

Measurement of Head Impacts in a Senior Amateur Rugby League Team with an Instrumented Patch: Exploratory Analysis

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Abstract

Accelerometer devices can quantify the magnitude of head impacts during sport to ascertain potential for brain injury. There are no published head impact data for rugby league. The objective of this study was to quantify head impacts for amateur senior rugby league players to ascertain potential for brain injury. Data on head impact magnitude, frequency and distribution were collected with instrumented behind-the-ear XPatches (accelerometers) worn by 42 premier senior amateur rugby league players participating in 2014 and 2015 domestic seasons of matches. During the study there were 20,837 impacts >10g recorded. The mean number of impacts per player over the season was 672 ± 237 resulting in 52 ± 79 impacts to the head per player, per match. Players recorded a median [IQR] linear (14 [10 to 23] g), and rotational (3,181 [1830 to 5,612] rad/s²) accelerations over the study. Over the study there were 103 impacts (0.5%) for linear acceleration, and 4,505 impacts (22%) for rotational acceleration, above previously published linear and rotational injury tolerance thresholds. The median peak linear acceleration of 14g was lower, while the median rotational acceleration of 3,181 rad/s² was higher than the medians reported in American high school football, collegiate football and youth ice hockey. The potential for brain injury in rugby league players as indicated by head impact acceleration is likely similar to American football and rugby union. Given world-wide growth of rugby codes, sports clinicians need to be aware of the potential for head injury and likely concussion prevention and management options.

Key points:

- Linear acceleration characteristics for head impacts per player per game for rugby league were similar to those reported for American high school football, collegiate football and youth ice hockey.
- Rotational acceleration characteristics for head impacts per player per game for rugby league were higher than those reported for American high school football, collegiate football and youth ice hockey.
- The majority of linear and rotational acceleration impacts recorded in senior amateur rugby league fell into the mild category of impact severity.

Keywords: Injury, Linear Acceleration, Rotational Acceleration, Head Impact, Rugby League.

1. INTRODUCTION

Played at junior, amateur, semi-professional and professional levels, 1 rugby league is an intermittent collision sport involving numerous collisions and tackles. 1 Played with 13 players on-field, with 4 reserves, the game is typically (but not always) played under a limited interchange rule where up to 12 interchanges of

players are permitted in matches. Each team is permitted six tackles in possession of the ball with which they must advance into the opposition's territory and score a try. 2-4 The ball must only be passed backwards but can be carried or kicked into the opposition's territory. 2, 4 At the completion of six tackles the ball is immediately given to the opposition team to

commence their set of six tackles.^{2, 3} Most teams often kick the ball after the fifth tackle (ceding the possession to the opposition) to avoid being tackled a sixth time, in an attempt to gain further territorial advantage. The same players are therefore involved in both attack and defence.

At the professional level of rugby league, players can experience from 34 to 72 tackle situations per match either as the tackler or the ball carrier.⁵ As a result of the tackle situations, many impacts to the body and head occur from match participation in rugby league. Knowledge of the potential metabolic and ultra structural 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.⁶ Technology, such as accelerometers in the helmets of American football players,⁷⁻⁹ and New Zealand amateur rugby union players¹⁰ have increased the knowledge and analysis of injury biomechanics of the forces, accelerations, frequencies and velocities of head injuries.¹¹

Despite more studies reporting impacts to the head and concussions, none have identified a data acquisition threshold that constitutes where a subconcussive impact occurs. Impacts under 10g are reported¹² to be a result of non-contact activities such as walking, jumping, running and sitting.^{9, 13} Impacts over 10g that do not result in a participant presenting with acute signs or symptoms of concussion, have been identified to be subconcussive impacts¹⁴. Repetitive subconcussive impacts may have negative long-term effects.¹⁵ Several studies have utilized data acquisition thresholds greater than 10g (i.e. 14.4g,¹⁶⁻¹⁸ 15g^{7, 19, 20} and 30g⁶) to report findings and may have removed a large number of subconcussive impacts from their dataset. The data obtained from these types of impacts is not normally distributed. Non-helmeted sports have utilized accelerometers in measuring impacts from sports participation. Heading the ball by female soccer youths yielded peak accelerations of 63g and 8,869 rad/s².²¹ No concussions were reported,²¹ as no injury nor injury risk was assessed; even though some of the rotational accelerations were within the nominal values for an injury to the head when compared with American football data²² and injury risk tolerance levels.²³ Although head impact data are accumulating for soccer,^{24, 25} ice hockey,²⁶⁻²⁸ American football^{16, 18, 29} rugby union^{10, 30} and junior³¹ and women's³² rugby league, there are

no published head impact data for male senior amateur rugby league. Given that rugby league is a different contact sport when compared to rugby union, there is a need to explore the impacts to the head within this sporting code. Therefore, this study quantified impacts to the head via an instrumented patch worn behind the ear for amateur rugby league players over two premier seasons of domestic matches in New Zealand.

2. METHODS

A cross-sectional study was conducted on a senior club level amateur rugby league team over two competitive seasons (2014, 2015) in New Zealand. There were 33 players enrolled in 2014 and 35 players enrolled in 2015. The majority of the players (78.7%) played in both competition seasons. A total of forty-two players were enrolled in the study with a mean \pm SD age, body mass and height of 23.3 \pm 4.3 yr. 93.6 \pm 14.4 kg and 1.80 \pm 0.05 m. The players were considered amateur receiving no remuneration for participating in rugby league activities. The matches were played under the laws of New Zealand Rugby League. Players were placed into three positional groups: (1) hit-up forwards (n= 4: 2 x prop, 2 x second row); (2) outside backs (n= 5: 2 x centre, 2 x wing and fullback); and (3) adjustables (n= 4: hooker, halfback, five-eight, and loose forward).³³ The researcher's university ethics committee (AUTEC 12/156) approved all procedures in the study and all players gave informed consent prior to participating in the study.

Every player wore the XPatch impact-sensing skin patch (X2Biosystems Ltd, Seattle, Washington, United States of America; www.x2biosystems.com) on the skin covering their right-side mastoid process during each match sampling at 1,024 Hz. The positioning of the XPatch over the mastoid process is important to ensure that the sensor was not activated by enhanced soft-tissue effects when impacts occur²⁵ and was placed on the players by the lead researcher 15 minutes prior to the match starting. The XPatch 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 acceleration and rotational velocity. The XPatch calculated rotational acceleration of the heads' centre of gravity for all impacts that occurred during matches. The time history incorporated three axes (x, y, z) of acceleration

and three axes of velocity. Standing in an upright position these planes describe the medial-lateral, anterior-posterior and vertical acceleration and deceleration.

A data acquisition limit of $10g^{10, 34}$ was utilised for the study. If an impact exceeded the predetermined $10g$ linear acceleration threshold, 100 milliseconds (ms) of data (10 ms pre-trigger and 90 ms post-trigger) from each accelerometer and gyroscope were recorded to the on-board memory for later downloading. All matches were videotaped (Sony HDR-PJ540 Camcorder) to enable verification of the impacts recorded. The time stamp of the match was synchronized with the X2 XPatch prior to every game.

Following the match, the XPatch was removed from each player and downloaded to the Injury Management Software (IMS) (X2Biosystems). The IMS enabled the raw accelerometer data to be transformed to the head centre of gravity by using a rigid-body transformation for linear acceleration and a 5-point stencil for rotational acceleration.^{10, 25} The biomechanical measures of head impact severity consisted of peak linear acceleration (g), and peak rotational head acceleration (rad/s^2).³⁵ False impacts were removed by the X2Biosystems proprietary 'de-clacking' algorithm¹⁰ by comparing the waveform of each impact to a 'Gaussian-like' reference waveform using cross-correlation.¹⁰ The XPatch impact data were adjusted to enable correlation with a head form criterion standard as previously reported.³⁶ Impacts with a peak linear acceleration of $<10g$ were removed. The remaining impacts to the head were downloaded to an Excel 2016 spreadsheet and time-filtered to include only those impacts that occurred during match participation. Three measures of impact frequency were computed for each player: (1) *player position impacts*, the total and average number of head impacts recorded for the playing position for all matches; (2) *player group impacts*, the total and average number of recorded head impacts for the playing group (hit-up forwards, adjustables and outside backs) for all matches; and (3) *impacts per match*, the total and average number of impacts per match for all matches

The head impact location variables were computed as azimuth and elevation angles relative to the centre of gravity (CG) of the head centered on the mid-sagittal plane.^{10, 30, 37} These were categorized as front, side, back and top. Impacts to the top of the head were defined as

all impacts above an α of 65° from a horizontal plane through the CG of the head.³⁸ Head impacts were also assessed for injury tolerance^{19, 39, 40} and impact severity,^{23, 41, 42} Head Impact telemetry Severity profile (HIT_{SP})³⁸ and Risk Weighted Exposure Combined Probability (RWE_{CP}).¹⁸ The HIT_{SP} is a weighted composite score including linear and rotational accelerations, impact duration, and impact location³⁸ and the RWE_{CP} is a logistic regression equation and regression coefficient of injury risk prediction of an injury occurring based on previously published analytical risk functions.¹⁸ The RWE_{CP} combines the linear and rotational accelerations to elucidate individual player and team-based exposure to head impacts. As a value of 63 is a 75% indicator for a concussive injury^{38, 43} the HIT_{SP} values were evaluated by limits of less than 25% risk (<21), 25% to 75% risk (21-63) and $>75\%$ risk (>63). The RWE_{CP} values were evaluated by the same values of 25% risk (<0.2500) 25% to 75% risk (0.2500-0.7500) and $>75\%$ risk (>0.7500). The cumulative impact burden of the HIT_{SP} and RWE_{CP} values were calculated for every match over the duration of the study. Although there is no accepted method to quantify cumulative impact burden,³⁹ the sum of resultant PLA(g), PRA(rad/s^2), HIT_{SP} and RWE_{CP} associated with each individual head impact per-match over the course of the study was calculated for all of these parameters.

3. STATISTICAL ANALYSIS

All filtered data on the Excel 2016 spreadsheet were analysed with SPSS V.24.0.0. The impact variables were not normally distributed (Kolmogorov-Smirnov; $p < 0.001$) therefore, data were expressed as mean (SD), median [IQR], and 95th percentile.^{44, 45} Additionally the cumulative impact burden per-match was analysed using a Kruskal-Wallis one-way ANOVA with a Dunn's post-hoc test for all pair wise comparisons with player positions. Head impact exposure including impact duration, frequency, magnitude and location of impacts were quantified using previously established methods.^{9, 46} Median peak linear and rotational accelerations and impact locations between player positions were assessed using a Friedman repeated measures ANOVA on ranks with a Wilcoxon signed-rank test for post hoc analysis. Impact locations were analysed by front, back,

side and top impacts using a Friedman repeated measures ANOVA on ranks by comparing impacts sustained in each location. A one sample chi-squared (χ^2) test and risk ratio (RR) with 95% confidence intervals (CI) was used to determine whether the observed impact frequency was significantly different from the expected impact frequency. The HIT_{SP} and RWE_{CP} were analysed by total, forwards, outside backs and adjustables impacts using a Friedman repeated measures ANOVA on ranks. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied. Statistical significance was set at $p < 0.05$.

4. RESULTS

Thirty-one matches were completed over the study resulting in a match exposure of 536 match hours. A total of 20,837 impacts to the head were recorded that were above the 10g data acquisition threshold (see Table 1). The mean number of impacts to the head per-player over the season of matches was 672 ± 237 . This resulted in 52 ± 79 impacts to the head per-player, per-match. Players recorded a median [IQR] of 14 [10 to 23] g for resultant PLA (g), and 3,181 [1,830 to 5,612] rad/s² for resultant PRA (rad/s²) over the duration of the study.

Table 1. Impacts to the head greater than 10g in senior amateur rugby league for total impacts recorded and impacts per player positional group^{3,3} over two seasons of matches for total impacts, impacts per match, impacts per player per match, linear and rotational accelerations. Data are presented as mean (\pm SD), median [25-75th interquartile range], 95th percentile and total frequency impact burden.

	Impacts			Peak Linear Acceleration (g)				Peak Rotational Acceleration (rad/s ²)			
	Number impacts recorded	Average per match Mean \pm SD	Average per player Mean \pm SD	Mean \pm SD	Median [IQR]	95 %	Total Frequency Impact burden ⁱ	Mean \pm SD	Median [IQR]	95%	Total Frequency Impact burden ⁱ
Total (31 games)											
Player Position ¹	20,837	672 \pm 237	52 \pm 79	19 \pm 13	14 [10-23]	47	400,281	4,350 \pm 3,837	3,181 [1,830-5,612]	12,417	90,639,647
Hit-Up Forwards ²	9,464 ^{bc}	321 \pm 243	80 \pm 120	22 \pm 14	17 [12-26] ^{bc}	50	204,787	4,932 \pm 4,052	3,631 [2,172-6,379] ^{bc}	13,292	46,671,515
Outside Backs ³	4,746 ^{ac}	153 \pm 94	31 \pm 39	17 \pm 12	13 [10-19] ^{ac}	42	62,945	3,879 \pm 3,571	2,889 [1,544-5,015] ^{ab}	11,441	14,397,615
Adjustables ⁴	6,627 ^{ab}	214 \pm 145	53 \pm 68	17 \pm 12	12 [10-19] ^{ab}	41	111,718	3,688 \pm 3,528	2,622 [1,398-4,746] ^{bc}	11,284	24,442,095

PLA (g) = peak linear acceleration; PRA (rad/s²) = peak rotational acceleration in radians/second/second (rad/s²); IQR = interquartile range; (i) = The total impact frequency is the sum of all of the impacts by linear and rotational accelerations; (1) = 13 player positions; (2) = 4 player position; (3) = 5 player position; (4) = 4 player positions; Significant difference ($p < 0.05$) than (a) = Hit-Up Forwards; (b) = Outside backs; (c) = Adjustables; (d) = 2014

Over the study the hit-up forwards recorded more total impacts (n=9,464) than adjustables (n=6,627; $p < 0.001$) and outside backs (n=4,746; $p < 0.001$) (see Table 1). Hit-up forwards recorded a higher median PLA (g) (17 [12 to 26] g) than outside backs (13 [10 to 19] g; $p < 0.001$) and adjustables (12 [10 to 19] g; $p < 0.001$). Adjustables recorded a lower median PRA (rad/s²) (2,622 [1,398 to 4,746] rad/s²) than outside backs, 889 [1,544 to 5,015] rad/s²; $p < 0.001$) and hit-up forwards (3,631 [2,172 to 6,379] rad/s²; $p < 0.001$).

the front (n=5,896; 28%), back (n=5,623; 27%) or top (n=652; 3%) of the head. Hit up forwards recorded more impacts to the front of the head than outside backs (RR: 1.9 [95% CI: 1.1 to 1.3]; $p < 0.0001$) and adjustables (RR: 1.6 [95% CI: 1.5 to 1.7]; $p < 0.0001$) (see Table 2). Hit-up forwards (15 [11 to 23] g) recorded a higher median PLA (g) to the side of the head than outside backs (11 [10 to 18] g; $p < 0.0001$) and adjustables (11 [10 to 15] g; $p < 0.0001$) over the study. Hit-up forwards recorded a higher median PRA (rad/s²) (3,775 [2,206 to 6,809] rad/s²) than outside backs (3,152 [1,757 to 5,451] rad/s²; $p = 0.0046$) and adjustables (3,601 [1,961 to

The side of the head was the most common impact location (n=8,666; 42%) compared with

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6,731] rad/s²; $p=0.8966$) to the back of the head. As a result, hit-up forwards recorded the highest median RWE_{CP} (0.0020[0.0005to 0.0382]) than outside backs (0.0011[0.0003to 0.0091];

$p<0.0001$) and adjustables (0.0017 [0.0003 to 0.0343]; $p<0.0001$) to the back of the head over the study.

Table2. Impacts to the head greater than 10g in senior amateur rugby league by player positional group³³ over two competition match seasons for impact location, total impacts recorded, linear accelerations, rotational accelerations and risk weighted exposure combined probability. Data are presented as mean (\pm SD), median [25-75th interquartile range], 95th percentile and range of impacts recorded.

	Peak Linear Accelerations (g)				Peak Rotational Accelerations (rads/s ²)				Risk Weighted Exposure Combined Probability (RWE _{CP})				
	mean \pm SD	Median [IQR]	95%	Range	mean \pm SD	Median [IQR]	95%	Range	mean \pm SD	Median [IQR]	95%	Range	
Total Impacts													
Front	5,896 (28.3)	21 \pm 14	16 [12-25] ^{efg}	50	10-116	5,059 \pm 3,818	3,826 [2,533-6,270] ^{efg}	13,296	34-32,671	0.109 \pm 0.2661	0.0020[0.0006-0.0223] ^{efg}	0.9438	0.0001-1.0000
Back	5,623 (27.0)	21 \pm 14	16 [11-25] ^{dfg}	48	10-144	4,841 \pm 4,022	3,568 [2,028-6,422] ^{dfg}	13,148	12-37,012	0.1128 \pm 0.2684	0.0016[0.0004-0.0246] ^{dfg}	0.9320	0.0001-1.0000
Side	8,666 (41.6)	17 \pm 12	12 [10-19] ^{deg}	42	10-144	3,459 \pm 3,524	2,384 [1,253-4,341] ^{deg}	10,916	4-34,240	0.0659 \pm 0.2113	0.0005[0.0002-0.0034] ^{deg}	0.6558	0.0001-1.0000
Top	652 (3.1)	23 \pm 13	19 [14-29] ^{def}	51	10-101	5578 \pm 3,937	4,311 [2,745-7,467] ^{def}	13,559	6-21,387	0.1483 \pm 0.2988	0.0032[0.0008-0.0729] ^{def}	0.9602	0.0001-0.9999
Hit-Up Forwards													
Front	3,169 (15.2)	23 \pm 17	18 [12-28] ^{bcefg}	53	10-116	5,212 \pm 3,996	3,917 [2,570-6,495] ^{efg}	13,559	34-32,671	0.1190 \pm 0.2755	0.0024[0.0006-0.0292] ^{efg}	0.9614	0.0001-1.0000
Back	2,715 (13.0)	22 \pm 15	18 [12-27] ^{bcd}	50	10-144	5,134 \pm 4,192	3,775 [2,206-6,809] ^{bdg}	13,539	12-37,012	0.1271 \pm 0.2835	0.020[0.0005-0.0382] ^{bdg}	0.9560	0.0001-1.0000
Side	3,205 (15.4)	20 \pm 14	15 [11-23] ^{bcdg}	48	10-135	4,377 \pm 3,454	3,052 [1,836-5,458] ^{bcdg}	12,296	6-34,240	0.0990 \pm 0.2541	0.0010[0.0003-0.0103] ^{bcdg}	0.8894	0.0001-1.0000
Top	375 (1.8)	24 \pm 14	20[14-32] ^{df}	54	10-94	5,835 \pm 4,169	4,626 [2,503-8326] ^f	13,618	6-20,248	0.1760 \pm 0.3155	0.0044[0.0006-0.1392] ^{df}	0.9617	0.0001-0.9998
Outside Backs													
Front	1,332 (6.4)	19 \pm 13	14 [11-21] ^{acefg}	47	10-103	4,943 \pm 3,657	3,799 [2,567-5,996] ^{cef}	13,338	477-25,463	0.1017 \pm 0.2628	0.0018[0.0006-0.0154] ^{cef}	0.9420	0.0001-1.0000
Back	1,429 (6.9)	18 \pm 13	13 [10-20] ^{adfg}	42	10-119	4,279 \pm 3,729	3,152 [1,757-5,451] ^{adf}	11,831	341-28,402	0.0805 \pm 0.2320	0.0011[0.0003-0.0091] ^{adf}	0.7900	0.0001-1.0000
Side	1,838 (8.8)	16 \pm 11	11 [10-18] ^{acdeg}	39	10-91	3,272 \pm 3,287	2,352 [1,040-4,320] ^{acdeg}	10,189	8-22,574	0.0548 \pm 0.1887	0.0005[0.0001-0.0032] ^{acdeg}	0.4772	0.0001-1.0000
Top	147 (0.7)	23 \pm 14	19 [13-27] ^{def}	53	10-101	5,529 \pm 4,117	4,163 [2,811-6,821] ^f	14,354	767-21,384	0.1404 \pm 0.3132	0.0028[0.0009-0.0325] ^f	0.9819	0.0001-0.9999

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Adjustables													
Front	1,395 (6.7)	19±1 4	14 [11-23] ^{abefg}	48	10-100	4,808 ±3,530	3,688 [2,410-6,041] ^{befg}	12,2 99	183- 24,563	0.0943 ±0.2462	0.0017[0 .0005- 0.0162] ^{ab efg}	0.86 59	0.0001- 1.0000
Back	1,479 (7.1)	20±1 3	16 [11-26] ^{adfg}	47	10-135	4,845 ±3,917	3,601 [1,961-6,731] ^{dfg}	13,0 55	230- 24,837	0.1177 ±0.2705	0.0017[0 .0003- 0.0343] ^{df g}	0.92 74	0.0001- 1.0000
Side	3,623 (17.4)	14±1 0	11 [10-15] ^{abdeg}	33	10-144	2,742 ±3,074	1,891 [904-3,354] ^{abde g}	9,21 1	4- 25,478	0.0423 ±0.1732	0.0003[0 .0001- 0.0013] ^{ab deg}	0.25 86	0.0001- 1.0000
Top	130 (0.6)	21 ±11	17 [13-26] ^{def}	45	10-59	4,894 ±2,829	4,608 [2,951-6,127] ^{def}	11,0 75	831- 15,840	0.0772 ±0.2089	0.0027[0 .0009- 0.0235] ^{de f}	0.71 53	0.0001- 0.9937

rad/ s² = radians/second/second; IQR = interquartile [25th to 75th] range; (1) = 4 player positions; (2) = 5 player position; (3) = 4 player position; Significant difference (p<0.05) than (a) = Hit-Up Forwards; (b) = Outside backs; (c) = Adjustables; (d) = Front; (e) = Back; (f) = Side; (g) = Top

There were 103 impacts (0.5%) above the linear injury tolerance threshold and 4,505 impacts (22%) above the rotational injury tolerance threshold over the study (see Table 3). There were proportionally more impacts recorded above the linear injury tolerance threshold (>96 g) in the first, than the second year, of the study (24% vs. 16%; p<0.001). Hit-up forwards recorded more impacts in the moderate PLA(g) (66g to 106g) in the first, than the second year, of the study (3% vs. 2%; p=0.0193). As a result, hit-up forwards recorded more moderate HIT_{SP} (21 to 63) (23% vs. 16%; p<0.001) and RWE_{CP} (0.2500 to 0.7500) (6% vs. 4%; p=0.0040). Hit-

up forwards (29%) recorded more impacts above the rotational injury tolerance threshold (>5,500 rad/s²) than outside backs (21%; p<0.001) and adjustables (20%; p<0.001) in the first year of the study. Adjustables (11%) recorded fewer impacts in the moderate (4,500 to 7,900 rad/s²) rotational injury severity threshold than hit-up forwards (14%; p=0.0287) and outside backs (14%; p=0.0174) in the second year of the study. Hit-up forwards recorded more severe HIT_{SP} (>63) (2%) and RWE_{CP} (>0.7500) (6%) when compared with outside backs (1%; p=0.0011; 4%; p<0.0001) and adjustables (1%; p=0.00135; 4%; p<0.0001) over the study.

Table3. Impacts to the head greater than 10gin senior amateur rugby league for total impacts recorded and impacts per player positional group³³ over two competition match seasons for injury tolerance level,^{19, 39, 40} and impact severity limits,^{23, 41, 42} head impact telemetry severity profile³⁸ and risk weighted cumulative exposure (combined probability)¹⁸ by total impacts recorded and percentage of impacts recorded (%).

	All players			Hit-Up Forwards			Outside Backs			Adjustables		
	2014	2015	Total	2014	2015	Total	2014	2015	Total	2014	2015	Total
	n= (%)	n= (%)	n= (%)	n= (%)	n= (%)	n= (%)	n= (%)	n= (%)	n= (%)	n= (%)	n= (%)	n= (%)
Injury Tolerance												
>95g	71 (0.5)	32 (0.5)	103 (0.5)	46 (0.7) ^c	14 (0.6)	60 (0.6) ^c	13 (0.5)	6 (0.3)	19 (0.4)	12 (0.3) ^a	12 (0.5)	24 (0.5) ^a
>5,500 rad/s ²	3,377 (24.3) ^e	1,128 (16.2) ^d	4,505 (21.6)	1,984 (28.5) ^{bce}	465 (18.6) ^{cd}	2,449 (25.9) ^{bc}	574 (20.9) ^{ae}	336 (16.8) ^{cd}	910 (19.2) ^{ac}	819(19. 6) ^{ae}	327 (13.4) ^d	1,146 (25.8) ^{ab}
Injury Severity (Linear)												
<66g	13,542(97.5)	6,802 (98.0)	20,344 (97.6)	9,737 (96.7)	2,440 (97.7)	9,177 (97.0)	2,688 (98.0)	1,961 (98.0)	4,649 (98.0)	4,117(1 9.6)	2,401 (98.3)	6,518(9 8.4)
66g- 106g	319 (2.3) ^e	123 (1.8) ^d	442 (2.1)	208 (3.0) ^e	52 (2.1) ^{cd}	260 (2.7) ^{bc}	51 (1.9)	37 (1.8)	88 (1.9) ^d	60(1.4) ^d	34 (1.4)	94 (1.4) ^a
>106g	34 (0.2)	16 (0.2)	50 (0.2)	21 (0.3)	6 (0.2)	27 (0.3)	5 (0.2)	3 (0.1)	8 (0.2)	8 (0.2)	7 (0.3)	15 (0.2)
Injury Severity (Rotational)												
<4,600 rad/s ²	9,585 (69.0) ^e	5,483 (79.0) ^d	15,068 (72.3)	4,468 (64.1) ^{be}	1,907 (76.3) ^{cd}	6,375 (67.4) ^{bc}	1,961 (71.5) ^{ae}	1,566 (78.2) ^d	3,527 (74.3) ^{ac}	3,156(7 5.4) ^{ae}	2,010 (82.3) ^d	5,166 (78.0) ^{ab}
4,600- 7,900 rad/s ²	2,496 (18.0) ^e	887 (12.8) ^d	3,383 (16.2)	1,394 (20.0) ^e	336 (13.5) ^{cd}	1,730 (18.3) ^{bc}	499 (18.2) ^{ce}	276 (13.8) ^c	775 (16.3) ^{ac}	603(14. 4) ^{abe}	275 (11.3) ^{bd}	878 (13.2) ^{ab}
>7,900 rad/s ²	1,814 (13.1) ^e	572 (8.2) ^d	2,389 (11.5)	1,104 (15.8) ^{be}	255 (10.2) ^{cd}	1,359 (14.4) ^{bc}	284 (10.3) ^{ae}	160 (8.0) ^d	444 (9.4) ^a	426(10. 2) ^{ae}	157 (6.4) ^d	583 (8.8) ^a

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Injury Severity (HIT _{SP})												
<21	11,262(81.1) ^e	5,865(84.5) ^d	17,127(82.2)	5,234(75.1) ^{be}	2,059(82.4) ^{cd}	7,293(77.1) ^{bc}	2,393(87.2) ^a	1,706(85.2)	4,099(86.4) ^a	3,635(86.9) ^a	2,100(86.0)	5,735(86.5) ^a
21-63	2,446(17.6) ^e	997(14.4) ^d	3,443(16.5)	1,603(23.0) ^{be}	403(16.1) ^{cd}	2,006(21.2) ^{bc}	323(11.8) ^a	275(13.7)	598(12.6) ^a	520(12.4) ^a	319(13.1)	839(12.7) ^a
>63	187(1.3)	80(1.2)	267(1.3)	129(1.9) ^b	36(1.4) ^c	165(1.7) ^{bc}	28(1.0) ^a	21(1.0)	49(1.0) ^a	30(0.7) ^a	23(0.9)	83(0.8) ^a
Injury Severity (RWE _{CP})												
<0.2500	12,407(89.3) ^e	6,495(93.6) ^d	18,902(90.7)	6,059(87.0) ^{be}	2,293(91.8) ^d	8,352(88.3) ^{bc}	2,508(91.4) ^a	1,877(93.8)	4,385(92.4) ^a	3,840(91.8)	2,325(95.2)	6,165(93.0) ^a
0.2500-0.7500	675(4.9) ^e	227(3.3) ^d	902(4.3)	414(5.9) ^{be}	109(4.4) ^{cd}	523(5.5) ^{bc}	103(3.8) ^{ae}	54(2.7) ^d	157(3.3) ^a	158(3.8) ^{ae}	62(2.6) ^d	222(3.3) ^a
>0.7500	813(5.9) ^e	220(3.2) ^d	1,033(5.0)	493(7.1) ^{be}	96(3.8) ^{cd}	589(6.2) ^{bc}	133(4.8) ^{ae}	71(3.5) ^{cd}	204(4.3) ^a	187(4.5) ^{ae}	53(2.2) ^{bd}	240(3.6) ^a

rad/ s² = radians per second per second; HIT_{SP} = Head Impact telemetry Severity profile; RWE_{CP} = Risk Weighted Exposure Combined Probability; Significant difference (p<0.05) than (a) = Hit-Up Forwards; (b) = Outside backs; (c) = Adjustables; (d) = 2014; (e) = 2015

The total impact frequency burden per-match can be seen in Table 4. There was a median of 576 [467 to 840] impacts to the head per-match over the duration of the study. As a result, there was a median annual total impact frequency burden of 10,652 [8,073 to 15,056] g for linear accelerations, 2,532,897 [1,727,794 to

3,441,539] rad/s² for rotational accelerations; 11,520 [9,340 to 16,800] for HIT_{SP} and 47 [30 to 69] for RWE_{CP} per-match. The total impact frequency burden of the RWE_{CP} was higher in 2014 (55[40 to 86] than 2015 (34 [23 to 47]; p=0.0096) on post-hoc analysis.

Table4. Total im

	Mean ±SD	Median [IQR]	95%
2014			
No Impacts	686 ±269	633 [467-901]	1,144
PLA(g)	14,601 ±7,454	11,310 [8,723-21,006]	26,908
PRA(rad/s ²)	3,407,670 ±1863,989	2,954,443 [2,127,490-4,852,391]	6,623,892
HIT _{SP}	13,724 ±5,385	12,660 [9,330-18,010]	22,884
RWE _{CP}	79 ±60	55 [40-86] ^c	192
2015			
No Impacts	579 ±192	572 [416-673]	858
PLA(g)	10,239 ±3,695	9,729 [7,363-12,848]	15,982
PRA(rad/s ²)	2,158,670 ±736,247	2,214,129 [1,476,511-2,659,462]	3,247,945
HIT _{SP}	11,570 ±3,834	11,440 [8,320-13,450]	17,150
RWE _{CP}	38 ±17	34 [23-47] ^b	64
Total			
No Impacts	672 ±264	576 [467-840]	1,169
PLA(g)	12,912 ±6,558	10,652 [8,073-15,056]	25,667
PRA(rad/s ²)	2,923,860 ±1,632,653	2,532,897 [1,727,794-3,441,539]	6,129,579
HIT _{SP}	13,443 ±5,271	11,520 [9,340-16,800]	23,370
RWE _{CP}	63 ±52	47 [30-69]	185

pact frequency burden^a of senior amateur rugby league players for two consecutive domestic competition seasons by number of impacts recorded per match, linear and rotational accelerations, head impact telemetry severity profile and risk weighted exposure combined (linear and rotational) probability by mean (SD), median [25th to 75th interquartile range] and 95th percentile

(a) = The total impact frequency is the sum of all of the impacts by linear and accelerations, calculated HIT_{SP} and RWE_{CP}; PLA (g) = peak linear acceleration; PRA (rad/s²) = peak rotational acceleration in radians/second/second (rad/s²); IQR = interquartile range; HIT_{SP} = Head Impact telemetry Severity profile; RWE_{CP} = Risk Weighted Exposure Combined Probability; Significant difference (p<0.05) than (b) = 2014; (c) = 2015

5. DISCUSSION

Players received an average of 52 impacts to the head over 10g per game over the course of the study. As there are no published studies reporting impact biomechanics in rugby league

the inter-study comparisons are limited to New Zealand senior amateur rugby union, American high-school and collegiate football studies. Not every study reviewed utilised the same reporting format, or data acquisition limit, necessitating the reporting of data as mean (±SD), median

[25th-75 IQR] and 95th percentile at the 10g data acquisition limit. Even with using these reporting formats, some studies utilised the 75th percentile, the median of the 95th percentile,⁴⁶ while other studies did not report rotational accelerations¹³ limiting inter-study comparisons. Some studies combined matches and practices and only reported the total biomechanical data while others incorporated both match and practice biomechanical data,⁴⁶ again limiting potential comparisons. As shown in this study, there are a variety of magnitudes able to be reported and as we have provided mean (\pm SD), median [IQR] and 95th percentile this does make it complex to read but provides data for a wider inter-study analysis to be completed. A consensus³⁴ needs to be established on what the reporting formats for impact biomechanical data (i.e. match vs practice and not combined) should be, and what parameters should be reported (i.e. PLA(g), PRA(rad/s²), HITsp, GSI, HIC₁₅, RWE_{CP}) to enable future inter-study comparisons to be completed.

The median PLA(g) value recorded (14g) were similar to youth rugby union (15 g),³⁰ but lower than American youth (20.2 g, 22g),^{47, 48} high school (21.7 g)¹⁸ and collegiate (15g, 21g, 22g)^{13, 46, 49} football players and high school (30.9 g) and collegiate (31.9 g) soccer players.²⁴ The mean PLA(g) (19g) was lower than the mean reported for American youth (25.5 g, 32g),^{48, 50} and collegiate (21 g),⁴⁹ football players and New Zealand senior amateur rugby union (22g) players.¹⁰ The median PRA (rad/s²) value recorded (3,181 rad/s²) was higher than the median (671 rad/s²; 1,013 rad/s²) but similar to the 95th percentile (2,743 rad/s²; 2,347 rad/s²) reported in American high school football.^{8, 18} When compared with American collegiate football, the median PRA(rad/s²) value recorded was higher than the median of impacts reported (1,392 rad/s²),⁵¹ sub concussive rotational accelerations (872-981 rad/s²),¹⁷ but lower than the concussive PRA(rad/s²) recorded (4,948 rad/s²).¹⁷ When reviewed by the mean PRA(rad/s²) (4,350 rad/s²), this was higher than studies reporting data for American high school players (1,670 rad/s²)⁵² but similar to New Zealand senior amateur rugby union¹⁰ players (3,990 rad/s²). When compared to the median of the 95th percentile of American collegiate football players (3,147 rad/s²)⁵¹ the findings were lower than the mean of the impacts recorded, but the 95th percentile of the peak rotational accelerations recorded in this study

were higher (11,562 rad/s²). The higher extreme values could be reflective of the activities undertaken in rugby league when compared with American football and rugby union. Rugby league requires that players are tackled and taken to the ground after having a 10 m running gap between the defensive and attacking sides. The tackle typically requires two to three players wrestling the ball carrier to the ground with the focus to dominate the tackle, while the ball carrier tries to maintain an upright position in an effort for a fast play-the-ball. Further studies are warranted to identify the tackling differences between rugby league, rugby union and American football.

The distribution of impacts by location showed that 42% of impacts occurred to the side of the head which is in conflict with other studies reporting impacts in American high school (front of the head)⁷ and collegiate (top of the head)^{13, 51} football but similar to head impact position for New Zealand senior amateur rugby union.¹⁰ When viewed by positional groups the front of the head was the most common impact location for hit-up forwards (36%) which was similar for studies reporting American youth (43%)⁴⁸ and collegiate (36%)¹³ football impacts in games but different to that reported in senior amateur rugby union in New Zealand.¹⁰ The differences in the impact locations when viewed by positional groups are likely reflective of the roles these groups play during rugby league matches when compared with American football and senior amateur rugby union. Hit-up forwards are more involved in taking the ball straight into the opposition defensive line and are involved in more front on tackle situations and therefore recorded more impacts to the side and front of the head (15%). In contrast, the outside backs (side: 8.8%) and adjustable (side: 17.4%) are involved in wider roaming roles to either go outside the defensive line or to attack the defensive line on an angle with the aim of breaking through the line to score a try.

It has been suggested that concussions, or a combination of concussions and sub-concussive head impacts, may result in long-term conditions such as chronic traumatic encephalopathy,⁵³ mild cognitive impairment⁵⁴ and depression⁵⁵ but the exact mechanisms that result in these conditions is not yet fully understood. Although cumulative impact burden is suspected to play a role in the development of these conditions,³⁹ this has yet to be established.

The large number of impacts per-match, linear and rotational accelerations, HIT_{SP} and RWE_{CP} values recorded over the duration of this study may be an indicator of the possible risk these players may have for these long-term conditions. However, the data should in no way be interpreted as evidence to refute or support a cause-and-effect³⁹ that these players may have, or will have, any of these conditions. The signs and symptoms of these conditions typically occur after players have ceased playing contact sports and currently cannot be attributed directly to the exposure to these impacts. This study only recorded impacts to the head from match activities and did not account for exposure to impacts in the training environment or through other activities of daily living that individual players may be exposed to.

6. LIMITATIONS

Data from X2Biosystems XPatch accelerometers have been reported in previous studies,^{24, 25, 30, 56-58} of which two studies^{24, 25} tested the biomechanical validity in different settings. By comparing in-vivo performance of the XPatch via video capture in a simulated low-impact soccer setting, Wu et al.²⁵ studied 25 impacts, one impact location, one mastoid placement location and one XPatch accelerometer on a single subject. It was reported²⁵ that the XPatch over-estimated individual linear and rotational accelerations that was likely to be related to the subject's viscoelastic properties of the soft tissues. In another study, McCuen et al.²⁴ evaluated the X Patch on a Hybrid III head form as a prelude to live-play soccer. There were 250 impacts over five impact locations with two mastoid placement locations and five different XPatch accelerometers. It was reported²⁴ that there was significant XPatch measurement root mean square error related to individual impacts for PLA and PRA of ~50%. The study also looked at aggregate performance over a larger number of impacts and reported that the "average values over a large number of acceleration events can be determined with good accuracy."²⁴ In another study utilising the XPatch in collegiate football, Reynolds et al.⁵⁷ reported that the number and linear severity of head impacts were favorable comparable to published studies reporting^{7, 9, 13, 50, 59, 60} data for helmet based accelerometers. However, there were discrepancies reported⁵⁷ between the rotational severity of head impacts measured by

the XPatch and similar published data from helmeted systems.⁵⁶ More recently Chrisman et al.³⁶ evaluated the XPatch on a Hybrid III headform to a criterion standard and reported there was an over-estimation for PLA and an underestimation for PRA. As a result, they adjusted the XPatch results to the criterion standard. These adjustment calculations were therefore incorporated into the results of our study.

The use of the XPatch was novel in that the patch incorporates the accelerometer and gyroscope into a reusable monitor adhered to the side of the head behind the ear directly over the mastoid process of the player. The patches were applied utilising an adhesive patch to hold the patch to the adhesive and this was applied to the side of the head behind the ear. The effects of sweating by the player, and some extreme weather conditions, resulted in some of the adhesives falling off the player during the match activities. Players who were grabbed around the head during the tackle sometimes had the patch pulled off. As a result, the data reported were incomplete and the number of impacts would be more than have been reported. It is unlikely that the XPatch was tested under all of the activities seen in rugby league matches such as the tackle and scrum situations and how these correlate to the laboratory conditions results. Although we have reported these data, there are no consistent reliability studies for the XPatch and the interpretation of these results should be undertaken with some caution.

All games were captured on video to enable verification of the impacts recorded. The percentage of impacts that were able to be identified by video review and analysis was only 90% of the total impacts recorded per match, as only one video recorder was used. The ball carrier with possession of the ball is required to be tackled to the ground and, in most cases, this required two or more defenders to be involved in the tackle. The aim of the tackler was to stop the momentum of the ball carrier from gaining ground, or to cause the ball carrier to lose possession of the ball. Once momentum is stopped the objective is to take the ball carrier to the ground and, ideally, turned on their back to slow down the play-the-ball situation. Defending players joining the tackle in an attempt to put the ball carrier on the ground would result in multiple impacts to the ball carrier being recorded. As a result, not all the

impacts recorded were able to be identified with the use of only one camera. This is a limitation of the study and future studies should include at least three high definition video cameras placed on one side of the field and one at each end of the playing field, preferably in an elevated position.

7. CONCLUSION

The study was conducted to describe the magnitude, frequency and distribution of head impacts sustained by a single amateur senior premier rugby league team over a competition season of matches. By utilising accelerometer fitted patches applied behind the ear of players in a single premier team throughout the 2014 and 2015 domestic seasons of matches there were 20,837 impacts recorded. Median linear accelerations were lower than high school and collegiate American football while the median rotational accelerations were higher. Further studies should further explore head impact characteristics at all levels of participation in rugby league.

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