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Head impacts measured with a monitoring mouthguard for an amateur women's rugby union team in New Zealand

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Abstract

Background: The immediate and long-term effects of multiple and repeated blows to the head that athletes receive in contact sporting environments are a growing concern in clinical practice.

Purpose: Quantifying head impacts utilising instrumented mouthguard acceleration analyses for amateur women rugby-15s players in New Zealand.

Study design: Prospective observational cohort study.

Methods: Twenty-four players were fitted with a moulded impact monitoring mouthguard (Prevent Biometrics; www.preventbiometrics.com) and pre-season baseline tested with the King-Devick Test. Players resultant peak linear and peak angular accelerations were recorded during every match.

Results: Over the competition season of nine matches there were 885 impacts recorded ≥10 g (range 10 g to 110.7 g) with a mean of 97.2±44.1 head impacts per-match, resulting in a mean of 12.7±11.5 head impacts per-player per-match. Outside-backs recorded more impacts to the top of the head than front-row forwards ($\chi^2(1)=20.2$; $p<0.0001$; d=0.66), back-row forwards ($\chi^2(1)=34.3$; $p<0.0001$; d=0.99) and inside-backs ($\chi^2(1)=43.5$; $p<0.0001$; d=1.06). Three concussions were recorded over the competition season resulting in a concussion injury rate of 16.7 (95% CI: 0.0 to 35.6) per 1,000 match-hrs and had a difference in their post injury King-Devick Test scores of -10.6 [-20.2 to -6.5] sec when compared with their baseline scores.

Discussion: The finding that backs recorded more impacts than forwards was unexpected and may reflect the match tactics employed by the amateur women's rugby union team cohort. Further studies are warranted with identical head impact technology to enable the establishment of the range of peak linear acceleration and peak angular acceleration values for participation and concussion risk.

Conclusion: An average of thirteen head impacts above 10 g per-player per-match means the effects of sub-concussive impacts to the brain need to be examined.

What is known about this subject:

- Only 8% of head impact biomechanics studies have reported on female only sports and only one study has reported on head impact biomechanics in women' rugby union.
- Collegiate women's rugby union reported 0.4 impacts per-player per-game for impacts >15g.
- The immediate and long term effects of multiple and repeated head impacts in contact sporting environments are a growing concern in clinical practice.

What this study adds to existing knowledge:

- Head impacts recorded per-match and per-player per-match, were less than previous studies reporting on senior men's amateur rugby union and women's rugby league but higher than junior rugby union, women's domestic netball and women's collegiate rugby union.
- Total head impact distribution varied by impact location with the top of the head recording the highest number of impacts which is in conflict with other studies reporting on head impact biomechanics in rugby union.
- Players took an average of 28 days to recover from concussion before they were cleared to return to full training activities.

Introduction

Rugby Union (more commonly known as rugby) is a contact team sport played in 121 countries worldwide, with more than 9.1 million registered players, of which 2.4 million (26%) are female [1]. Played over two 40-minute halves, interspersed with a 10-minute rest interval [2-4], rugby is a full contact collision sport characterised by frequent bouts of both high-intensity (e.g. running, tackling, rucks, mauls, passing and sprinting) and low intensity (e.g. jogging and walking) intermittent activities throughout match activities [2,5]. As rugby is a physical sport, players are exposed to repeated collisions and impacts. This integral part of the game [6] gives rise to an inherent risk of injuries such as concussion [7].

The immediate and long term effects of multiple and repeated head impacts that athletes receive in contact sporting environments are a growing concern in clinical practice. Concern has intensified about the effects of subconcussive head impacts and how these affect cerebral functions [8,9]. Subconcussive events are impacts that occur where there is an apparent brain insult with insufficient force to result in the hallmark signs and symptoms of a concussion [9,11,12]. Although subconcussive events do not result in observable signs and apparent behavioural alterations [13,14], they can cause damage to the central nervous system and have the potential to transfer a high degree of linear and angular acceleration forces to the brain [15]. Proposed decades previously [16,17], exposure to repetitive subconcussive blows to the head result in similar, if not greater damage than a single concussive event [11] and have cumulative effects [18].

Although there have been multiple studies reporting on head impact biomechanics, 19 only 8% of these studies have reported on female only sporting activities. In addition, there have been only three (1.2%) studies [1,20,21], on rugby union using different instrumentation with only one study [1] reporting on women's rugby union. These studies were on junior (Male; XPatch; X2Biosystems, Seattle, WA); 21 amateur premier domestic (Male; XGuard; X2Biosystems, Seattle, WA) [20], and collegiate (Women's; Headband; Smart Impact Monitors; Triax Technologies, Inc., Norwalk, CT) 1 levels of participation.

Recently, there has been a call for research efforts to be directed towards development of an evidenced based framework towards an understanding of women's physiological, training, injury and illness surveillance data [22,23]. In order to address this call, the aim of this study was to quantify head impacts via instrumented mouthguard acceleration analyses for amateur women rugby union players over a competition season of matches in New Zealand.

Materials and methods

A prospective observational cohort study was conducted on a women's club level amateur rugby union team during the

2021 competition in New Zealand. All 24 female players (mean ± SD age; 26.9±9.2 yrs.) received no remuneration for participating in rugby union activities. The matches were played under the laws of the New Zealand Rugby Football Union. The players participated in nine competition matches resulting in a match exposure of 179.6 match hrs. The Health and Disability ethics committee approved all procedures in the study (HDEC 18/STH/224/AM02) and all players gave informed consent prior to participating.

Participants: Players were categorised according to their playing and positional groups: [24] (1a) Forwards (loose-head prop, hooker, tight-head prop, left lock, right lock, blind-side flanker, open-side flanker, and number eight) and (1b) Backs (scrum half, fly half, left wing, inside centre, outside centre, right wing, and full back); and (2a) Front Row Forwards (FRF) (loose-head prop, tight-head prop; left lock, right lock); (2b) Back Row Forwards (BRF) (hooker; blind-side flanker, open-side flanker, number eight); (2c) In-Side Backs (ISB) (scrum half; fly half, inside centre, outside centre) and (2d) Out-Side Backs (OSB) (left wing, right wing, full back). The hooker was included in the BRF group due to their roving style of play [25].

Instrumentation

Players were fitted with a moulded Impact Monitoring Mouthguard (IMM) (Prevent Biometrics, Minnesota, USA; www.preventbiometrics.com) during the preseason period. The IMM was a Generation 1.3 wireless three channel linear acceleration and three channel of angular [rotational] acceleration ('3a3w') gyroscope Data Acquisition System (DAQ) that was hermetically sealed inside a player's mouthguard [26]. The structural plastic is a safe TPU and EVA blend (Polyshok™, Sportsguard Laboratories, Kent OH) that provides a protective bite resistant cover for the electronics and battery [27]. The DAQ contains kinematic sensors with bandwidth and range to estimate skull motion during impact using the ADXL372 accelerometer (Analog Devices, Boston MA, USA) and the BMG250 gyroscope (Bosch, Gerlingen, Germany) integrated into the onboard firmware for data transformation from the teeth to the heads Centre of Gravity (CG). Once an impact occurs over the preset trigger of 10 g Peak Linear Acceleration (PLA(g)) the DAQ samples at 3,200 Hz recording a pre-trigger duration of 10 ms and post trigger duration of 40 ms providing a total of 50 ms of data. The data were stored in a non-volatile flash memory, powered by a wireless rechargeable battery, and used Bluetooth low energy for wireless data download. The IMM was independently validated through Virginia Tech [28] and Stanford University [29] and has been reported to have an active-minute Positive Predictive Value (PPV) for head impacts of 96.4% (95% CI: 93.3 to 99.0%) and a conCordance Correlation Coefficient (CCC) to a reference headform and the kinematic measurements of 0.97 [28]. However it is important to note that no on-field head impact telemetry system is perfect in comparison with the gold standard of the instrumented headform [30-32]. The IMM can continuously monitor linear and angular accelerations, direction, and orientation of the player during match-play. Prior to each game the IMM was charged in the manufacturer's charging box for a minimum of 24 hrs. On the day of the match, players were provided with their individually fitted IMM and the connection was Bluetooth checked with the iPhone app before leaving the changing room. Only players on the field during match participation had their impacts recorded. Anytime a player was substituted the data collection would stop for the retiring player and commence for the new player. A record was kept of the times players were substituted. Impacts <10g of linear acceleration were considered negligible in regards to impact biomechanical features and to eliminate head accelerations from non-impact events such as jumping and running [33]. Their relationships to head trauma make it difficult to distinguish between head impacts and voluntary head movement [34].

King-Devick Test in association with Mayo Clinic developed in the 1970's by Alan King and Steven Devick to evaluate children suspected of dyslexia or impaired saccadic eye movements [35], the King-Devick Test (K-DT) is a rapid number naming task that takes <2 min to administer [36]. The participant reads aloud a sequence of single digit numbers from the left to the right of the screen that includes one demonstration card and three visually distinct test cards that increase in difficulty [37]. Utilised in the assessment of collegiate football, soccer and basketball players [37], amateur rugby union and rugby league players [38], professional ice hockey players, 39 boxers and mixed martial arts players, [40] the K-DT has been reported to have a high sensitivity (0.86; 95% CI: 0.79 to 0.92), specificity (0.90; 95% CI: 0.85 to 0.93) for identifying concussed versus non-concussed participants and an Intra-Class Correlation (ICC) of 0.91 (95% CI: 0.85 to 0.97) [41,42]. In addition, the K-DT has been reported to have significant correlations (p<0.0001) with the Visual Motor Speed (VMS), Reaction Time (RT), Verbal Memory (VEM) and Visual Memory (VIS) of the Immediate Post-concussion Assessment Cognitive Test (ImPACT®) [43], computerised concussion evaluation system. The K-DT relies upon comparing the differences between baseline and post-injury results to provide an insight into a potential concussive injury [44] and has been utilised by parents and non-health care professionals [45]. The K-DT has not been recommended for use as a standalone diagnostic tool [41,46] and the K-DT should be utilised in conjunction with other concussion assessment tools as a sideline screening tool [46,4]. Screening of players using the K-DT test manufacturers recommendation is that any slowing (worsening) of >1 s from the players established baseline is a "fail" and concerning for a potential concussion [44].

All players were tested during pre-season with a tablet (iPad; Apple Inc., Cupertino, CA) according to the developer's recommendations (v4.2.2; King-Devick technologies Inc.). All baseline testing was completed at training to mimic the sideline playing field environments. Players were asked to read card numbers from left to right as quickly as they could without making any errors using standardized instructions. Time was kept for each test card, and the entire test K-DT summary score was based on the cumulative time taken to read all three test cards [48]. The number of errors made in reading test cards was recorded. The best time (fastest) of two trials 5-minutes apart without errors became the established baseline K-DT time [40].

Concussion were classified as witnessed (a concussive injury that met the definition of a concussion [49], that was identified during match activities resulting in removal from match activities and had >3 s for pre to post-match K-DT, and later confirmed by a physician's clinical assessment) or unwitnessed (changes >3 s for pre to post-match K-DT36, [38] with associated changes, and later confirmed by a physician's clinical assessment). The 3s threshold for changes in post-match K-DT was identical to studies reporting K-DT test use [50,51].

Concussion

The definition of a concussion utilised for this study was "any disturbance in brain function caused by a direct or indirect force to the head. It results in a variety of non-specific symptoms and often does not involve loss of consciousness. Concussion should be suspected in the presence of any one or more of the following: (a) Symptoms (such as headache), or (b) Physical signs (such as unsteadiness), or (c) Impaired brain function (e.g., confusion) or (d) Abnormal behaviour" [49]. An 'unwitnessed' concussion was defined for the purpose of this study as "any disturbance in brain function caused by a direct, or indirect force, to the head that does not result in any immediate observable symptoms, physical signs, impaired brain function or abnormal behaviour but had a delay in the post-match K-DT score of >3s and associated changes in the post-match SCAT5" [38]. A subconcussive impact was defined as any "impact that does not result in a concussion diagnosis, does not result in time-loss of participation in practice or games and does not result in concussion related symptoms that linger for a prolonged period of time [52].

Match day procedures

During matches, the team medic (lead researcher), observed players for any signs of direct contact to the head, or being slow to rise from a tackle or collision, or being unsteady on their feet following a collision. If this occurred, players were assessed on-field. If there were any signs of delayed answering, incorrect answers to questions, or if the player appeared to be impaired in any way, the player was removed from match activity and rested on the sideline. Players who reported any sign(s) of a concussion, who were suspected to have received a concussion, or who were removed from match participation were initially screened with the sideline K-DT after a 15-minute rest period; not allowed to return to play on the same day; and, referred for further medical assessment. The test was administered once using the same instructions, and time and errors were recorded and compared to the participant's baseline. Worsening time and/or errors identified on the sideline or post-match K-DT have been associated with concussive injury [37,39,40]. The K-DT performance has been shown to be unaffected in various noise levels and testing environments [53].

Players' who had been identified with delayed (worsening) post-match K-DT times were not allowed to return to training or match activities without a full medical clearance. Players with a loss of consciousness were treated for a cervical spine injury and managed accordingly. All suspected concussive injuries were evaluated by the player's own health professional. All players that were identified with a delay (worsening) of the K-DT from their baseline were assessed by their health professional for a formal assessment. No player was allowed to return to full match activities until they were medically cleared and, had returned to their baseline K-DT score.

Statistical analysis

Post-match data was downloaded onto an Excel spreadsheet (Microsoft V2107) and trimmed (to include on-field match-play time) using proprietary software (Prevent Biometrics, Edina, MN, USA). All matches were videotaped (Sony HDR-PJ540 Camcorder) to enable verification of the impacts recorded and the video was reviewed after every match. The resultant data was entered onto a Microsoft Excel spreadsheet and analysed with SPSS (IBM SPSS Statistics for Windows, Version 21.0.1.0 Armonk, NY: IBM Corp). Data were checked for normality and homogeneity of variance using a Shapiro-Wilk test and one sample t-test were conducted for PLA (g) and PAA (rad/s2). If tolerances were not met, equivalent non-parametric tests were utilised. The impact variables were not normally distributed (PLA(g):W(885)=0.234; p<0.0001; t(884)=46.0; p<0.0001; PAA (rad/s2):W(885)=0.171; p<0.0001; t(884)=34.9; p<0.0001), therefore data were expressed as median [IQR]. As the data were positively skewed and to control for this violation of normality, the impact magnitudes the data were natural log transformed before analysis. It must be noted that, for interpretability, all impact magnitude results are presented in the original non-transformed units.

Four measures of impact frequency were computed for each player: player impacts per match, the total and average number of head impacts recorded for a player during all matches; and player group and positional group impacts, the total and average number of recorded head impacts for the playing group (forwards and backs) and positional group (FRF; BRF; ISB; OSB) for all matches.

The impact location variables were computed as azimuth and elevation angles relative to the Centre of Gravity (CG) of the head centred on the mid-sagittal plane [54]. These were categorized as front, side, back top and bottoms. 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 [55]. Impact locations were analysed by left and right side, low and high and front and rear impacts using a Friedman repeated measures ANOVA on ranks.

Head impacts were assessed for injury tolerance level for a concussion occurring using previously published injury tolerance levels [15,56,57] for linear (>95g) and angular acceleration (>5,500 rad/s2). Head impacts were assessed for impact severity using previously published levels for PLA(g) (mild <66 g, moderate 66-106 g, severe >106 g) and PAA (rad/s2) (mild <4,600 rad/s2, moderate 4,600-7,900 rad/s2, severe >7,900 rad/s2) [58,59]. Both injury tolerance and impact severity levels were analysed using a Friedman repeated measures ANOVA on ranks. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied. Additional analysis was undertaken to establish the Risk Weighted Exposure Combined Probability (RWECP) [60]. Combining the linear and angular accelerations to elucidate individual player and team-based exposure to head impacts, the RWECP is a logistic regression equation and regression coefficient of injury risk prediction for an injury occurring based on previously published analytical risk functions [60]. The logistic regression equations and regression coefficients of the injury risk functions utilised in the prediction of injury (Table 1), β0, β1, β2 and β3 are regression coefficients, a is the measured linear acceleration, and α is the measured angular acceleration for the combined probability risk function [60]. The RWECP values were evaluated by values of 25% risk (<0.25) 25% to 75% risk (0.25-0.75) and >75% risk (>0.75). The RWECP was analysed by player position impacts and player group impacts utilising a Friedman repeated measures ANOVA on ranks. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied.

Total frequency impact burden per-match was analysed using a Kruskal-Wallis one-way ANOVA with a Dunn's post-hoc test for all pairwise comparisons with player positions. Although there is no accepted method to quantify total frequency impact burden [15] the sum of linear and angular accelerations associated with each individual head impact per-match over the course of the study was calculated for all of these parameters. The total sum of the resultant peak linear and the peak angular accelerations recorded was undertaken for each match, player

Table 1: Logistic regression equation, risk function and regression coefficients for the Risk Weighted Exposure Combined Probability (RWECP).

Logistic Regression equation	Risk function	Regression coefficients
$cp = \frac{1}{1+e^{-(\beta_o+\beta_1 a+\beta_2 \alpha+\beta_3 a\alpha)}}$	Combined Probability (CP)61	β_o= -10.2, β_1= 0.0433, β_2= 0.000873, β_3= -9.2E-07

role, player position and for the study duration. Head impact exposure including impact frequency, magnitude and location of impacts were quantified using previously established methods [62,63].

Median peak linear and angular 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 with a Bonferroni correction applied. 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), were used to determine whether the observed impact frequency was significantly different from the expected impact frequency. Differences in the K-DT scores were compared on those players with a medically diagnosed concussion for baseline and post-injury K-DT time scores using a 2-tailed t-test. Cohen's d effect sizes were also computed to complement interpretation of results, with effect sizes being interpreted as negligible/very small (d<0.20), small (d=0.20 to 0.49), medium (d=0.50 to 0.79), or large (d>0.80) [64,65]. Statistical significance was set at p<0.05.

Results

Over the 2021 domestic rugby union season of matches there were a total of 885 impacts (range 10 g to 110.7 g) recorded ≥10 g (see Table 2) with a mean of 97.2±44.1 head impacts per-match resulting in a mean of 12.7±11.5 head impacts per-player per-match. Players recorded a median [IQR] of 14.2 [11.6 to 19.5] g for peak linear, and 1,633 [993 to 2284] rad/s2 for peak rotation acceleration. There were three impacts recorded >95g over the nine competition matches. Backs recorded more impacts (508 vs. 377; RR: 1.35 [95% CI: 1.23 to 1.48]; p<0.0001; d=0.21) than forwards and had a higher resultant median PAA (rad/s2) (1,727.0 rad/s2 vs. 1,462.0 rad/s2; χ^2(1)=4.3; p=0.0391; z=-2.52; p=0.0118; d=0.07).

Table 2: Head impacts greater than 10 g in amateur women's rugby union in New Zealand over a single domestic competition season of matches for total players, player group by number of impacts recorded, average impacts per-match and per-player per-match, resultant peak linear and angular accelerations, and risk weighted exposure combined probability by mean and standard deviation and median with interquartile range and total impact burden.

				PLA(g)		PAA (rad/s2)		RWECP	
	Number impacts recorded	Average per-match Mean ± SD	Average per-player per-match Mean ±SD	Median [IQR]	Total Impact burden$ Sum	Median [IQR]	Total Impact burden$ Sum	Median [IQR]	Total Impact burden$ Sum
Total1	885	97.2 ±44.1	12.7 ±11.5	14.2 [11.6-19.5]	15,812.3	1,633.0 [993.0-2,284.0]	1,716,680.0	0.0003 [0.0002-0.006]	11.5072
	377b	41.9 ±24.8	10.8 ±12.2	14.9 [11.0-23.5]	6,953.7	1,662.5b [1,035.5-2,796.5]	707,051.0	0.0003b [0.0002-0.0011]	6.0838
Prop	64hijmnop	8.0 ±3.4	4.0 ±1.9	13.2ko [10.9-16.5]	1,029.2	1,615.0hop [906.0-2,194.3]	113,412.0	0.0003k [0.0001-0.004]	0.9453
Hooker	31giklnop	4.4 ±3.2	4.4 ±3.2	13.9k [12.3-18.8]	511.1	913.5gkop [562.0-1,707.5]	33,394.0	0.0002kop [0.0001-0.0004]	0.0100
Lock	180ghjklmo	22.5 ±20.5	11.3 ±10.0	14.5 [10.0-20.4]	3,489.1	909.5p [702.8-2,111.3]	364,975.0	0.0001 [0.0001-0.0007]	4.6171
Flanker	29giklnop	5.8 ±3.3	2.9 ±1.7	14.9l [11.0-23.5]	534.0	1,662.5o [1,035.5-2,796.5]	50,808.0	0.0003o [0.0002-0.0011]	0.0403
No. 8	73hijmnp	10.4 ±8.0	10.4 ±8.0	17.0ghlno [11.8-23.3]	1,390.3	1,714.5hm [1,052.3-3,276.0]	144,462.0	0.0003ghlm [0.0002-0.0017]	0.4711
	244d	27.1 ±22.9	15.3 ±16.0	14.5e [10.0-20.4]	4,518.3	909.5f [702.8-2,111.3]	478,387.0	0.0001f [0.0001-0.0007]	5.5624
	133cef	14.8 ±13.8	7.0 ±5.9	14.9 [11.0-23.5]	2,435.4	1,662.5f [1,035.5-2,796.5]	228,664.0	0.0003 [0.0002-0.0011]	0.5214
	508a	46.8 ±22.8	13.6 ±10.2	13.4 [10.8-20.2]	8,858.6	1,203.0a [697.5-1,682.8]	1,009,629.0	0.0002a [0.0001-0.0004]	5.4234
Half-Back	55hijmnop	18.3 ±5.9	18.3 ±5.9	12.0jko [11.0-16.0]	776.2	1,685.0 [1,389.0-2,055.0]	94,059.0	0.0003k [0.0002-0.0004]	0.0277
1st five-eight	22giklnop	3.1 ±2.2	3.1 ±2.2	13.4 [10.8-20.2]	423.0	1,203.0kop [697.5-1,682.8]	28,918.0	0.0002ko [0.0001-0.0004]	0.0173
Centre	148ghjklmop	18.5 ±11.0	9.8 ±5.9	14.0ko [10.0-19.5]	2,683.3	1,554.0p [579.5-2,157.3]	286,992.0	0.0002p [0.0001-0.0005]	2.8246
Wing	90ghijlmnp	10.0 ±6.3	5.0 ±3.3	18.6ghlm [13.8-46.4]	1,762.0	2,523.5ghjmp [1,731.0-5,306.5]	190,373.0	0.0007hjm [0.0003-0.0250]	1.2248
Fullback	193ghjklmno	26.1 ±4.9	26.1 ±4.9	14.5 [11.6-19.4]	3,214.1	1,740.0ghimno [1,436.8-2,408.5]	409,287.0	0.0003hn [0.0002-0.0006]	1.3290
	225df	25.0 ±18.2	12.5 ±10.7	13.4c [10.8-20.2]	3,882.5	1,203.0cdf [697.5-1,682.8]	409,969.0	0.0002f [0.0001-0.0004]	2.8697
	283de	21.8 ±14.5	15.1 ±9.8	14.5 [11.6-19.4]	4,976.1	1,740.0e [1,436.8-2,408.5]	599,660.0	0.0003ce [0.0002-0.0006]	2.5538

SD: Standard Deviation; IQR: Inter-Quartile Range; FRF: Front Row Forwards; BEF: Back Row Forwards; ISB: Inside Backs; OSB: Outside Backs; Significantly (p<0.05) different than (a) = Forwards; (b) = Backs; (c) = Front Row Forwards; (d) = Back Row Forwards; (e) = Inside Backs; (f) = Outside Backs; (g) = Prop; (h) = hooker; (i) = Lock; (j) = Flanker; (k) = No. 8; (l) = Halfback; (m) = 1^{st} five-eight; (n) = Centre; (o) = Wing; (p) = Fullback; 1 = 15 positions; 2 = 8 player positions; 3 = 7 player positions; 4 = 4 players; 5 = 3 players; $: The sum of the accelerations associated with each individual head impact [15].

Back-row forwards recorded fewer impacts (n=133) than FRF (RR: 1.8 [95% CI: 1.5 to 2.2]; p<0.0001; d=0.65), ISB (RR: 1.7 [95% CI: 1.4 to 2.1] p<0.0001; d=0.63) and OSB (RR: 2.1 [95% CI: 1.8 to 2.6]; p<0.0001; d=0.49) (Table 2). The No. 8 forward recorded a significantly higher median resultant PLA(g) (17.0 [11.8 to 23.3]g) than the prop ($\chi^2(1)$=7.6; p=0.0060; z=-3.1; p=0.0019; d=0.29), hooker ($\chi^2(1)$=3.9; p=0.0482; z=-2.3; p=0.0197; d=0.26), and centre ($\chi^2(1)$=8.2; p=0.0041; z=-3.0; p=0.0032; d=0.07). The first five-eight recorded a significantly lower median resultant PAA (rad/s2) (1,203.0 [697.5 to 1,682.8] rad/s2) than the No. 8 forward ($\chi^2(1)$=11.6; p=0.0006; z=-3.0; p=0.0030; d=0.55), wing ($\chi^2(1)$=8.9; p=0.0028; z=-3.2; p=0.0015; d=0.62) and fullback ($\chi^2(1)$=6.5; p=0.0105; z=-2.6; p=0.0099; d=0.79) over the season. The hooker recorded a significantly lower RWECP (0.0002 [0.0001 to 0.0004]) than the No. 8 ($\chi^2(1)$=11.6; p=0.0006; z=-3.3; p=0.0011; d=0.21), wing ($\chi^2(1)$=9.3; p=0.0023; z=-3.2; p=0.0013; d=0.29) and fullback ($\chi^2(1)$=11.6; p=0.0006; z=-3.3; p=0.0011; d=0.13).

The front of the head recorded more impacts (n=252) than the back (RR: 2.7 [95% CI 2.2 to 3.3]; p<0.0001), left (RR: 4.0 [95% CI: 3.1 to 5.2]; p<0.0001 and right (RR: 3.4 [95% CI: 2.6 to 4.3]; p<0.0001) sides of the head (see Table 3). The top of the head recorded a higher PLA (15.2 [12.1 to 21.0]g) than the front ($\chi^2(1)$=8.6; p=0.0034; z=-3.1; p=0.0019; d=0.35) and rear ($\chi^2(1)$=5.3; p=0.0218; z=-2.7; p=0.0063; d=0.34) of the head. Outside backs recorded a higher median resultant PLA(g) 14.8g [12.0 to 20.1]g) to the front of the head than ISB ($\chi^2(1)$=5.1; p=0.0244; z=-2.5; p=0.0124; d=0.33). Front row forwards recorded a lower resultant median PAA (rad/s2) (1,651.5 [1,000.0 to 2,228.0] rad/s2) than OSB ($\chi^2(1)$=6.2; p=0.0126; z=-2.3; p=0.0193; d=0.18). Back row forwards recorded a higher median resultant PAA (rad/s2) to the left (1,405.0 [853.8 to 1,846.8] rad/s2) when compared to the right ($\chi^2(1)$=4.5; p=0.0348; z=-2.0; p=0.0409; d=0.83) side of the head. Inside backs recorded a higher medial RWECP to the left (0.0004 [0.0002 to 0.0014]) when compared with the right ($\chi^2(1)$=4.6; p=0.0325; z=-2.2; p=0.0258; d=0.45) side of the head.

There were three concussions recorded over the competition season resulting in a concussion injury rate of 16.7 (95% CI: 0.0 to 35.6) per 1,000 match-hrs (see Table 5). Although there was a median decline (worsening) of K-DT time score of -10.6 s [IQR: -20.2 s to -6.5 s] when compared with the player's established baseline, this was not significant (t(2)=-3.1; p=0.0921).

Discussion

This study is the first to record and report head impacts in amateur women's rugby union in New Zealand. The main findings from this study were:

1. There were an average of 97.2±44.1 head impacts per-match that equated to an average of 12.7±11.5 head impacts per-player per-match over the competition;

2. The median PLA (g) recorded over the competition season was 14.2 g [11.6 to 19.5] g;

3. The median PAA(rad/s2) recorded over the competition season was 1,633.0 [993.0 to 2,284.0] rad/s2;

Table 3: Head impact location greater than 10 g of amateur women rugby union players in New Zealand over a single domestic competition season of matches by player group for number of impacts recorded, resultant peak linear and angular accelerations, and risk weighted exposure (combined probability) reported by median and inter-quarter range.

	Front row forward		Back row forward		Inside backs		Outside backs		Total	
	n=	Median [IQR]	n=	Median [IQR]	n=	Median [IQR]	n=	Median [IQR]	n=	Median [IQR]
PLA (g)										
Front	60	13.0 [10.9-19.3]	45c	13.2 [11.2-18.4]	82b	12.0d [11.0-17.0]	65	14.8c [12.0-20.1]	252fghj	13.1i [11.0-18.4]
Back	35bc	16.2 [11.9-22.1]	6ad	16.5 [14.6-29.0]	11ad	17.0 [14.0-22.8]	42bc	13.9 [11.9-21.3]	94egij	15.0 [12.0-21.8]
Left	20	16.2 [12.7-23.5]	14	14.5 [11.2-20.7]	14	12.8 [11.1-20.1]	15	16.2 [12.8-19.1]	63efij	15.0 [12.0-20.0]
Right	32bd	13.6 [12.4-18.0]	11ac	14.0 [11.0-19.0]	25bd	13.0 [11.3-18.8]	7ac	18.0 [13.9-24.0]	75e	14.0 [12.0-18.6]
Top	52cd	15.9 [12.5-22.0]	38d	15.9 [12.7-26.0]	31ad	14.0j [12.0-23.4]	110abc	14.8 [12.0-19.1]	231fghj	15.2ej [12.1-21.0]
Bottom	45b	14.0 [11.7-20.4]	18acd	15.8 [12.1-26.4]	62b	13.9i [10.4-17.0]	45b	13.5 [11.3-19.0]	170efgi	14.0i [11.1-18.7]
PAA (rad/s2)										
Front	60	1,270.0cd [796.0-1,774.5]	45c	1,196.0d [787.0-1,733.0]	82b	1,740.0a [1,313.3-2,141.0]	65	1,935.0ab [1,576.0-2,417.5]	252fghj	1,658.5h [1,085.0-2,096.3]
Back	35bc	1,709.0 [982.0-2,961.0]	6ad	980.5 [652.0-3,620.3]	11ad	1,247.0 [831.0-1,668.0]	42bc	1,685.0 [1,307.5-2,844.0]	94egij	1,627.0h [1,005.3-2,671.3]
Left	20	1,685.0 [1,088.5-2,900.3]	14	1,405.0h [853.8-1,846.8]	14	1,367.0 [787.5-2,212.5]	15	1,146.0 [871.0-1,631.0]	63efij	1,462.0hi [954.0-2,138.0]
Right	32bd	1,447.0 [1,176.5-1,814.0]	11ac	798.0 [543.0-1,142.0]	25bd	1,013.0 [711.0-1,688.0]	7ac	1,353.0 [1,263.0-1,772.0]	75e	1,263.0efgi [798.0-1,758.0]

Top	52cd	1,651.5d [1,000.0-2,228.0]	38d	1,504.0 [724.0-3,282.0]	31ad	1,507.0 [1,058.0-2,666.0]	110abc	1,969.0a [1,623.5-2,562.5]	231fghj	1,827.0ghj [1,253.0-2,562.0]
Bottom	45b	1,305.0 [815.0-2,254.5]	18acd	2,252.5 [1,255.3-3,623.5]	62b	1,388.0 [625.3-2,003.8]	45b	1,703.0 [885.0-2,357.5]	170efgi	1,514.0i [798.8-2,358.0]
RWECP										
Front	60	0.0002f [0.0000-0.0005]	45c	0.0003d [0.0001-0.0004]	82b	0.0001d [0.0000-0.0002]	65	0.0003bcf [0.0002-0.0005]	252fghj	0.0003h [0.0002-0.0005]
Back	35bc	0.0000e [0.0000-0.0000]	6ad	0.0003 [0.0002-0.0009]	11ad	0.0001 [0.0000-0.0002]	42bc	0.0000e [0.0000-0.0001]	94egij	0.0003h [0.0002-0.0008]
Left	20	0.0003h [0.0002-0.0008]	14	0.0004 [0.0002-0.0014]	14	0.0002h [0.0002-0.0003]	15	0.0002 [0.0001-0.0004]	63efij	0.0003hi [0.0002-0.0005]
Right	32bd	0.0000g [0.0000-0.0002]	11ac	0.0002 [0.0002-0.0003]	25bd	0.0000g [0.0000-0.0001]	7ac	0.0002 [0.0001-0.0007]	75e	0.0002efgi [0.0001-0.0004]
Top	52cd	0.0003 [0.0001-0.0005]	38d	0.0003 [0.0002-0.0008]	31ad	0.0003j [0.0001-0.0020]	110abc	0.0000 [0.0000-0.0001]	231fghj	0.0003gj [0.0002-0.0008]
Bottom	45b	0.0002c [0.0001-0.0007]	18acd	0.0006d [0.0002-0.0024]	62b	0.0000ai [0.0000-0.0001]	45b	0.0002b [0.0001-0.0006]	170efgi	0.0002hi [0.0001-0.0006]

PLA(g): Peak Linear Acceleration in gravitational forces; PAA(rad/s2): Peak Angular Accelerations in radians per second squared; RWECP: Risk Weighted Exposure (combined probability).
IQR: Interquartile Range; Significance difference (p<0.05) then (a) = Front-Row Forward; (b) = Back-Row Forward; (c) = Inside Back; (d) = Outside Back; (e) = Front; (f) = Back; (g) = Left; (h) = Right; (i) = Top; (j) = Bottom.

Most impacts recorded were in the low injury severity for PLA(g) (<65.9g: 97.9%), PAA (rad/s2) (<4,500 rad/s2: 95.4%) and RWECP (<0.2499; 98.3%) range (Table 4). Forwards recorded a lower median resultant PAA (rad/s2) (1,371.5 [826.8 to 1,988.3] rad/s2) in the low injury severity range (<4,500 rad/s2) than backs ($\chi^2(1)=356.0$; p<0.0001; z=16.4; p<0.0001; d=0.09) over the season.

Table 4: Head impacts greater than 10 g of amateur women rugby union players in New Zealand over a single domestic competition season of matches for total impacts recorded and impacts per player group for injury tolerance level, [15,56,57] impact severity limits, [58,59,66] and risk weighted cumulative exposure (combined probability) 60 by total impacts recorded and percentage of impacts recorded (%).

	Total			**Forwards1**			**Backs2**		
	n=	**median [IQR]**	**%**	**n=**	**median [IQR]**	**%**	**n=**	**median [IQR]**	**%**
Injury Tolerance									
>95.0	3	107.0 [103.5-110.7]	0.3	1	107.0	0.3	2	107.1 -	0.4
>5500.0 rad/s2	26	8,130.5 [6,724.0-10,432.8]	2.9	14	8,094.0 [6,527.8-10,432.8]	3.7	12	8,130.5 [6,761.3-11,154.0]	2.4
Injury severity (Linear)									
<65.9 g	866	14.1 [11.6-79.0]	97.9	370	14.5 [11.9-20.0]	98.1	501	14.0 [11.4-18.5]	98.6
66-106 g	17*	73.8 [69.7-78.0]	1.9	6	70.9 [67.8-76.1]	1.6	6	76.3 [72.5-85.1]	1.2
>106.1 g	2	108.9 -	0.2	1	107 -	0.3	1	110.7 -	0.2
Injury Severity (Angular)									
<4599 rad/s2	844*	1,604.5 [952.3-2,141.0]	95.4	356	1,371.5b [826.8-1,988.3]	94.4	488	1,697.5a [1,101.8-2,241.5]	96.1
4600-7899 rad/s2	28	5,494.0 [4,978.3-6,724.0]	3.2	14	5,636.0 [4,874.5-6,727.5]	3.7	14	5,436.5 [5,064.8-6,761.3]	2.8
>7900 rad/s2	13*	10,251.0 [8,655.0-13,699.0]	1.5	7	10,251.0 [8,958.0-13,473.0]	1.9	6	10,336.0 [8,549.5-16,214.0]	1.2
Risk Weighted Risk Weighted Exposure combined probability (RWECP)									
<0.2499	871	0.0003 [0.0002-0.0005]	98.3	369	0.0002 [0.0001-0.0005]	97.9	501	0.0003 [0.0002-0.0006]	98.6
0.2500-0.7499	8*	0.3532 [0.3158-0.5546]	0.9	4	0.2049 [0.0487-0.5877]	1.1	4	0.3378 [0.3158-0.4758]	0.8
>0.7500	7*	0.9755 [0.8780-0.9989]	0.8	4	0.9755 [0.8780-0.9946]	1.1	3	0.9989 [0.9428-0.9996]	0.6

n: number of impacts; %: percentage; IQR: Inter-Quartile Range; g: gravitational force; rad/s2: Radians per second per second; *: concussions recorded in this range; (1) = 8 player positions; (2) = 7 player positions; Significant difference (p<0.05) than (a) = Forwards; (b) = Backs

4. Backs recorded more head impacts than forwards; and

5. The incidence of concussions recorded for the season were 16.7 per 1,000 match-hrs with a resultant median PLA(g) of 78 [68.7 to 103.5]g, PAA(rad/s2) of 17,783.0 [13,473 to 86,100] rad/s2 and RWECP of 0.9755 [0.5190 to 0.9996] of those players identified as concussed.

The reported 97 head impacts per-match resulted in an average of 13 impacts per-player per-match, was less than previous studies reporting on senior men's amateur rugby union (564 per-match; [77] per-player per-match) [20], and women's rugby league (184 per-match; 14 per-player per-match) [67], similar to junior rugby league (116 per-match; 13 per-player per-match); 68 but higher than those reported for junior rugby union (46 per-match; 10 per-player per-match) [21], women's domestic netball (22 per-match; 3 per-player per-match) [69], women's collegiate rugby union (2.9 per player-season) [70], youth ice hockey (5 per-player per-match) [71], and collegiate women's soccer (2.2 per-player per-game) [72] The differences in the number of impacts recorded in the sporting activities other than rugby union and rugby league may be as a result of the different sports being undertaken, safety equipment utilised and rules of participation [67]. As women participate in rugby union under the same rules and regulations as their male counterparts, the

Table 5: Combined results of three concussions in amateur women's rugby union in New Zealand over a single domestic competition season of matches for Impact Monitoring Mouthguard reporting parameters and King-Devick test scores by median and inter-quartile ranges.

Reporting parameters	Median [IQR]
Impact Monitoring Mouthguard	
PLA(g)	78.0 [68.7 to 103.5]
PAA (rad/s2)	17,483.0 [13,473.0 to 86,100]
RWECP	0.9755 [0.5190 to 0.9996]
King-Devick test	
Baseline 1	48.9 [31.1 to 56.7]
Baseline 2	41.2 [26.2 to 43.6]
Baseline	41.2 [26.2 to 43.6]
Diff 1-2	7.7 [4.9 to 13.1]
Post injury	51.8 [32.7 to 63.8]
Diff BL-PI	-10.6 [-20.2 to -6.5]

PLA(g): Peak Linear Acceleration in gravitational forces; PAA (rad/s2): Peak Angular Accelerations in radians per second squared; RWECP : Risk Weighted Exposure (combined probability); IQR: Interquartile range; Diff: Difference; BL: Baseline; PI: Post-Injury.

impacts and injuries theoretically should be similar. However, females reportedly have higher injury risks, even though they have lower physiological indices (e.g. reduced speed and less agility, lower muscular power, lower estimated maximal aerobic power) compared with males [73]. This may be, in part, the reason for the lower number of impacts recorded in this study. Another possible reason for the differences in the reported number of impacts may be the use of different technologies to record these impacts. The studies reporting on rugby union and rugby league have utilised the XGuard [20,74] and the XPatch [21,67,68,75,76] and these have their own reported differences in impact capture and recording [77-79]. Further research is warranted in head impact biomechanics utilising the same technology to enable development of a profile of the impacts that occur in women's sport such as rugby union and rugby league.

The higher contact and collision demands of forwards [25,80] combined with the greater body mass and increased momentum [81,82], have been suggested as possible explanations for the higher incidence of injury in forwards than backs [83]. Although the body mass of the players was not recorded, it was reported in a similar cohort involving more than half of the current players that the forwards were older and had a greater body mass than backs [84,85]. The finding that backs recorded more impacts than forwards (508 vs. 377) was unexpected and may be reflective of the match tactics employed by the team under study. However, when viewed by player groups, OSB's recorded the highest number of impacts with the fullback recording the highest total and mean impacts per-match. This is in conflict with the study [20] reporting male amateur rugby union where forwards recorded more total and mean impacts per match and per-player per-match than backs and the hooker recorded the highest total impacts and mean impacts per-player per-match. Further studies reporting on head impact biomechanics in women's rugby union is warranted to establish differences between player roles and player groups.

This study utilised a linear acceleration of ≥10 g to enable comparisons with similar studies reporting on rugby union [20,21], rugby league [67,68,75,76] and Australian Football league [86,87]. However a recent study [88] has recommended a minimum of 20 g to capture more meaningful head impact events. It was reported in a previous study that altering the impact threshold from 10 g to 20 g resulted in a loss of nearly 60% of the impact data. Despite this, studies have identified that the positive predictive value increased from 16% to 66% when the threshold was increased from 10 g to 20 g. This was similar in another study where 31% of impacts were recorded as false positive at the 10 g threshold but only 6% at the 20 g threshold. More recently researchers have identified that the accumulation of the impacts irrespective of severity may be deleterious to long-term brain health [89]. As a result of this, it is becoming increasingly important to identify any head impact regardless of severity [90].

The median PLA (g) value recorded (14 g) was similar to the median PLA(g) recorded for women's rugby league (XPatch: 15 g), 67 junior rugby union players (XPatch; 15 g), 21 and collegiate American football players (15 g) [91]. However, the median PLA(g) value reported for junior rugby league (XPatch: 16 g), 68 senior amateur rugby union (XGuard: 16 g), sub-elite Australian rules football (XPatch: 17 g), 87 American youth and high school (Head Impact Telemetry system (HITs): 22 g) football players, [60,92] collegiate women's rugby union (Triax Technologies; 29 g) and high school (XPatch: 31 g) and collegiate (XPatch: 32 g) soccer players [93] were higher than the PLA(g) recorded in the current study. The median PAA value recorded (1,633 rad/s2) was similar to the median value reported for sub-elite Australian rules football (XPatch: 1,556 rad/s2), [87] higher than the median (HITs: 671 rad/s2; 1,013 rad/s2) reported in American high school football [60,94]. However, the median PAA values for senior amateur rugby union (XGuard: 2,625 rad/s2), [74] junior rugby league (XPatch: 2,773 rad/s2), 68 junior rugby union (XPatch: 2,296 rad/s2) 21 and women's amateur rugby league (XPatch: 3,265 rad/s2) were higher than the median PAA recorded in amateur women's rugby union. The differences in the PLA and PAA's may be related to the different sporting activities under study but may also be influenced by the different technologies utilised. Further studies are warranted with identical head impact technology to enable the establishment of the range of PLA and PAA values for participation and concussions.

Total head impact distribution varied by impact location with the top of the head recording the highest number of impacts (28.5%). This is similar to a previous study reporting on collegiate (top of the head) [95] football but conflicts with studies reporting on collegiate women's rugby union (back of the head), [70] American high school football (front of the head), [96] women's domestic netball (side of head), [69] male and female amateur rugby league (side of head), [75] and New Zealand senior amateur (side of head) 20 and junior (side of head) 21 rugby union. When viewed by positional groups, the front of the head was the most common impact location for FRF (25%), BRFs (34%), and ISB (36%) but the top of the head was the most common impact location of OSB's (46%). This conflicts with a previous study in amateur male rugby union 20 where the side was the most common for forwards (43%) and backs (48%) and in amateur women's rugby league [67] where the side was the most commonly reported impact area for hit-up forwards (43%) and adjustables (57%) however, the front of the head recorded the most impacts for outside backs (43%). The differences in player roles, tackle techniques and head impacts may also be a factor in the risk of concussion and future studies should consider these aspects. The finding that the head was the most common impact area was unexpected and further research is warranted into the tackling techniques and styles utilised in male and female rugby union participants.

Although only three concussions were recorded over the study with impacts in the moderate to severe risk range, there were a total of seven impacts in the RWECP severe (>0.7500) range and a further eight impacts within the moderate (0.2500 to 0.7499) range. Only one player reported concussive type symptoms and they were tested post-match with the K-DT and sent for further evaluation by a health professional where they were diagnosed with a concussive injury. It has been previously reported [38] that there was a six-fold difference between the number of witnessed and unwitnessed concussive events. If there were two concussions witnessed and one reported, then there is the potential for a further [11] unwitnessed concussive injuries to have occurred placing some of the players at further risk of possible long term problems. Similar to a previous study, [97] these players took an average of 28 days to recover before they were cleared to return to full training activities. No players in this study with a medically diagnosed concussion were allowed to commence contact training in preparation for match participation until they had equalled or surpassed (faster) their baseline K-D test despite the presentation of a medical clearance by their own health practitioner. As a result, no player was allowed to return to full match participation until they had completed two contact training sessions, were symptom free and, there were no worsening (slower) time of their K-D test from their baseline. For one player this meant sitting out the rest of the competition season.

Limitations: A limitation to this study was not having multi-angled video footage of the matches to enable correlation between the head impacts recorded and physical contacts during match participation. Although the first few matches were videoed with a hand-held camcorder (Sony HDR-PJ540 camcorder) standing on the sideline, the quality was poor and it was not possible to identify which player was tackled and whether the contact was to the body, or when the body impacted with the ground, particularly in field positions that were on the other side of the field from the camera. As such, we were unable to establish whether the impacts were from body contact or from contact with the ground and hence, the results must be interpreted accordingly. Previous studies [90,98,99] have reported that some instrumented mouthguards failed to detect 16% 98 to 36% of video classified contact events whereas other studies [88,100] have reported a high number (35% 88 to 83% 100) of false-positive impacts. This reportedly 19 equates to as few as four but as many as nine out of 10 evens recorded by head impact sensors being possibly false-positives. However, a previous study [26] has reported that there were no cases of video-collision data being reported where there is no IMM data and vice-versa. As the Prevent Biometrics IMM is a new product to the research environment. future head impact studies should use high quality multiple angled cameras in an elevated position to enable verification of the impacts recorded and more studies on contact and collisions sports for both males and females are recommended to establish the sensitivity and reportability of these monitors.

Conclusion

This study recorded the head impacts from match participation in an amateur women's rugby union team in New Zealand. The finding of 97 head impacts per-match that resulted in an average of 13 impacts per-player per-match were less than previous studies reporting on senior men's amateur rugby union, women's rugby league and junior rugby league. The finding that backs recorded more impacts than forwards and had a higher resultant median peak angular acceleration was unexpected and may be reflective of the match tactics employed by the team under study. However, when viewed by player groups, outside backs recorded the highest number of impacts with the fullback recording the highest total and mean impacts per-match. Further studies are warranted with identical head impact technology to enable the establishment of the range of peak linear acceleration and peak angular acceleration values for participation and concussions.

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