Similar head impact acceleration measured using instrumented ear patches in a junior rugby union team during matches in comparison with other sports

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OBJECTIVE Direct impact with the head and the inertial loading of the head have been postulated as major mechanisms of head-related injuries, such as concussion.

METHODS This descriptive observational study was conducted to quantify the head impact acceleration characteristics in under-9-year-old junior rugby union players in New Zealand. The impact magnitude, frequency, and location were collected with a wireless head impact sensor that was worn by 14 junior rugby players who participated in 4 matches.

RESULTS A total of 721 impacts > 10g were recorded. The median (interquartile range [IQR]) number of impacts per player was 46 (IQR 37–58), resulting in 10 (IQR 4–18) impacts to the head per player per match. The median impact magnitudes recorded were 15g (IQR 12g–21g) for linear acceleration and 2296 rad/sec² (IQR 1352–4152 rad/sec²) for rotational acceleration.

CONCLUSIONS There were 121 impacts (16.8%) above the rotational injury risk limit and 1 (0.1%) impact above the linear injury risk limit. The acceleration magnitude and number of head impacts in junior rugby union players were higher than those previously reported in similar age-group sports participants. The median linear acceleration for the under-9-year-old rugby players were similar to 7- to 8-year-old American football players, but lower than 9- to 12-year-old youth American football players. The median rotational accelerations measured were higher than the median and 95th percentiles in youth, high school, and collegiate American football players.

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KEY WORDS injury; linear; rotational; impact; rugby union; wireless head impact sensor; trauma

SPORTS-related concussion has received increased media and public awareness with concern for player safety and the risk of injury. Knowledge about the potential metabolic and ultrastructural consequences of impacts to the head has grown, as has the appreciation for repetitive concussive and subconcussive impacts and the possible deleterious effects in some individuals. Using technology, such as accelerometers in the helmets of American football players, has increased knowledge of the injury biomechanics of the forces, accelerations, frequencies, and velocities of head injuries. This knowledge can be applied to reduce the circumstances where head injuries can occur.

Youth football players are physically smaller in stature and body mass, have a lower impact velocity, and participate less than older senior rugby players. However, the risk of a concussive injury, from impacts during sports activities such as football, is higher for younger players when compared with adults. As well as a higher risk of a concussive event, younger players can also have a prolonged recovery process when compared with adults. In American youth football (6- to 9-year-old players) there was a reported average of 107 impacts per player per season, with an average linear and rotational acceleration of 18g and 901 rad/sec². Most impacts occur during practice (59%) and have a higher magnitude than those recorded in American football players.
A prospective observational cohort study was conducted on a junior rugby union team during 4 consecutive matches in a 2015 competition in New Zealand. The objective of this explorative study was to investigate the head impact acceleration characteristics via wireless head impact sensors during 4 matches in junior rugby union players in New Zealand.

Methods

Methods

A prospective observational cohort study was conducted on a junior rugby union team during 4 consecutive matches in a 2015 competition in New Zealand. The objective of this explorative study was to investigate the head impact acceleration characteristics via wireless head impact sensors during 4 matches in junior rugby union players in New Zealand.
All filtered data on the Microsoft Excel spreadsheet were analyzed using SPSS (version 22.0.0). The impact variables were not normally distributed (Kolmogorov-Smirnov test; p < 0.001). Therefore, data were expressed as median (IQR) and as severity measures (95th percentile of linear acceleration and 95th percentile of rotational acceleration).\textsuperscript{20,21} Additionally, the cumulative impact burden per match and per player per match were analyzed using Kruskal-Wallis 1-way ANOVA on ranks for pairwise comparisons. Although there is no accepted method for quantifying cumulative impact burden,\textsuperscript{2} the sum of the linear and rotational accelerations associated with each individual head impact over the course of the study was calculated for all of these parameters.

The impact location variables were computed as the azimuth and elevation angles relative to the center of gravity of the head centered on the midsagittal plane.\textsuperscript{7} These were categorized as front (0° to 180° [left] and θ = 180°–315° [right]), side (θ = –135° to –45° [left] and θ = 135°–45° [right]), back (θ = –45° to 0° [left] and θ = 45° to 0° [right]) and top (θ = 180° through negative θ to 0° [left] and θ = 180° through positive θ to 0° [right]). Impacts to the top of the head were defined as all impacts above an α value of 65° from a horizontal plane through the center of gravity of the head.\textsuperscript{10} Impact locations were analyzed as front, back, side, or top using a Friedman repeated-measures ANOVA on ranks.

Head impacts were assessed for the injury tolerance level for a concussion using previously published injury tolerance levels\textsuperscript{2,3,17} for linear (> 95g) and rotational acceleration (> 5500 rad/sec\textsuperscript{2}). Head impacts were assessed for impact severity using previously published levels for linear acceleration (mild < 66g, moderate 66g–106g, and severe > 106g) and rotational acceleration (mild < 4600 rad/sec\textsuperscript{2}, moderate 4600–7900 rad/sec\textsuperscript{2}, severe > 7900 rad/sec\textsuperscript{2}).\textsuperscript{10,31,40} Both injury tolerance and impact severity levels were analyzed using Friedman repeated-measures ANOVA on ranks. Post hoc analysis with the Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied. Statistical significance was set at p < 0.05.

Prior to the first match, the players completed a baseline King-Devick (K-D) test using 2 of the 3 test cards. The K-D test recommends using test cards 1 and 2 for player data, concussive injury per 1000 match-hours with 95% confidence intervals and median (25th–75th interquartile range) for the K-D scores. Differences in K-D scores at pre-competition (baseline establishment) were calculated, and baseline and post-match K-D scores were compared using the Wilcoxon signed-rank test by the sporting code and combined composite score. The sensitivity and specificity of the K-D test was calculated using a 2 × 2 contingency table with 95% CI and Cohen kappa (κ) was used to assess for intra-rater concordance.\textsuperscript{1,24} Test-retest reliability was also estimated by utilizing the intraclass correlation coefficient with 95% CI to examine agreement between first and second baseline test scores and the post-study scores.

Results

Fourteen players participated in the 4 matches observed in this pilot study. There were 721 impacts to the head greater than 10g (range 10g–141g) recorded over the duration of the study (Table 1). The median (IQR) number of impacts per player over the evaluation period was 46 (IQR 27–58), resulting in 10 (IQR 4–18) impacts to the head per player per match with a duration of 6.0 (IQR 4.0–11.0) msec per impact.

The impact magnitudes were skewed to the lower values (D = 0.226; p < 0.001) with a median (IQR) acceleration of 15g (IQR 12g–21g). Rotational accelerations were also skewed to lower values (D = 0.172; p < 0.001) with a median (IQR) acceleration of 2296 rad/sec\textsuperscript{2} (IQR 1352–4152 rad/sec\textsuperscript{2}). There were 121 impacts (16.8%) above the rotational injury risk limit and 1 (0.1%) impact above the linear injury risk limit (Table 2).

The number of impacts to the areas of the head varied over the evaluation period (Table 2). The side of the head (n = 448) recorded the most impacts. The front of the head recorded the highest median resultant linear acceleration (19g) when compared with the top (p = 0.008), side (p < 0.001), and back (p = 0.008) of the head. The front of the head recorded the highest median resultant rotational ac-
TABLE 1. Resultant linear and rotational accelerations of junior rugby union players for impacts > 10g

<table>
<thead>
<tr>
<th>Motion Type</th>
<th>Total Recorded</th>
<th>Median (IQR)</th>
<th>95th Percentile (IQR)</th>
<th>Median (IQR) Total Frequency Impact Burden*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLA, g</td>
<td>721</td>
<td>15 (12–21)</td>
<td>46 (37–55)</td>
<td>3411 (3351–3605)</td>
</tr>
<tr>
<td>PRA, rad/s²</td>
<td>721</td>
<td>2296 (1352–1452)</td>
<td>10,434 (9287–10,760)</td>
<td>595,624 (585,834–599,359)</td>
</tr>
</tbody>
</table>

* Total impact frequency burden is the sum of all impacts in terms of linear and rotational accelerations.

celeration (4003 rad/sec²) when compared with the top (p = 0.008), side (p < 0.001), and back (p = 0.008) of the head.

There were observable learning effects between the first and second K-D test baseline testing (50.3 vs 46.8 seconds; z = -3.29; p < 0.0001) and baseline and post-study (46.8 vs 45.5 seconds; z = -2.02; p = 0.0431) (Table 3). There were no observed concussions over the duration of the study. Four players had a delay (i.e., worsening) in their K-D score times with a median (IQR) delay of 4.7 seconds (IQR 4.1–5.0 seconds) (z = -1.83; p = 0.079) from their baselines scores. K-D testing demonstrated a sensitivity of 1.00 (95% CI 0.48–1.00), specificity of 0.61 (95% CI 0.39–0.81), and a κ value of 0.36 (95% CI 0.06–0.62).

Discussion

This study reports, for the first time, the head impact characteristics (frequency, magnitude, and location) experienced by a team of under-9-year-old junior rugby union players. By utilizing accelerometer-fitted patches worn behind the ear of each participant in a single junior rugby union team over 4 consecutive matches, there were 721 impacts recorded.

The 4 players who had a delay (worsening) in their K-D tests from their baseline values were withheld from further participation in the match, and the parents were advised to have their child examined medically in order to exclude a concussive injury. Three of the 4 players were diagnosed by a qualified health practitioner as having a concussive injury (players 1, 3 and 4) (Table 4) and underwent a medically supervised, return-to-sport, graduated, stepwise protocol. Player 2 was retested when he returned to play 2 weeks later and had returned to his baseline score. No player who had a decrease in K-D test recorded an impact over 67g of resultant linear acceleration, but all of these players did record a resultant rotational acceleration over the 5500 rad/sec² injury tolerance level.

The under-9-year-old age group is where tackling is first introduced into match activities in New Zealand, and therefore tackling-related skills are developing. The current cohort experienced match participation head impacts with higher magnitudes (> 80g) than expected. The magnitudes were similar to impacts reported in American high school1–5 and collegiate6,7,9 football players, but the New Zealand rugby union players were younger, had less body mass, and played at a slower speed than the American players.10,39 Unlike American football, rugby union does not have the same protective equipment worn during match activities.

Comparing impact data between studies can be difficult given the different thresholds used to count an impact. For example, the data acquisition limit used for recording impacts to the head in Pop Warner youth football37 players was any linear acceleration greater than 30g, while other studies used 10g10 and 14.4g6,11,39 limits. No rotational accelerations were reported in Pop Warner youth football. By using a 30g data acquisition limit for Pop Warner football, approximately 80% to 85% of the impacts may have been excluded from the data set.37 Daniel et al.10 examined American football players aged 6 to 9 years, and approximately 85% of the impacts recorded had a linear acceleration below 30g. This was similar in 9- to 11-year-old American football players, with 80% of impacts recording linear accelerations below 30g.6 Unless the data were reported at different data acquisition limits used in previous studies (i.e., 10g10 14.4g6,11,21, and 30g37), resulting in complex tables or large amounts of data presented, then interstudy comparisons are limited.

Although these published studies were included as comparisons with the current study, the comparisons should be undertaken with caution as the reported data acquisition limit used in the current study was set at 10g. A standardized reporting format for impacts needs to be established to identify what parameters should be included (i.e., resultant linear [PLA (g)] and rotational acceleration [PRA (rad/sec²)]), Head Impact Criterion (15 msec), Gadd Severity Index, Head Impact Telemetry severity profile) and what linear data acquisition limit the data should be reported. The identification of thresholds for head impacts that are subconcussive versus non-subconcussive is needed.

In youth football (6–9 years old), players averaged 44 impacts during matches, or 5.8 impacts to the head per player per match.10 This study had similar impacts to the current study with players recording a median of 46 impacts to the head during matches but a higher median number of impacts (10) per player per match. In a slightly older youth football team (12–14 years old),11 players recorded an average of 112 impacts during matches, or 12 impacts per player per match. Although the numbers of impacts per player per match are similar, the total impacts per match were higher. Similar to other studies that report head impact biomechanics, the magnitudes recorded were characterized by a skewed frequency distribution with most (64%) impacts having a linear acceleration of between 10g and 20g. There were, however, 3 impacts recorded over the duration of the study that were above 80g. This magnitude has been previously described28 as “high” and highlights that youth players can be exposed to impacts over a competition that are considered high magnitude at any level of participation. Despite the number of high-magnitude impacts recorded, there were no witnessed concussive events recorded throughout the duration of the study.

Previous studies that reported the impacts for youth American football players have shown that the median
<table>
<thead>
<tr>
<th>Variable</th>
<th>Location</th>
<th>Overall</th>
<th>Front</th>
<th>Side</th>
<th>Back</th>
<th>Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of impacts (%)</td>
<td>721</td>
<td>124 (17.2)</td>
<td>448 (62.1)</td>
<td>140 (19.4)</td>
<td>9 (1.3)</td>
<td></td>
</tr>
<tr>
<td>Median no. per player</td>
<td>46 (27–58)</td>
<td>7 (6–14)</td>
<td>23 (14–29)</td>
<td>10 (5–15)</td>
<td>1 (1–2)</td>
<td></td>
</tr>
<tr>
<td>Median PLA per player in g</td>
<td>15 (12–21)</td>
<td>19 (14–29)</td>
<td>14 (12–18)</td>
<td>17 (13–28)</td>
<td>16 (14–22)</td>
<td></td>
</tr>
<tr>
<td>Median PRA per player in rad/sec²</td>
<td>10,434 (9297–10,760)</td>
<td>4003 (2548–7506)</td>
<td>1841 (1128–3014)</td>
<td>3020 (1723–5232)</td>
<td>3197 (2499–4670)</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Head impacts, resultant accelerations by location of impact, number, percentage, and median values with IQR of head impacts by injury tolerance level,² ³ ¹⁷ impact severity limits,¹⁹ ²¹ ⁴⁰ and resultant accelerations per player in junior rugby union.**

* Values are reported as median (25th–75th IQR) unless otherwise stated. Significant difference (p < 0.05) compared with front (a), side (b), back (c), and top (d).
recorded linear acceleration (15g) was lower when compared with other levels of participation. Observations of 7- to 8-year-old American football players showed a median linear acceleration of 16g, which was similar to the current study. This was lower than 9- to 12-year-old youth American football players with a median head impact of 18g, while 12- to 14-year-old players recorded a slightly higher median linear acceleration of 22g. Although it appears that the players in the current study may have a lower resultant linear acceleration than similarly aged American football players, this could reflect how these games differ. American football players wear full protective equipment, including rigid helmets and padding, whereas junior rugby players are only required to wear a fitted mouth guard and any other protective equipment must be soft in order to reduce the risk of possible injury to other players through accidental contact to any part of the body.

When comparing the resultant rotational accelerations with youth American football players, the median rotational acceleration (2296 rad/sec²) was higher than the median and 95th percentiles reported for 7- to 8-year-old players (686 rad/sec² and 2052 rad/sec², respectively) and 9- to 12-year-old players (829 rad/sec² and 1884 rad/sec², respectively). When compared to 12- to 14-year-old players (987 rad/sec² and 2709 rad/sec², respectively), high school players4,5 (903 rad/sec² and 2527 rad/sec², respectively), and collegiate American football players (904–981 rad/sec² and 2787–2975 rad/sec², respectively), this was similar to the current study that recorded a higher median and 95th percentile (9615 rad/sec²) resultant rotational acceleration. This may be related to the type of activity undertaken in the junior rugby union, where players are required to tackle the player to the ground and use a different tackle technique, which may include a rotational type of movement that increases the rotational forces re-

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of players enrolled</td>
<td>14</td>
</tr>
<tr>
<td>Mean age ± SD in yrs</td>
<td>8.4 ± 0.6</td>
</tr>
<tr>
<td>Matches played (match-hours)</td>
<td>4 (22.0)</td>
</tr>
<tr>
<td>Total no. of concussive incidents (witnessed; unwitnessed)</td>
<td>4 (0; 4)</td>
</tr>
<tr>
<td>Concussion incidence per 1000 match-hours (95% CI)</td>
<td>181.8 (3.6–360.0)</td>
</tr>
<tr>
<td>Median (IQR) preseason K-D test, sec</td>
<td>50.3 (46.4–53.0)</td>
</tr>
<tr>
<td>Median (IQR) preseason K-D test, sec</td>
<td>46.8 (40.0–50.0)</td>
</tr>
<tr>
<td>Median (IQR) difference test 1 vs test 2, sec</td>
<td>−3.3 (−4.1 to −2.7)</td>
</tr>
<tr>
<td>Median (IQR) post-study K-D test, sec</td>
<td>43.6 (37.2–49.6)</td>
</tr>
<tr>
<td>Median difference baseline vs postseason, sec</td>
<td>−2.5 (−5.8 to −2.3)</td>
</tr>
<tr>
<td>ICC (95% CI), K-D baseline 1 vs baseline 2</td>
<td>0.97 (0.79–0.99)</td>
</tr>
<tr>
<td>ICC (95% CI), K-D baseline vs postseason</td>
<td>0.96 (0.85–0.99)</td>
</tr>
<tr>
<td>K-D test sensitivity (95% CI)</td>
<td>1.00 (0.48–1.00)</td>
</tr>
<tr>
<td>K-D test specificity (95% CI)</td>
<td>0.61 (0.39–0.81)</td>
</tr>
</tbody>
</table>

ICC = intraclass correlation coefficient.
* Significant difference (p < 0.05) from test 1 baseline.
† Significant difference from established baseline.

<table>
<thead>
<tr>
<th>Player No.</th>
<th>Total Impact Frequency</th>
<th>Last Impact Recorded</th>
<th>Median (IQR) Impact Duration (msec)</th>
<th>Median (IQR) K-D Decrease From Baseline (sec)</th>
<th>Range of Accelerations Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>20 (14–49)</td>
<td>6.5 (5.0–13.0)</td>
<td>5.0</td>
<td>10–55</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>20 (14–49)</td>
<td>4.0 (3.0–6.5)</td>
<td>5.5</td>
<td>11–67</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>40 (14–59)</td>
<td>10.0 (10–18)</td>
<td>4.4</td>
<td>14–25</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>40 (14–59)</td>
<td>7.0 (6.0–14.8)</td>
<td>5.1</td>
<td>14–25</td>
</tr>
</tbody>
</table>

K-D Decrease From Baseline: The sum of all impacts by linear and rotational accelerations.
corded at the head. No other study has reported how the different tackle techniques seen in rugby union differ from tackles in American football, where the play ceases once the ball or the player carrying the ball is grounded. Further research is warranted to explore if these differences have an effect on the forces recorded at the head.

Another possible explanation for the differences observed may be the different biomechanical properties of the head and neck observed in children when compared with adults. Younger children have an increased head-to-body ratio that can result in a higher center of gravity and increased head momentum. Children have less developed neck and shoulder musculature when compared with adults. A consequence of the higher head-to-body ratio, and the decreased neck and shoulder musculature, is the inability to dissipate impact forces that occur from match participation. Greater forces are required to cause similar concussive injuries in smaller brains than larger brains with greater mass. As a result, children exhibiting the signs and symptoms of a concussion may have sustained greater forces than an adult presenting with similar signs and symptoms of a concussion.

The current study reported the linear and rotational accelerations by the median (IQR) and 95th percentile results. These results were used for comparisons with limited previous studies that reporting on American Pop Warner, youth, and high-school football players. Other studies have used either a median and/or 95th percentile result format, or only reported linear accelerations, which has limited interstudy comparisons. This has resulted in the information provided by these studies being left to stand alone and await future studies that report similar data acquisition limits and formats in order to to enable comparisons to be completed.

As this was an evaluative study with only 4 matches observed, the results of this study must be interpreted with caution. No video recording was undertaken, as these participants were minors, and there was no way to verify what match activity resulted in the impact. The players in this evaluative study were all younger than age of 9 years, and the impact characteristics maybe specific to this age group. The head impact exposure experienced by this cohort of players may vary when compared with other junior rugby union players at different age levels, as the head impact exposure likely varies by age.

Although the XPatch has undergone some reported validation studies and has been compared with the Head Impact Telemetry System, the results have varied. The accelerometers used in this study have been reported to have a strong correlation with anterior-posterior translation \((r^2 = 0.93)\) and rotational accelerations of between 1882 rad/sec\(^2\) (IQR 730–4387 rad/sec\(^2\)) (corrected for overprediction) and 9184 rad/sec\(^2\) (IQR 5416–16,607 rad/sec\(^2\)) (corrected for underprediction). Although we found these data, there are no consistent reliability studies for the XPatch, and the interpretation of these results should be undertaken with some caution.

Conclusions

Median linear acceleration measured over 4 matches in an under-9-year-old rugby union team was similar to the median linear accelerations reported in studies for American Pop Warner and Youth football. Median rotational accelerations were higher than American Pop Warner and Youth football. There is a need to standardize the reporting of head impact biomechanics in order to enable accurate comparisons across published studies.

Acknowledgments

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References


Disclosures
The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions
Conception and design: King, Hume, Clark. Acquisition of data: King, Gissane. Analysis and interpretation of data: King, Hume, Gissane. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: King. Statistical analysis: King, Gissane.

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