Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rjsp20

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To cite this article: Gregory Roe, Thomas Sawczuk, Lindsay Starling, Mark S. Gilthorpe, Danielle Salmon, Éanna Falvey, Sharief Hendricks, Karen Rasmussen, Keith Stokes, James Tooby, Cameron Owen, Ross Tucker & Ben Jones (25 Mar 2025): Contact-events and associated head acceleration events in semi-elite women's rugby union: A competition-wide instrumented mouthguard study, Journal of Sports Sciences, DOI: 10.1080/02640414.2025.2481355

To link to this article: https://doi.org/10.1080/02640414.2025.2481355

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2025.2481355

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Contact-events and associated head acceleration events in semi-elite women's rugby union: A competition-wide instrumented mouthguard study

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ABSTRACT

This study aimed to quantify contact-events and associated head acceleration event (HAE) probabilities in semi-elite women's rugby union. Instrumented mouthguards (iMGs) were worn by players competing in the 2023 Farah Palmer Cup season (13 teams, 217 players) during 441 player-matches. Maximum peak linear acceleration (PLA) and peak angular acceleration (PAA) per-event were used as estimates of *in vivo* HAE (HAE_{max}), linked to video analysis-derived contact-events and analysed using mixed-effects regression. Back-rows had the highest number of contact-events per full-match (44.1 [41.2 to 47.1]). No differences were apparent between front-five and centres, or between half-backs and outside-backs. The probability of higher HAE_{max} occurring was greatest in ball-carries, followed by tackles, defensive rucks and attacking rucks. Probability profiles were similar between positions but the difference in contact-events for each position influenced HAE_{max} exposure. Overall, most HAE_{max} were relatively low. For example, the probability of a back-row experiencing a PLA HAE_{max} ≥25*g* was 0.045 (0.037–0.054) for ball carries (1 in every 22 carries), translating to 1 in every 2.3 full games. This study presents the first in-depth analysis of contact-events and associated HAE_{max} in semi-elite women's rugby union. The HAE_{max} profiles during contact-events can help inform both policy and research into injury mitigation strategies.

KEYWORDS
Injury prevention; concussion; athlete health; instrumented mouthguards; monitoring; collision sport

Introduction

Rugby union is a contact sport played by both men and women globally. While the professionalism and participation numbers of women's rugby union have rapidly increased in the last decade (Heyward et al., 2022), there is still a dearth of literature pertaining to the women's game (West, Shill, Clermont, et al., 2022). Like men's rugby, most injuries in women's rugby union occur during contact events, particularly ball-carrying into contact, tackling, and rucking (Starling et al., 2023; Williams et al., 2022; Yeomans et al., 2021). Concerningly, the most common injury diagnosis reported in the men's and women's literature is concussion (Starling et al., 2023; West, Shill, Sutter, et al., 2022; Williams et al., 2022; Yeomans et al., 2021). Such findings have motivated research efforts to identify contact-related risk factors for concussions to inform injury prevention interventions (Cross et al., 2019; Tucker et al., 2017). However, although to date the majority of research has been conducted in professional men's players, with unknown relevance for/translation to the women's game (Hunzinger & Schussler, 2023).

During contact-events that do not result in a concussion, players may still experience a head acceleration event (HAE) (Tooby et al., 2023), which is an acute acceleration of the head in response to an external force resulting from impact to the body or head (Iverson et al., 2023; Kuo et al., 2022). These HAEs also need to be considered when designing injury prevention interventions (Tierney, 2021) as they may have negative consequences for medium- and long-term brain health (Daneshvar et al., 2023; Ntikas et al., 2022), although it is possible that only athletes at higher levels of competition may be susceptible (Iverson et al., 2023). Thus, quantifying contact-events and associated HAEs experienced by players is an important first step in the injury prevention process(Finch, 2006).

Currently, research investigating contact-events in women's rugby union match-play is sparse in comparison to men's and is limited to relatively small sample sizes, single teams, and

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/02640414.2025.2481355

higher-level analyses (Dane et al., 2022; Paul et al., 2022). HAEs associated with contact-events have only been reported in a relatively small sample of elite women's players (Tooby et al., 2023), limiting the applicability of findings to other playing levels. Therefore, a competition-wide investigation was undertaken with the aim of quantifying tackles, ball-carries, rucks and associated HAEs in semi-elite women's rugby union and to provide a comprehensive and in-depth analysis of these events experienced by different positional groups.

Methods

Study design

A prospective observational cohort study was conducted in players from 13 Provincial Unions competing in the 2023 season of the Farah Palmer Cup in New Zealand (the highest level of domestic competition for female players in New Zealand). Taking into account the specific position played in each match, players were clustered into the following positional groups (Quarrie et al., 2013); front-five ($n = 92$), back-row ($n = 48$), half-backs ($n = 31$), centres ($n = 27$) and outside-backs ($n = 46$) players. Further participant details are provided in supplementary Table S1. Ethics approval was received from the University Ethics Committee (REF: 108638).

Instrumented mouthguards

All players underwent 3D dental scans and were provided with custom-fit instrumented mouthguards (iMGs)(Prevent Biometrics, Minneapolis, MN, USA). The iMG contained an accelerometer and gyroscope that sampled at 3200 hz with measured ranges of ± 200g and ±35 rad/s. Coupling of the iMG to the upper dentation was determined by way of infrared proximity sensors. Proximity sensor data were processed in-house by Prevent Biometrics and provided the research team with timestamps of on-the-teeth periods in which the iMG was properly worn by the user. Laboratory validation of the Prevent Biometrics iMG yielded a concordance correlation coefficient of 0.984 (95% CI: 0.977–0.989), while field-based video-verification analysis yielded a positive predictive value of 0.94 (0.92–0.95) and a sensitivity value 0.75 (0.67–0.83) during on-field video-verification validation (Jones et al., 2022).A discretised period of kinematics data (−10 ms and +40 ms from trigger point) was stored for each HAE. Linear kinematics were transformed to the head centre of gravity (CoG) using the relative acceleration equation. Values for peak linear acceleration (PLA) and peak angular acceleration (PAA) below 5g and 400 rad/s^2 respectively were excluded at this point based on previous recommendations (Tooby et al., 2023). Each HAE was classified as a true positive or false positive by an in-house Prevent Biometrics algorithm based on proximity sensor readings and kinematics. Linear and angular kinematics were filtered by Prevent Biometrics using a 4-pole, zero phase, low-pass Butterworth filter with a 200 hz cut-off frequency. Another in-house Prevent Biometrics algorithm classified iMG-recorded HAEs based on the level of noise in the signal, events classified with low noise ($n = 11687$) were not re-filtered, while those classified with moderate ($n = 383$), or severe ($n = 126$) noise were re-filtered with 100 and 50 hz cut-off frequencies, respectively. Peak linear acceleration and PAA values were calculated by extracting peak resultant values from each HAE.

Data processing

Video analysis data of all contact-events during 2023 Farah Palmer Cup season were acquired from Opta, provided by StatsPerform (Chicago, IL, USA), a commercial sports performance analysis company which provides performance analysis data to numerous competitive sports leagues worldwide. Events were coded by StatsPerform's expert analysts. Contact-event, and contact type definitions are provided in Supplementary material (Table S2). In addition, data were annotated with details regarding the player ID, match ID, and contact-event ID, which grouped together player events in the same contact event (e.g., a tackler, ball carrier and rucking players within the same tackle event). Instrumented players' data were exported from the Prevent Biometrics Portal (Prevent Biometrics, Minneapolis, MN, USA) for synchronisation with contact-event data. Accelerometer, gyroscope, and proximity sensor data were synchronised to video timestamps of contact-events using Matlab (MathWorks, UK, version R2023a). An HAE was linked to a collision event if their timestamps occurred within 10 seconds of one another. Only contact-events that had corresponding proximity sensor data for (i.e., the mouthguard was on the teeth) the instrumented player were used in the analysis (Tooby et al., 2023). This method had an 92% accuracy (Tooby et al., 2025). Contact events that had proximity sensor data for the instrumented player were used in the analysis (Tooby et al., 2023).

Where no iMG data were recorded for an identified contact-event, the iMG data value for that contact-event was denoted as "*not recorded*". Due to differences in the kinematics between the teeth (where the trigger threshold is activated) and the head CoG (the location of the iMG-recorded HAE), this *not recorded* data consists of true and false negatives (Wang et al., 2021). A true negative occurs when the kinematics at the head CoG falls below the recording threshold and the kinematics at the teeth are lower than the trigger threshold. A false negative may occur when the kinematics at the head CoG are above the recording threshold but the kinematics at the teeth are below the trigger threshold. It is currently not possible to distinguish between these two types of "missing data" and thus the *not recorded* category is required.

The process of linking HAEs to contact-events converted the truncated iMG-recorded HAE distribution, where an unknown number of observations could have occurred below the trigger threshold, to a censored distribution, where the total number of observations was related to the total number of contact-events that occurred (Fox, 2015). Previously, similar studies have utilised both distributions. In a study by Tooby et al. (2023), individual iMG observations were considered within a censored distribution, assuming that all *not recorded* observations fell below an arbitrary threshold (10g and 1000 rad/s^2), and data were not modelled to account for the hierarchical data structure (Fielding & Goldstein, 2006). Bussey et al. (2023) did not consider the *not recorded* values, analysing the truncated distribution of iMG data aggregated at a count level (i.e., counts of iMG-recorded HAE in a specific magnitude range). This study uses an ordinal mixed-effects regression which allows data to be split into ordered categories and estimates the probability of each category occurring (Bürkner & Vuorre, 2019). It also allows the hierarchical structure of the data to be appropriately modelled. However, to perform this analysis, each observation must be weighted equally. As *not recorded* data can only be assigned as one data point (i.e., it is missing), all iMG-recorded HAE data must also have a single value. Therefore, for those contact-events in which more than one iMG-recorded HAE occurred, the maximum peak linear acceleration (PLA) and peak angular acceleration (PAA) were used, henceforth referred to as HAE_{max}.

Data analyses

Contact-events

Two types of analysis were completed in this study. In the first, two generalised linear mixed models assuming a Poisson distribution were produced to estimate the frequency with which different positional groups were involved in contact-events per match. Total contact-event exposures were estimated using the number of contact events a player was involved in during each match as the dependent variable. Positional group (categorical variable) and minutes played (dependent variable) were included as interacted fixed effects. A breakdown of contact-event exposures were estimated by using the number of individual contact-events a player was involved in per match (e.g., tackles, carries, attacking and defensive rucks separately) as the dependent variable. Contact-event (categorical variable), positional group and minutes played were included as fully factorial fixed effects. In both models, player ID and match ID were included as individual random effects. All contact-event counts are estimated per full game equivalent (FGE).

Head acceleration events

In the second analysis, an ordinal mixed effects regression model was used to estimate the probability of a contact-event, contact type or positional group resulting in different ranges of HAE_{max} magnitudes. Probabilities were estimated at eight ranges for PLA (not recorded, 5–14.99*g*, 15–24.99*g*, 25–34.99*g*, 35–44.99*g*, 45–54.99*g*, 55–64.99*g*, ≥65*g*) and PAA (not recorded, 400–999 rad/s^2, 1000–1999 rad/s^2, 2000–2999 rad/s^2, 3000–3999 rad/s^2, 4000–4999 rad/s^2, 5000–5999 rad/s^2, and ≥6000 rad/s^2) based on previous research in rugby union (Roe, Sawczuk, Owen, et al., 2024; Roe, Sawczuk, Tooby, et al., 2024).

Three ordinal models were built. In the first, contact-event (carry, tackle, attacking or defensive ruck) was included as a categorical fixed effect to estimate HAE_{max} magnitude range

Table 1. The expected number of full game equivalents for a player to experience one HAE_{max} at magnitudes ≥ 25*g*, 45*g*, 65*g*, 2000rads/s^2, 4000rads/s^2. or 6000 4000rads/s^2. Data presented as FGE.

	Average Player	Front-five	Back Row	Half-backs	Centre	Outside-Backs
≥25*g*						
Overall	1.3	1.1	0.9	1.7	1.2	1.9
Ball-carry	3.3	2.9	2.9	4.5	2.8	3.7
Tackle	3.1	2.9	2.3	3.2	2.7	4.5
Defending Ruck	18.9	16.2	12	23.2	18.4	31.8
Attacking Ruck	19.8	14.1	12.7	35.7	21.6	35.1
≥2000rads/s^2						
Overall	1.6	1.3	1.1	2.1	1.5	2.3
Ball-carry	4	3.6	3.5	5.5	3.3	4.4
Tackle	3.7	3.4	2.7	3.7	3.2	5.2
Defending Ruck	23.3	19.9	14.8	28.6	22.6	39.1
Attacking Ruck	24.8	17.7	15.8	44.7	27	43.9
≥45*g*						
Overall	10.6	8.8	7.6	13.8	9.9	15.6
Ball-carry	21.3	18.9	18.5	29.3	17.8	23.6
Tackle	21.9	21.8	17.2	23.7	20.1	33.4
Defending Ruck	151.5	138.8	103.2	199.0	157.4	272.5
Attacking Ruck	247.5	160.6	144.0	406.1	245.6	399.0
≥4000rads/s^2						
Overall	16	13.3	11.3	20.7	14.8	23.4
Ball-carry	49.7	39.7	38.8	61.5	37.4	49.7
Tackle	43.9	44.7	35.4	48.5	41.2	68.5
Defending Ruck	378.8	320.0	238.1	459.1	363.1	628.4
Attacking Ruck	495	413.2	370.5	1044.8	632.1	1026.8
≥65*g*						
Overall	53.2	44.2	37.8	69.2	49.3	77.9
Ball-carry	99.5	88.9	86.9	137.7	83.7	111.2
Tackle	125.3	114.9	91.0	124.8	106.0	176.2
Defending Ruck	1010.1	814.2	605.8	1167.9	923.7	1598.7
Attacking Ruck	1650.2	1158.3	1038.6	2929.0	1771.9	2878.4
≥6000rads/s^2						
Overall	84.1	69.8	59.7	109.2	77.9	123.0
Ball-carry	184.3	162.6	159.1	251.9	153.2	203.4
Tackle	208.9	196.0	155.4	213.0	181.0	300.6
Defending Ruck	1782.5	1541.2	1146.7	2210.7	1748.4	3026.2
Attacking Ruck	3300.3	2355.2	2111.8	5955.6	3602.8	5852.7

probabilities for each collision-event (Contact-Event Model). In the second, Opta event types for each individual contact-event (Table 1) were used as categorical fixed effects (Event-Type Model). This provided the probabilities of HAE_{max} magnitude ranges occurring within different types of contact-events. In the third, contact-event was interacted with positional group in a fully factorial model (Positional Model) to provide HAE_{max} magnitude range probabilities for each positional group and contact-event combination. In each model, player ID was nested within match ID and included as a random effect to account for repeated measurements within players and within matches. Contact-event ID was also included as a random effect to account for the correlation of player events within the same contact-event (Doedens et al., 2022; Fielding & Goldstein, 2006). This random effect accounts for the assumption that if, one player within the contact-event experiences a high HAE, then another player may also experience a high HAE. Without accounting for these correlations within the hierarchical data structure, model estimates, standard errors, and confidence intervals may be biased, and inaccurate statistical inferences may be drawn (Doedens et al., 2022).

Median probabilities and 95% confidence intervals (CI) were produced via bootstrapping with 1000 resamples (Field et al., 2010). Exceedance probabilities (i.e., the probability that HAE_{max} magnitudes greater than or equal to a certain value would occur) were also calculated in the same way. Although the results are plotted as individual HAE_{max} magnitudes, on some occasions the probability profile is referenced. This relates to the array of probabilities across the HAE_{max} magnitude ranges occurring for a specific event.

Results are presented as mean and 95% CIs to one decimal place for count data and to three decimal places for probabilities. Indicative differences in both ordinal and Poisson models were identified when the confidence intervals of the estimates did not overlap (Noguchi & Marmolejo-Ramos, 2016). Indicative differences in both ordinal and Poisson models were identified when the confidence intervals of the estimates did not overlap (Noguchi & Marmolejo-Ramos, 2016). Indicative differences were used because we were unable to provide pairwise comparisons of probabilities from the ordinal models via the software implemented (emmeans versions 1.10.0). All analyses were conducted in R (version 4.3.0) using the *Ordinal* (Christensen, 2022), *emmeans* (Lenth, 2023) and *glmmTMB* (Brooks et al., 2017) packages.

Results

Contact-events during match-play

Per FGE overall, the average number of contact-events for a player was 31.3 (29.7 to 33.0). For specific positions, back-row players were involved in the highest number of total contact-events per FGE (44.1 [41.2 to 47.1]). Front-five (37.7 [35.5 to 40.0]) and centres (33.8 [31.2 to 36.5]) experienced more contacts than half-backs (24.1 [22.2 to 26.2]) and outside-backs 21.4 (19.9 to 23.0).

Overall, per FGE, the average number of tackles for a player was 11.4 (10.8 to 12.0), ball-carries was 6.7 (6.3 to 7.1), attacking and defensive rucks was 10.1 (9.6 to 10.7) and 3.3 (3.1 to 3.6) respectively, which are presented for each positional group in Figure 1. Back-rows were involved in a greater number of tackles than front-five, half-backs and outside-backs. On average centres, front-five and half-backs tackled more than outside-backs per FGE. For ball carries, front-five, back-rows and centres carried more than half-backs and outside-backs. Front-five and back-rows were involved in more attacking rucks than all other positions on average, while centres competed in more attacking rucks than half-backs and outside-backs. For defensive rucks, back-row had the highest involvements of all positional groups. Data from Figure 1 are provided in numerical form in supplementary table S3.

The probability of HAEmax occurring at different magnitudes during contact-events

Overall, the probability of no data being recorded when a contact-event occurred was 0.752 (0.736 to 0.769) for PLA and 0.752 (0.737 to 0.767) for PAA. For specific contact events, this ranged from 0.628 (0.602–0.654) for PLA in a ball-carry to 0.886 (0.870–0.899) for PAA in an attacking ruck (Figure 2, supplementary Table S4).

Overall, probabilities of HAE_{max} decreased as PLA and PAA magnitude increased. There were differences between all contact-events where an HAE was recorded up to 34.99*g* and 2999 rad/s^2, after which probabilities were mostly small and indistinguishable (0.000 to 0.004). Ball-carries had the highest probability at each HAE magnitude range, while attacking rucks had the lowest (Figure 2, supplementary Table S4).

The probability of HAEmax occurring at different magnitudes during contact-events for different positional groups

Figures 3 and 4 show the probability profiles of HAE_{max} magnitude ranges for the different positional groups for PLA and PAA respectively. Probability profiles were similar between positional groups for all contact-events with no differences present.

Expected exposure to HAE_{max} at higher magnitudes

Table 1 presents the expected number of FGEs for a player to experience one HAE_{max} at higher magnitudes based on exceedance probabilities (the probability of experiencing an HAE_{max} greater than a specified threshold). The exceedance probabilities are presented in supplementary Table S5. Overall, at magnitudes of > 25*g* and 2000rads/s^2, players would be expected to experience an HAE_{max} once every 1.1 to 2.3 matches on average from a contact-event, depending on the contact-event exposure of their positional group. For the specific contact-events, a player would be expected to experience a HAE_{max} once every 2.3 to 5.2 matches on average during ball-carries and tackles, and between 12 to 44.7 matches on average for defending and attacking rucks. At higher magnitudes, players would be expected to experience one HAE_{max} over one or more seasons, on average.

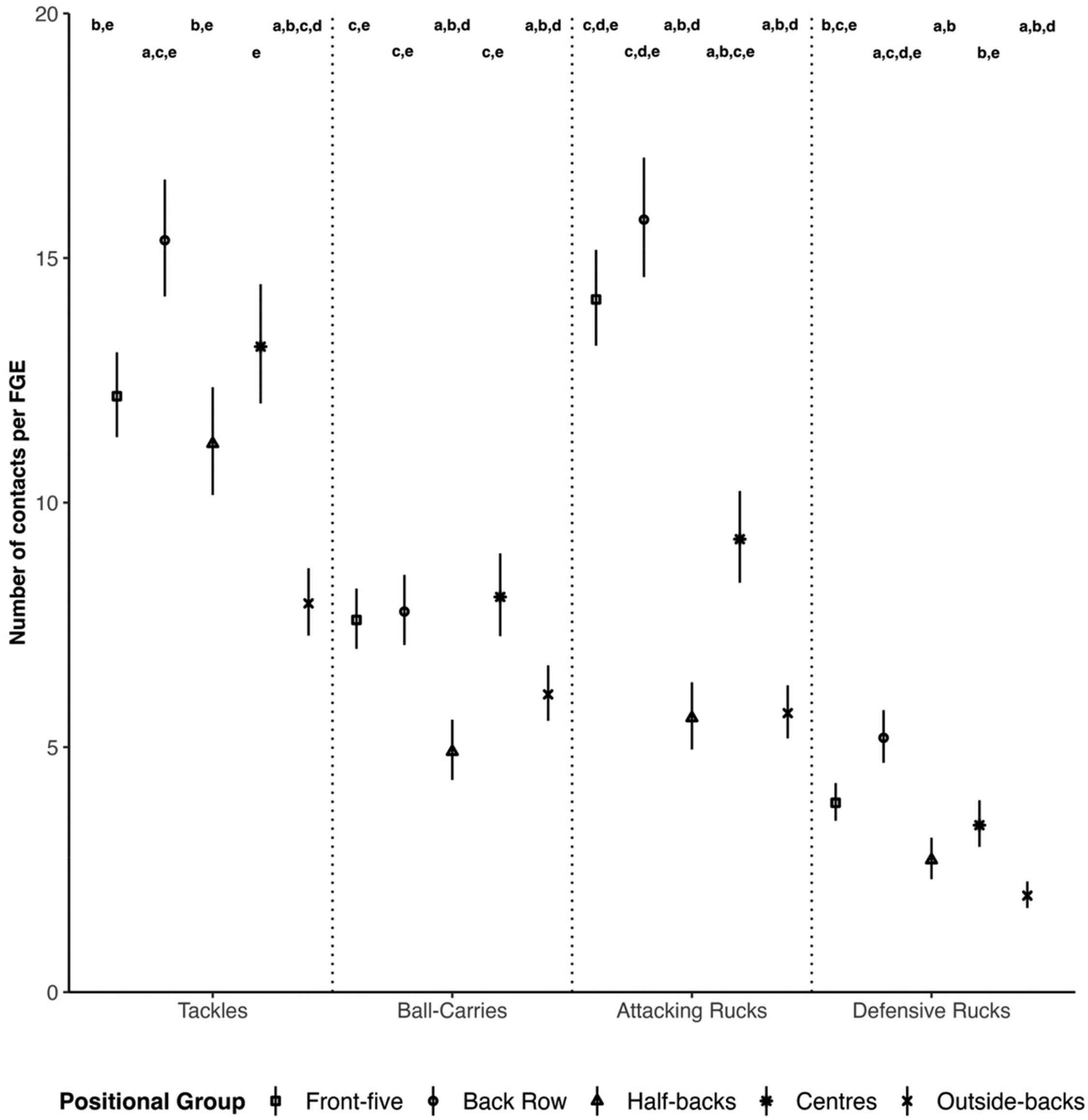

Figure 1. Mean (95% CI bars) total tackles, ball-carries, attacking and defensive rucks per player per full-game equivalent (FGE) for each positional group. A = different from front-five, b = different from back row, c = different from half-backs, d = different from centres, e = different from outside-backs.

Discussion

The aim of this study was to quantify tackles, ball-carries, rucks and associated HAEs in semi-elite women's rugby union match-play. Important differences between positional groups were identified with respect to the number of ball-carry, tackle, and attacking and defending ruck involvements per FGE. Although differences were observed in the probability of experiencing HAE_{max} between these different contact-events, the majority of HAE_{max} were relatively low. The probability of experiencing HAE_{max} did not vary by position but differences in contact-events per FGE meant that overall HAE_{max} exposure differed between positional groups. Injury prevention initiatives aiming to reduce HAE should therefore consider the number of contact-events that positional groups are exposed to, both within a match, and across a season and playing career, as a potential modifiable factor of HAE exposure.

This is the first study to quantify tackles, ball-carries, and rucks per FGE in an entire women's rugby union competition and conduct a detailed exploration of the differences between positional groups. The results demonstrate important positional similarities and differences that have not been captured to date (e.g., forwards vs backs (Tooby et al., 2023) or analysis at a team- or match-level only (Virr et al., 2014; West, Shill, Clermont, et al., 2022; Woodhouse et al., 2021). Of note, in semi-elite women's rugby union, back-row players were involved in the highest number of contact-events overall and competed in the most tackles and defensive rucks per FGE. When total contact-events were considered, no differences were apparent between front-five and centres, but front-five participated in more attacking and defensive rucks. There were no differences in the total contact-event involvements between half-backs and outside-backs, but half-backs were involved in more

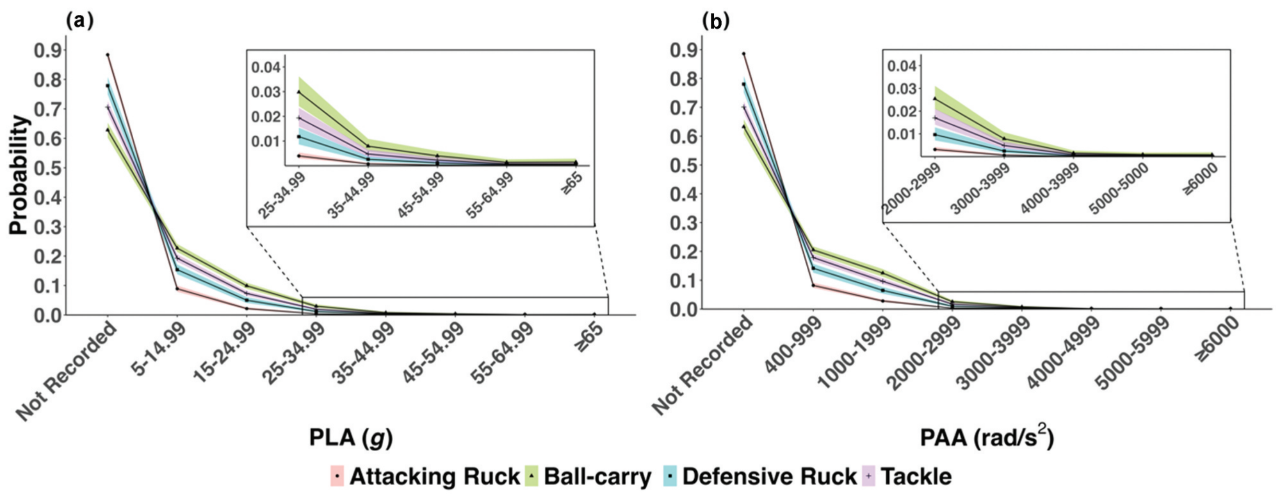

Figure 2. The probability of a HAE_{max} occurring in each HAE_{max} magnitude range for PLA and PAA during a tackle, ball-carry, attacking or defensive ruck. Differences between all contact-events were observed up to 34.99g and 2999 rad/s^2.

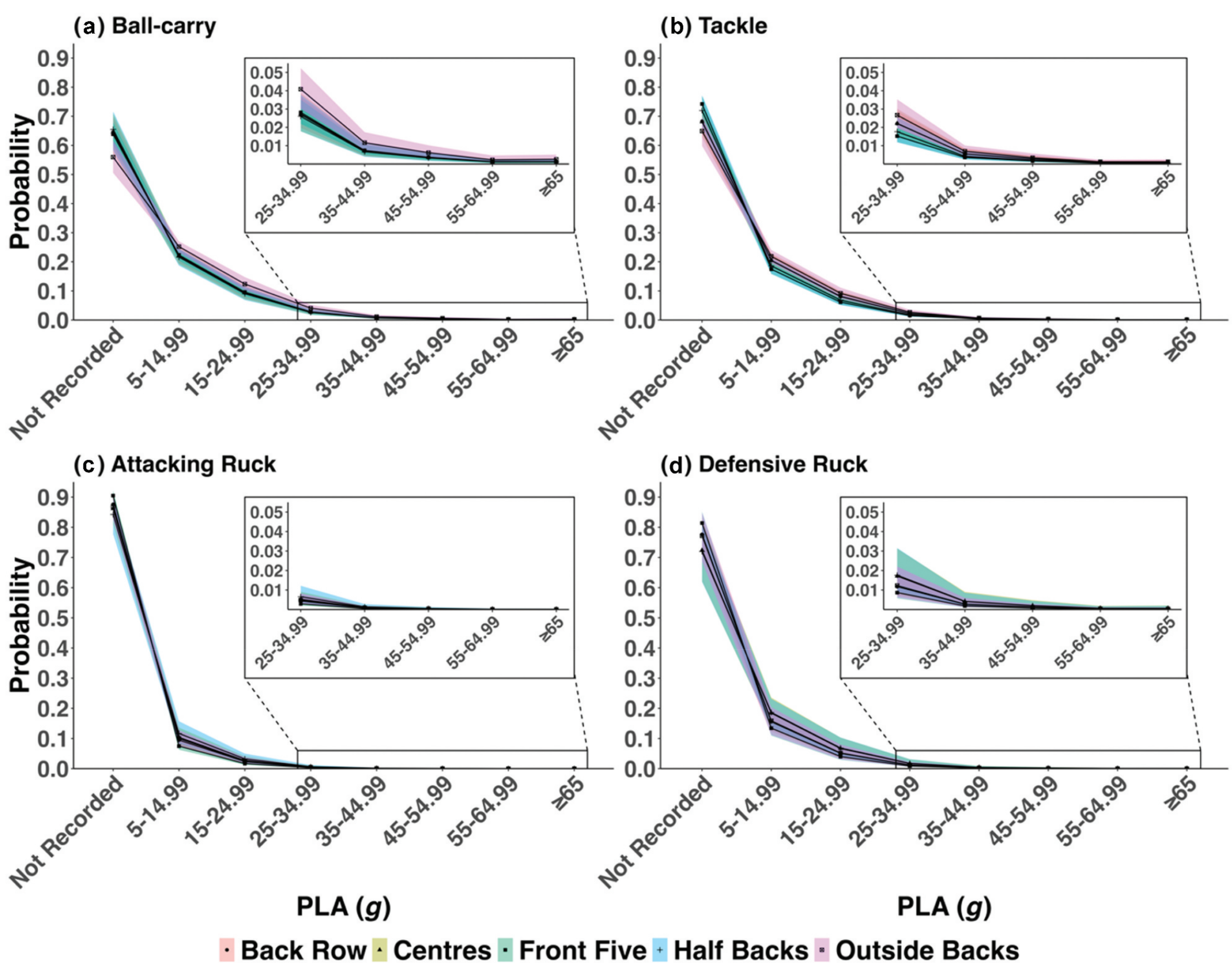

Figure 3. The probability of a HAE_{max} occurring in each magnitude range of PLA during a tackle, ball-carry, attacking or defensive ruck for each positional group.

tackles than outside backs. These findings may help practitioners improve the specificity of player injury rehabilitation and physical preparation programmes by providing position-specific data for contact-event exposure (Dane et al., 2022). To maximise preparedness for match-play, such data can be used to ensure that players have been exposed to an adequate position-specific volume of each contact-event during training before competition involvement. Furthermore, the results may

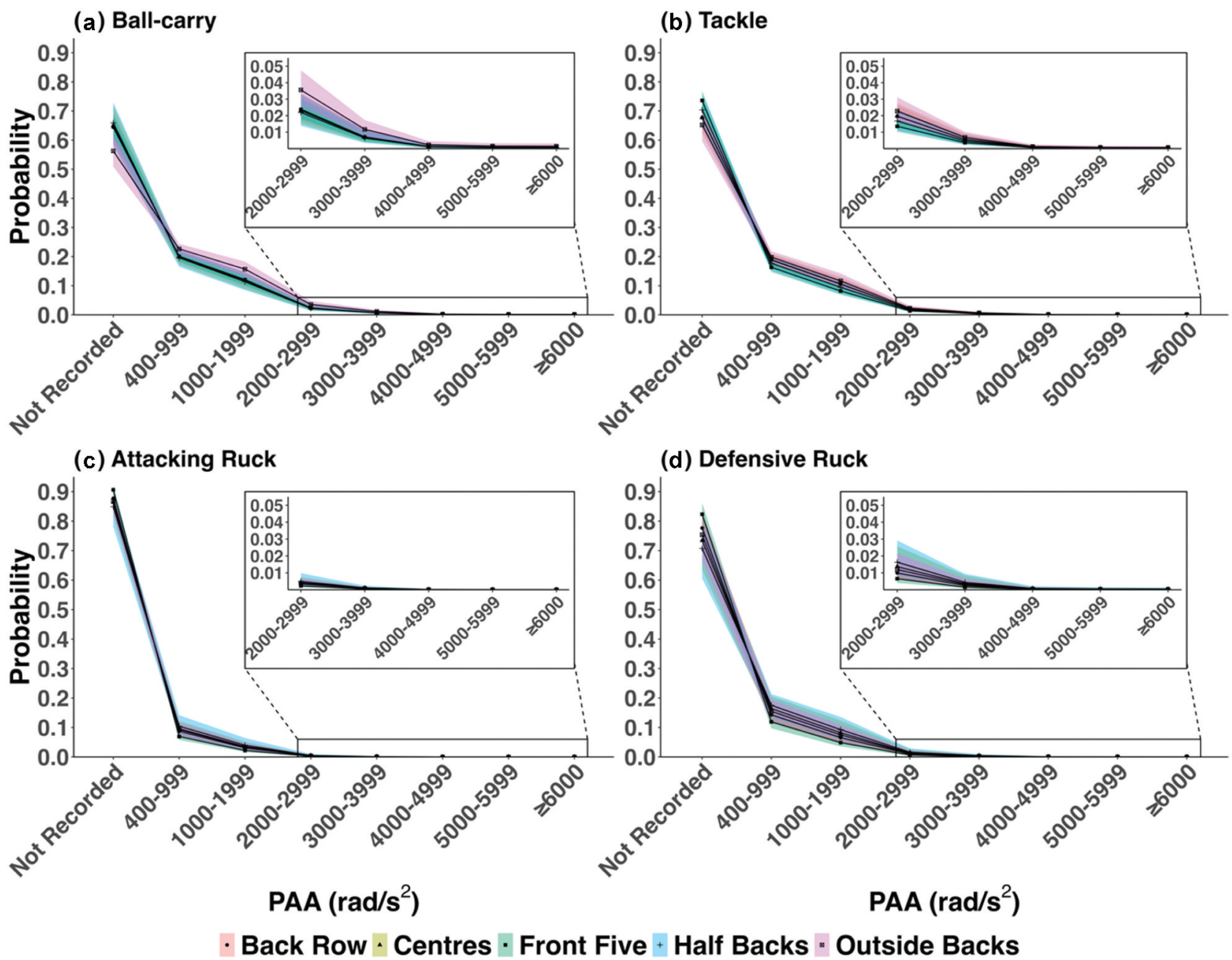

Figure 4. The probability of a HAE_{max} occurring in each magnitude range of PAA during a tackle, ball-carry, attacking or defensive ruck for each positional group.

provide useful information to policy makers regarding player contact-event exposure in semi-elite women's rugby union.

With respect to the HAE_{max} associated with contact-events, there was separation between the probability profiles (Figure 1). Ball-carries had the highest probability of an HAE_{max} occurring at all recorded magnitudes, followed by tackles, defending, and then attacking rucks, which is in accordance with findings in the professional men's game (Roe, Sawczuk, Owen, et al., 2024). However, this finding contrasts with Tooby et al. (2023). who observed no difference between tackles and ball-carries in elite women's rugby union match-play. The differences may be explained by the playing standard (semi-elite *vs* elite) or the larger sample size in the present study (271 vs 64 players) and thus sufficient to identify differences. Nonetheless, it is not surprising that ball-carries and tackles were associated with the highest recorded HAE_{max} probabilities. These contact-events involve the greatest energy transfer because of their unpredictable nature and high speed (West et al., 2021) and result in a large proportion of injuries sustained during match play in women's rugby (Burger et al., 2020; Starling et al., 2023; Yeomans et al., 2021).

However, the ruck has also previously been shown to contribute to injury risk, though with lower risk than tackling and carrying (Burger et al., 2020; Starling et al., 2023; Yeomans et al., 2021). With respect to HAE_{max}, a novel finding of the present study was the higher probabilities of recorded HAE_{max} in defending versus attacking rucks. In the men's professional game, defenders have been shown to be more susceptible to illegal and dangerous ruck cleanouts by attacking players (Kraak et al., 2019) and are more likely to experience an HAE_{max} when stealing the ball (Roe, Sawczuk, Owen, et al., 2024). While much focus has been placed on reducing HAEs during the tackle event, these findings suggest that specific ruck activities, in particular actions during defending rucks (e.g., ball stealing), may be an important area of focus for HAE mitigation strategies.

An interesting finding of the present study was that the highest probabilities were those associated with the *not recorded* category and ranged from 0.628 (95% CI 0.602–0.654) to 0.886 (95% CI 0.870–0.899). The *not recorded* category comprises true (i.e., HAE less than 5*g*) and false (i.e., HAE greater than 5*g* at the head CoG, but less than the 8*g* trigger threshold at the teeth) negatives. It is difficult to discern the relative quantities of true and false positives within this category, but recent research has demonstrated that most (86%) HAE above 20*g* exceed a 10*g* linear trigger threshold at the iMG location on the teeth (Wang et al., 2021). As such, it is logical to assume that lower *in vivo* HAE magnitudes (<20*g*) *are* more likely to result in data *not recorded* and consequently infer that the vast majority of match related HAE_{max} in semi-elite women's rugby are also relatively low. Indeed, in the present study, the probabilities of a player experiencing an HAE_{max} ≥35*g* during a contact-event were also comparatively low, ranging from 0.015 (ball-carries) to 0.001 (attacking rucks). However, future research is required to determine the clinical relevance of these findings before conclusions can be made regarding player safety, especially considering the suspected higher concussion occurrence compared to men in some cohorts (West, Shill, Sutter, et al., 2022).

The present study found no differences between positional groups with respect to the probability of experiencing an HAE_{max} during a contact-event. Nevertheless, as previously discussed, differences in contact-event exposure per FGE between positions were observed and would thus likely result in different HAE_{max} exposure between positions. For example, a back-row player is expected to be involved in approximately 12.2 tackles per FGE and thus may be expected to experience an HAE_{max} ≥25*g* once in every 2.3 full matches or HAE_{max} ≥45*g* once in every 17.2 full matches, on average. In comparison, an outside back is involved in approximately 7.9 tackles per FGE and therefore may only experience an HAE_{max} ≥25*g* once every 4.5 full matches, or HAE_{max} ≥45*g* once in every 33.4 full matches. Given that the cumulative exposure to head accelerations across a playing career may have consequences for long-term brain health (Daneshvar et al., 2023), consideration should be given to these positional differences when designing and implementing injury prevention initiatives. Furthermore, the specific magnitude of HAEs, whereby their accumulation is of clinical relevance, requires further research.

From a methodological perspective, when attempting to produce the Event-Type Model, the hessian matrix was numerically singular meaning that the model parameters could not be estimated accurately, and no results could be provided. The reason for this issue was that most observations fell within the first two HAE_{max} magnitude ranges (i.e., *not recorded* and 5–14.99*g*), therefore, not enough data was present in the latter ranges to provide accurate estimates. Although no values could be provided for the Event-Type Model, in the Contact-Event Model, the cumulative probabilities for contact-events <15*g* PLA and <1000 Rad/s^2 PAA (including *not recorded* values) were 0.856–0.973 and 0.838–0.968 respectively, showing the accumulation of observations within the lower magnitude ranges. These probabilities are higher than in male professional rugby union players (Super Rugby and Currie Cup), where the probabilities ranged from approximately 0.539–0.847 and 0.632–0.855 for PLA and PAA respectively (Roe, Sawczuk, Owen, et al., 2024). The differences likely reflect the dissimilarities in physical characteristics between men and women rugby union players (Posthumus et al., 2020; Yao et al., 2021) and thus the potential forces that can be produced and experienced during collision-events. Future studies within women's rugby may wish to consider different HAE_{max} ranges or adopt fewer categories to produce a more even distribution of probabilities. However, attempts should be made to ensure that magnitude ranges are approximately equal in size when doing so.

Although this study provides novel insights into semi-elite women's rugby union match-play, it has some limitations. The first of these, which is consistent with similar studies (Bussey et al., 2023; Tooby et al., 2023), is sampling bias. This is present in the form of non-random sampling (a convenience sample of volunteers from one competition was used) and volunteer bias (only players who volunteered were included). It is therefore possible that the sample and thus findings in this study are not fully representative of the population of players in the Farah Palmer Cup. Second is the use of the maximum PLA and PAA as estimates of *in vivo* HAEs for each contact-event. The inclusion of missing iMG data within the *not recorded* range could only result in one data point per contact-event (i.e., it is only known that data is missing). Consequently, only one summary value (i.e., HAE_{max}) could be provided for each contact-event to ensure observations were equally weighted within this probability-based analysis, excluding other potential iMG data available. Researchers should be aware that evaluating other iMG-recorded HAE characteristics may provide different results to those in this study. Furthermore, iMGs are susceptible to false negatives (Tooby et al., 2023) and thus the resulting missing values in the current data may have influenced the probabilities estimated. Additionally, although data from iMGs have previously been validated, kinematic filters and proximity sensors have yet to undergo individual validation. Moreover, the method used to link contact-event data and HAE_{max} data may have been subject to error. As a 10s window was used (Tooby et al., 2023), it is possible that some HAE_{max} may have been misattributed. Finally, contextual factors (e.g., team playing style, fixture importance, player physical characteristics) that may influence the number and magnitude of HAE_{max} experienced by players was not explored. Further research is required to identify factors that may causally influence HAE_{max} exposure to maximise mitigation strategy effectiveness (Wight et al., 2016).

Conclusion

This is the first study to quantify tackles, ball-carries, attacking and defending rucks per FGE and associated HAE_{max} in an entire women's rugby union competition and conduct a detailed exploration of the differences between positional groups. Positional differences with respect to contact-event exposure per FGE and the HAE_{max} exposure associated with each contact-event varied between playing groups. Overall, the magnitudes of the majority of HAE_{max} were relatively low, showing that a player would have to play in a high number of matches prior to experiencing a higher magnitude HAE_{max} (e.g., a back-row player is expected to experience HAE_{max} ≥45*g* once in every 17.2 full matches, on average). The findings from this study provide researchers and governing bodies with a set of reference data to help inform injury mitigation strategies and future research determining the clinical and practical relevance of HAEs in this cohort.

Disclosure statement

GR role is part-funded by World Rugby. TS role is part-funded by Premiership Rugby. CO is part-funded by the Rugby Football League. LS, ÉF and DS are employed by World Rugby. KR is employed by the New Zealand Rugby Union. KS is employed by the Rugby Football Union. JT role is part-funded by the Rugby Football League, Premiership Rugby and World Rugby. RT is employed by World Rugby as a consultant. BJ is employed by Premiership Rugby and Rugby Football League as a consultant and has received funding from Prevent Biometrics and World Rugby.

Funding

This research was funded by World Rugby.

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Data availability statement

Data is available from the corresponding author, GR, upon reasonable request.

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