>
<td>Total Sample</td>
<td>79.4 (4,762)</td>
<td>1,966</td>
<td>24.8</td>
<td>564</td>
<td>7.1</td>
<td>413</td>
<td>5.2</td>
<td>977</td>
</tr>
</tbody>
</table>

Note. The total number of impacts by playing positions (forwards/backs) was divided by the total minutes played by each playing position.

Insert Table 4 About Here

There were 1,291 impacts ≥20 g of which only half (n = 624, 48.3%) occurred during the game, with the majority of impacts occurring either before or after the game or after a sensor had become detached from the head (Fig. 1). Upon video review, 22 impacts were recorded after the sensor was...
seen detaching from a player, presumably from the sensor hitting the ground after falling or players stepping on it during the game. On two occasions, after the x-patch™ became dislodged, the players can be clearly visualized placing the sensor in their sock until the conclusion of the game, leading to 199 impacts ≥20 g being recorded from running. It is important that when sensor data is collected it is closely analyzed because there is potential for gross over-estimation of head impacts if not carefully processed to remove sensor impacts recorded outside of game play (Fig. 4) [16, 17]. Of the 624 impacts ≥20 g that were recorded during game play with the sensor properly attached, 90.4% were verified by video, revealing a high rate of agreement, similar to rates previously recorded in rugby league [16]. For 1,342 impacts recorded between 10–19.9 g the video verification rate drops to 72.8%. We focused on impacts ≥20 g to remove the larger number of “false-positive” impacts occurring from low acceleration events without an actual impact to the players body or head (e.g., running, jumping, sharp changes of direction), consistent with previous research [16, 17, 25, 26]. Cross-verification with a secondary source, such as video review, is recommended to reduce false-positive readings that may inflate players’ cumulative and average PLAs across a season. Of particular importance is the risk for fundamentally misinterpreting the highest acceleration readings, because those could be falsely attributed to high velocity blows to the head. Of the 45 impacts recorded as 80 g or greater, only 35.6% occurred during the game, while 55.6% were outside game time, and 8.9% were recorded while the sensor was known to be detached (Fig. 4). When viewing video footage during one of our prior studies, we saw one example where six 40 g or higher “head impacts” (ranging from 40.6–58.8 g) were recorded after a game when two players were shaking hands and one player tapped the side of the other player head, during the hand shake, presumably directly on the sensor.

In this study we employed a video verification approach with two reviewers independently reviewing 60 x-patch™ recorded head impacts ≥20 g that occurred during game time that were not verified by video. This was used for quality assurance to verify false-positive readings so that they could be confidently removed from head impact exposure data prior to analysis. Interestingly, upon close review of non-verified impacts, we discovered 33 impacts that occurred while the player was on the sideline. It is unclear how or why these impacts were recorded on the sensors because there was no available video of players on the sidelines. It is possible that these impacts occurred while players were preparing to enter the game by simulating tackles. Previously Cortes and colleagues [17], in a review of impacts in collegiate lacrosse, reported that 99 impacts ≥20 g occurred on the sideline. This suggests that a secondary source, such as video review, is important when trying to quantify in-game recorded head impacts to ensure reported impacts occurred while the player was involved in the game. If the non-game data is not removed, it would artificially inflate the number of head impacts a player sustains. There were also a number of clear head impacts seen on video review that did not register on the sensor, consistent with previous x-patch™ studies [30, 31]. There were a total of 2,399 video identified impacts to the head or body. Of these, the authors of this study visualized 858 (35.8%) impact events on video review that were either not recorded at all by the sensor, or that registered as less than 10 g, of which there were many observable direct head impacts (Fig. 2). The exact number of impacts is difficult to determine and may be higher because this number captures the number of events (e.g., tackles), and multiple impacts may have occurred in each event. We also found a large number of impacts were secondary impacts during tackle events that occurred after the initial contact with 46.3% of all verified impacts coming after the initial impact was seen on video. Of these secondary impacts, 83.8% occurred after the primary impact was either not recorded by the sensor or registered under the 20 g threshold. Having multiple impacts in tackle events makes it difficult to determine exactly how many “larger” impacts identifiable on video review were not registered by the x-patch™.

Limitations

This study consisted of a relatively small sample size, and no player played all games. Due to faulty equipment at the end of the season, the number of working sensors was less than the number of participating players in each game. Because of this, sensors were given to players likely to play more minutes throughout the game to maximize data collection. Further, due to time and personnel constraints, training sessions and two games throughout the season were unable to be staffed by research personnel; these data underrepresent the total accumulation of head impacts over the course of a full season. Similar to our previous study [16], false-negative incidences only included the initial impact as a single “missed” impact when there likely were more subsequent, or secondary, impacts also not registered by the sensor. Although we double verified each false-positive impact to ensure accuracy, all other impacts were coded by a single researcher creating a possibility of some impacts being missed due to human error.

This study utilized one high-definition sideline video camera that panned across the entire field which limits the ability to accurately verify impacts and signs of concussion. Some impacts may be obstructed from view by another player and thus the exact location of some impacts may be inaccurate. Research studies on professional sports with multiple camera angles may be more accurate in analyzing video signs of concussion and determining location of verified impacts. Critically, the process for synchronising, and interpreting, the video and x-patch data in a sport where continuous impacts are present is challenging. Given the volume of impact data collected from the x-patch when no apparent contact was observed (i.e., high sampling rate of the x-patch in the absence of verified impact), in combination with a sport that has a high frequency of body contact, it seems likely that the sensor is recording many impacts that are not actually impacts to the head or body.

5. Conclusion

The findings from this study are consistent with previous research, highlighting the importance of using a secondary source, such as video review, to verify and characterize x-patch™ recorded head impacts. That is, the x-patch™ has serious limitations as a primary data source [16, 17, 25, 30]. The current study identified similar high rates of false-positive direct head impacts recorded by the wearable sensors in junior representative rugby
league as were previously described in semi-professional men's rugby league and collegiate lacrosse respectively. The careful synchronization of impact sensors timestamps with video footage as cross-validation will reduce the over-estimation of athlete's exposure to direct head impacts and help characterize game situations and events that lead to higher frequency of direct head impacts. Double verification of impacts, particularly impacts not verified by video, can help ensure the accuracy of data collected. Although there is potential for impact sensors to play an assistive role to medical staff, more research is needed to ensure the accuracy of data collected and to establish its usefulness for injury surveillance. With ongoing improvements in methodology and technology, impact sensors might provide important information for junior or amateur sports in recording player exposure rates.

**Abbreviations**

HIA: head injury assessment; HIE: head impact events; IMS: injury management software; NRL: National Rugby League; NSW: New South Wales; PLA: peak linear acceleration; PRA: peak rotational acceleration; PRV: peak rotational velocity; SD: standard deviation; TM: trade mark

**Declarations**

**Ethics Approval and Consent to Participate**

The study was approved by The University of Newcastle’s Human Ethics Committee (reference number: H-2015-0323) and was performed in accordance with the standards of ethics outlined in the Declaration of Helsinki.

**Consent for Publication**

Not applicable

**Availability of data and material**

The data generated during the current study are not publicly available due to the institutional human ethics committee approval requirements that ‘only the researchers listed as investigators on the ethics application will have access to the data’ but may be available from the corresponding author on reasonable request.

**Competing Interests**

Lauchlan Carey, Peter Stanwell, Andrew McIntosh, and Doug Terry declare that they have no competing interests.

**Note**

Direct impacts are to the head and indirect impacts are to the body.

**Note**

Sensor detached refers to impacts recorded after the sensor has been visualized dislodging on video review (including players seen placing the sensor in their sock and continuing to play).

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**Authors’ Contributions**

LC conceived the design of the study, collected the study data, and drafted, revised, and finalised the manuscript. DT assisted with the statistical analysis and revised, and finalised the manuscript. GI revised and finalised the manuscript. PS revised and finalised the manuscript. AMc provided extensive revision and finalised the manuscript. AG conceived the design of the study, assisted with the collection of the study data, and drafted, revised, and finalised the manuscript. All authors read and approved the final manuscript.

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References


**Figures**

![Flow diagram comparison of sensor recorded impacts and video verification.](image-url)
Figure 2

Scatterplot of Video Verified Direct and Indirect Impacts 20g Recorded by the x-patch™.

Note: Direct impacts are to the head and indirect impacts are to the body.

Figure 3

Flow diagram showing video verified impacts.

2,399 Video Identified Impacts

- 564 (23.5%) 20g+ on Sensors
- 977 (40.8%) 10-<20g on Sensors
- 858 (35.8%) Not Recorded on Sensors
Figure 4

Scatterplot of all impacts 20g recorded by the x-patch™.

Note: Sensor detached refers to impacts recorded after the sensor has been visualized dislodging on video review (including players seen placing the sensor in their sock and continuing to play).