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Head Acceleration Events During Tackle, Ball-Carry, and Ruck Events in Professional Southern Hemisphere Men's Rugby Union Matches: A Study Using Instrumented Mouthguards

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ABSTRACT

Objectives: Describe head acceleration events (HAEs) experienced by professional male rugby union players during tackle, ball-carry, and ruck events using instrumented mouthguards (iMGs).

Design: Prospective observational cohort.

Methods: Players competing in the 2023 Currie Cup (141 players) and Super Rugby (66 players) seasons wore iMGs. The iMG-recorded peak linear acceleration (PLA) and peak angular acceleration (PAA) were used as in vivo HAE approximations and linked to contact-event data captured using video analysis. Using the maximum PLA and PAA per contact event (HAE_{max}), ordinal mixed-effects regression models estimated the probabilities of HAE_{max} magnitude ranges occurring, while accounting for the multilevel data structure.

Results: As HAE_{max} magnitude increased the probability of occurrence decreased. The probability of a HAE_{max} ≥15g was 0.461 (0.435–0.488) (approximately 1 in every 2) and ≥45g was 0.031 (0.025–0.037) (1 in every 32) during ball carries. The probability of a HAE_{max} >15g was 0.381 (0.360–0.404) (1 in every 3) and >45g 0.019 (0.015–0.023) (1 in every 53) during tackles. The probability of higher magnitude HAE_{max} occurring was greatest during ball carries, followed by tackles, defensive rucks and attacking rucks, with some ruck types having similar profiles to tackles and ball carries. No clear differences between positions were observed.

Conclusion: Higher magnitude HAE_{max} were relatively infrequent in professional men's rugby union players. Contact events appear different, but no differences were found between positions. The occurrence of HAE_{max} was associated with roles players

performed within contact events, not their actual playing position. Defending rucks may warrant greater consideration in injury prevention research.

1 | Introduction

Rugby union is a contact-based sport [1], with the men's professional game having one of the highest reported injury incidence rates in team sports [2]. The majority of injuries occur during contact events, particularly the tackle [2, 3]. Head injuries, more specifically concussions, are the most frequent injury diagnosis [2, 3], prompting researchers to identify which features of play are related to concussions, to guide injury prevention interventions [4–6]. To date, the majority of this work has focused on video analysis of head injury mechanisms during concussive events [4] or events that resulted in a head injury assessment (HIA) [5, 6].

Head acceleration events (HAEs) are acute accelerations of the head in response to an external force resulting from an impact to the body or head [7, 8]. Research has shown that the head may experience significant HAEs during contact events that do not result in concussions [8], and the accumulation of such events has been postulated to have negative consequences for brain health [9–11]. Thus, describing the HAEs experienced by players across different magnitudes for different contact events (e.g., rugby union tackle) and within different contexts (e.g., for different types of tackle and between playing positions) is an important first step in the injury prevention process [12].

Recent advances in instrumented mouthguards (iMGs) have provided researchers with a valid measure of linear and rotational head kinematics that can be used in the field to estimate HAEs [13, 14]. However, because of the relative recency of these advances, research investigating the HAE magnitudes experienced by professional men's rugby union players in contact events is scarce [15]. Furthermore, because of the technological limitations of iMGs (i.e., only recording data above an arbitrary threshold) that result in incomplete distributions of observations, previous literature has arbitrarily valued missing data and has not statistically modeled the data [15], limiting the inferences that could be drawn [16]. Therefore, the aim of this study was to describe the HAEs experienced by professional men's rugby union players during contact events, using statistical modeling techniques appropriate for iMG data. A secondary aim was to explore the differences between contact-event types and positional groups.

2 | Methods

A prospective observational cohort study was conducted in male professional rugby union players competing in the 2023 season of the Currie Cup ($n=8$ teams, 141 unique players; 558 player matches) and Super Rugby ($n=6$ teams, 66 unique players; 212 player matches). Players were distributed across the following positional groups [17]; front five ($n=82$), back row ($n=50$) players, half backs ($n=30$), outside backs ($n=44$), and centers ($n=29$). Institutional ethics approval was received, and player informed consent obtained (REF: 108638).

All players underwent 3D dental scans and were provided with custom-fit iMGs (Prevent Biometrics, Minneapolis, MN, USA). The iMGs 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. The laboratory and field-based validity of the Prevent Biometrics iMG has recently been published. Laboratory validation yielded a concordance correlation coefficient of 0.984 (95% confidence interval [CI]: 0.977–0.989), whereas 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 [13]. iMGs were fully charged prior to each match and distributed to players in the hour preceding kick-off. Data were downloaded immediately postmatch to a tablet device and uploaded to Prevent Biometrics cloud storage as soon as internet was available.

iMGs were used to approximate in vivo HAEs. A discretized period of kinematics (−10 and +40 ms from trigger point) was stored for each HAE and linear kinematics were transformed to the estimated head center of gravity (CoG) using the relative acceleration equation. Each HAE was classified as a true positive or false positive by an in-house Prevent Biometrics algorithm based on infrared 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 cutoff frequency. Another in-house Prevent Biometrics algorithm classified HAEs based on the level of noise in the signal, events classified with low noise ($n=11\,687$) were not re-filtered, while those classified with moderate ($n=383$) or severe ($n=126$) noise were re-filtered with 100 and 50 Hz cutoff frequencies, respectively. Peak linear acceleration (PLA) and peak angular acceleration (PAA) values were calculated by extracting peak resultant values from each HAE.

Tackles, ball-carrier, and ruck event data for all Currie Cup and Super Rugby matches for the 2023 seasons were acquired from commercially available video analysis data (Opta, StatsPerform, Chicago, IL). Contact event and type definitions are provided in Table S1. 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 synchronization with contact-event data. PLA and PAA below 5g and 400 rad/s^2, respectively, were excluded at this point based on previous recommendations [15]. Accelerometer, gyroscope, and proximity sensor data were synchronized to video timestamps of contact events using Matlab (MathWorks, UK, version R2023a). A HAE was linked to a contact event if their timestamps occurred within 10 s of one another [15]. This method had an 86.4% accuracy (unpublished data). Contact events that had proximity sensor data for the instrumented player were used in the analysis (Table S2) [15].

Where no iMG data were recorded for an identified contact event ($n = 5253$), the iMG data value for that contact event was denoted as "*not recorded*." Because of 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 consisted of both true and false negatives [18]. A true negative occurs when the kinematics at the head CoG fall below the recording threshold (i.e., 5*g*) and the kinematics at the teeth are lower than the trigger threshold (i.e., 8*g*). 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.

This 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 [19]. Previous literature has utilized both distributions. One study analyzed the truncated distribution of iMG data aggregated at a count level (i.e., counts of iMG-recorded HAE in a specific magnitude range) [20], thus values *not recorded* were not considered in the analysis, limiting the opportunity to consider contact-event characteristics. Another study considered individual iMG observations within a censored distribution, assuming that all *not recorded* observations fell below an arbitrary value (10g and 1000 rad/s^2), and data were not modeled to account for the multilevel data structure [15].

To advance these methods and to describe the HAEs experienced by players at different magnitude ranges, an ordinal mixed-effects regression model was used [21]. Ordinal regression splits data into ordered categories and estimates the probability of each category occurring. This method allows the analysis to consider the characteristics of each HAE individually and appropriately account for the multilevel structure of the data. Including a *not recorded* category allows data not collected due to the trigger threshold to be included within the analysis. However, missing data can only be observed as one data point per contact event (i.e., it is only known that data is missing). Therefore, to ensure observations were equally weighted within this probability-based analysis, only one summary value was provided for each contact event. For contact events where multiple HAE measurements were obtained, the highest PLA and PAA value from the contact event was reported; henceforth, referred to as HAE_{max}. Probabilities were estimated for HAE_{max} using eight magnitude ranges for PLA (*not recorded*, 5–14.99, 15–24.99, 25–34.99, 35–44.99, 45–54.99, 55–64.99, ≥65*g*) and PAA (*not recorded*, 400–999, 1000–1999, 2000–2999, 3000–3999, 4000–4999, 5000–5999, and ≥6000 rad/s^2). These ranges were chosen based on a trade-off between optimizing statistical power [22] and producing equal range widths where possible to enhance interpretability, while including a threshold (i.e., 25g) over which false negative are less likely to be present [18].

Three analyses were conducted. In the first, contact event (ball carry, tackle, attacking, and defensive ruck) was included as a categorical fixed effect. In the second, video analysis descriptions (contact event types, e.g., dominant, neutral, or ineffective tackle) for each individual contact event (Table S1) were used as categorical fixed effects. In the third, contact event was interacted with positional group in a fully factorial model. All fixed effects provided the probability of each HAE_{max} magnitude range occurring within a single contact event. 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 (i.e., the overall event identifier for each tackler, ball carrier, and player rucking in a single incident) was also included as a random effect to account for the multiple membership and cross-classification of all player contact events nested within different players, depending on the player combination involved in the contact event [23, 24]. 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 interdependencies within the multilevel data structure, model estimates, standard errors, and associated CIs may all be biased, and inaccurate statistical inferences may then result [23].

Median probabilities and 95% CIs for all estimates were produced using a bootstrapping approach with 1000 resamples [25]. Exceedance probabilities (i.e., the probability that a HAE_{max} magnitude greater than or equal to a certain value would occur during a contact event) were calculated using the same method (and are provided in tabular form in the Supporting Information). These are discussed specifically at ≥45*g* and ≥4000 rads/s^2 to enable comparisons with previous literature [15]. Differences were interpreted as clear and meaningful when the CIs of the estimates did not overlap. 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 contact event, contact-event type, or position. All statistical analyses were conducted in R (version 4.3.0) using the *Ordinal* [26] and e*mmeans* [27] packages.

3 | Results

3.1 | The Probability of HAE_{max} Occurring During Contact Events

Figure 1 shows the probability of individual HAE_{max} magnitude ranges for different contact events. For HAE_{max} magnitudes greater than 15*g* and 1000 rads/s^2, ball carries had the greatest probability of experiencing a HAE_{max} and attacking rucks had the lowest. Defensive ruck probabilities were closer to tackles than attacking rucks, but clear differences were present between all four events.

For all contact events, the probability of a HAE_{max} decreased as PLA and PAA magnitude increased (Figure 1, Table 1). From Table 1, a HAE_{max} of ≥15*g* would be expected on average approximately one in every two ball carries, three tackles, seven attacking rucks, and three defending rucks. A HAE_{max} of ≥1000 rads/s^2 would be expected on average to occur one in every two ball carries, three tackles, seven attacking rucks, and four defending rucks. At higher magnitudes of ≥45*g*, a HAE_{max} would be expected on average every 32 ball carries, 53 tackles, 333 attacking rucks, and 91 defending rucks while HAE_{max} occurrence at

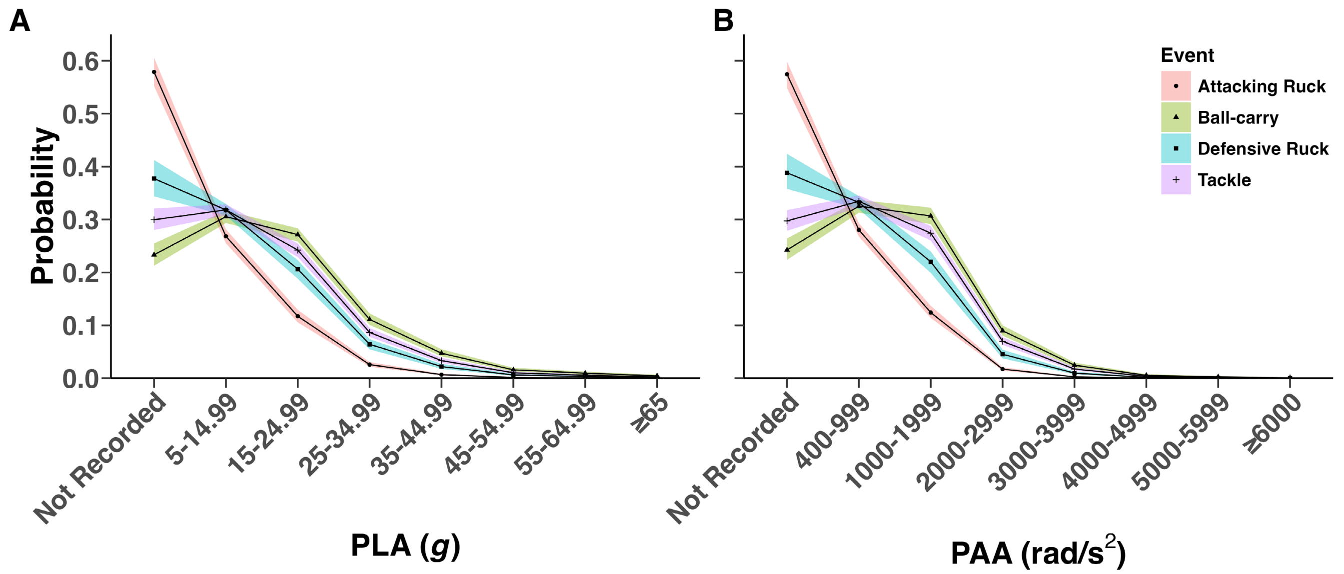

FIGURE 1 | The probability of a HAE_{max} occurring across a range of PLA (A) and PAA (B) magnitude ranges during a ball carry, tackle, attacking, or defensive ruck. Colored bands represent 95% confidence intervals.

≥3000 rads/s^2 would be expected on average every 29 ball carries, 42 tackles, 333 attacking rucks, and 77 defending rucks.

3.2 | The Probability of HAE_{max} Occurring During Different Contact-Event Types

Figure 2 depicts the probability of HAE_{max} ranges for each contact event type assessed with greater detail based on outcome and role/event characteristic. During ball carries, no differences were found between *dominant*, *ineffective*, and *neutral* contact event types at any HAE_{max} magnitude (Figure 2A). During tackles, however, at magnitudes of ≥15*g* and ≥1000 rad/s^2, *dominant* tackle probabilities were clearly greater than *ineffective* tackles (Figure 2C,D). In defensive rucks, those with an outcome of *turnover won* had greater probabilities of HAE_{max} occurrence at magnitudes of ≥15*g* and ≥1000 rad/s^2, than *nuisance* and *not clearing* defensive rucks (Figure 2G,H). Within attacking ruck types, there was large variability in the probability profiles, and outcomes of *secured* and *attended* had clearly lower probabilities of HAE_{max} at all magnitudes than *cleaned out* and *failed clearout* attacking rucks (Figure 2E,F).

3.3 | The Probability of HAE_{max} Occurring During Contact Events for Different Positional Groups

Figure 3 shows the probability of HAE_{max} during contact events for different positional groups. There were no clear differences between position groups for each contact event (Figure 3).

3.4 | The Probability of No iMG Data Being Recorded for a Contact Event

The probability of no data being recorded by an iMG when a contact event occurred (i.e., the in vivo HAE did not exceed the 8*g* trigger threshold at the teeth) ranged from 0.233 (95% CI 0.213–0.255) for ball-carry PLA to 0.579 (95% CI 0.552–0.606) for attacking ruck PLA.

4 | Discussion

The primary aim of this study was to describe the HAEs experienced by professional men's rugby union players during contact events, using statistical modeling techniques to account for the multilevel data structure. It was found that as the HAE_{max} magnitude increased, the probability of occurrence decreased, resulting in relatively small probabilities at higher HAE_{max} magnitudes. A secondary aim was to explore the differences between contact event type characteristics/outcomes and positional groups. Tackles and ball carries had a greater probability of HAE_{max} in higher magnitude ranges than rucks. The defensive ruck probability profile was closer to tackle and carry events than attacking rucks. However, in both attacking and defending rucks, there were some event types which were associated with higher magnitude HAE_{max} than others. There were no clear differences between positions for any contact events. Collectively, these results demonstrate that although higher magnitude HAE_{max} occur relatively infrequently in professional men's rugby union match play, specific contact events (e.g., ball carry) and the roles players perform within contact events (e.g., winning a turnover at the ruck) likely increase the chance of HAE_{max} occurrence.

An important finding of this study was that as the HAE_{max} magnitude increased the probability of occurrence decreased, resulting in comparatively low probabilities at higher magnitudes (Figure 1). For example, the probability of players experiencing a HAE_{max} at ≥45*g* when making a tackle was 0.019 (1 in every 53 tackles). On average, an openside flanker (often the highest tackler in a rugby union team) may be expected to make approximately 18 tackles per 80 mins in Super Rugby [28]. This suggests that he may on average experience one HAE_{max} of this magnitude approximately every three full games. However,

TABLE 1 | The exceedance probabilities of HAE_{max} occurring at different magnitude ranges of peak linear acceleration (PLA) and peak angular acceleration (PAA) during contact events.

Event type	PLA magnitude (*g*)	Probability (95% CI)	PAA magnitude (rad/s^2)	Probability (95% CI)
Ball carry	Recorded	0.767 (0.745–0.787)	Recorded	0.757 (0.736–0.776)
	≥15	0.461 (0.435–0.488)	≥1000	0.432 (0.407–0.457)
	≥25	0.189 (0.172–0.209)	≥2000	0.124 (0.111–0.140)
	≥35	0.078 (0.067–0.091)	≥3000	0.034 (0.028–0.041)
	≥45	0.031 (0.025–0.037)	≥4000	0.010 (0.007–0.012)
	≥55	0.014 (0.011–0.018)	≥5000	0.004 (0.003–0.006)
	≥65	0.005 (0.003–0.007)	≥6000	0.001 (0.001–0.002)
Tackle	Recorded	0.700 (0.679–0.720)	Recorded	0.703 (0.682–0.721)
	≥15	0.381 (0.360–0.404)	≥1000	0.368 (0.347–0.390)
	≥25	0.139 (0.126–0.154)	≥2000	0.094 (0.084–0.105)
	≥35	0.052 (0.045–0.061)	≥3000	0.024 (0.020–0.028)
	≥45	0.019 (0.015–0.023)	≥4000	0.006 (0.005–0.008)
	≥55	0.008 (0.007–0.011)	≥5000	0.002 (0.002–0.003)
	≥65	0.003 (0.002–0.004)	≥6000	0.001 (0.000–0.001)
Attacking ruck	Recorded	0.421 (0.394–0.448)	Recorded	0.425 (0.402–0.451)
	≥15	0.153 (0.136–0.171)	≥1000	0.145 (0.132–0.161)
	≥25	0.035 (0.030–0.042)	≥2000	0.021 (0.017–0.025)
	≥35	0.010 (0.008–0.012)	≥3000	0.003 (0.003–0.005)
	≥45	0.003 (0.002–0.003)	≥4000	0.001 (0.000–0.001)
	≥55	0.001 (0.001–0.001)	≥5000	0.000 (0.000–0.000)
	≥65	0.000 (0.000–0.000)	≥6000	0.000 (0.000–0.000)
Defensive ruck	Recorded	0.623 (0.587–0.656)	Recorded	0.612 (0.576–0.642)
	≥15	0.304 (0.271–0.337)	≥1000	0.279 (0.248–0.309)
	≥25	0.098 (0.082–0.116)	≥2000	0.058 (0.048–0.070)
	≥35	0.033 (0.027–0.042)	≥3000	0.013 (0.010–0.017)
	≥45	0.011 (0.008–0.015)	≥4000	0.003 (0.002–0.004)
	≥55	0.005 (0.003–0.007)	≥5000	0.001 (0.001–0.002)
	≥65	0.001 (0.001–0.002)	≥6000	0.000 (0.000–0.001)

Note: "Recorded" is the probability that a HAE_{max} greater than 5*g* was linked to the contact event.

studies are required to determine clinical relevance of these findings before any implications can be identified. For example, researchers may wish to investigate the association and causal links between the accumulation of HAEs of different magnitudes across players' playing careers and negative brain health outcomes (e.g., Daneshvar et al. [9] association study in American Football).

There was clear and meaningful separation between the probability profiles of different events. Tackles and ball carries were more likely to be associated with higher HAE_{max} magnitude probabilities than rucks (Figure 1). This finding concurs with recent literature demonstrating that most injuries sustained during professional rugby union match play occur during tackles [2, 3]. Similarly, research in community level rugby union demonstrated that 66%–75% of iMG-recorded HAE occurred during tackles and ball carries [20]. However, the finding that the defensive ruck probability profile was more comparable with tackles than attacking rucks is novel. To date, injury prevention research in rugby union has primarily focused on the tackle event [4, 29] and iMG research has indicated that elite players are less likely to experience HAE_{max} during rucks than tackles [15]. The results in the present study confirm this general finding but show that when the ruck is considered from defending and attacking perspectives, defensive rucks may warrant a greater consideration within the injury prevention interventions.

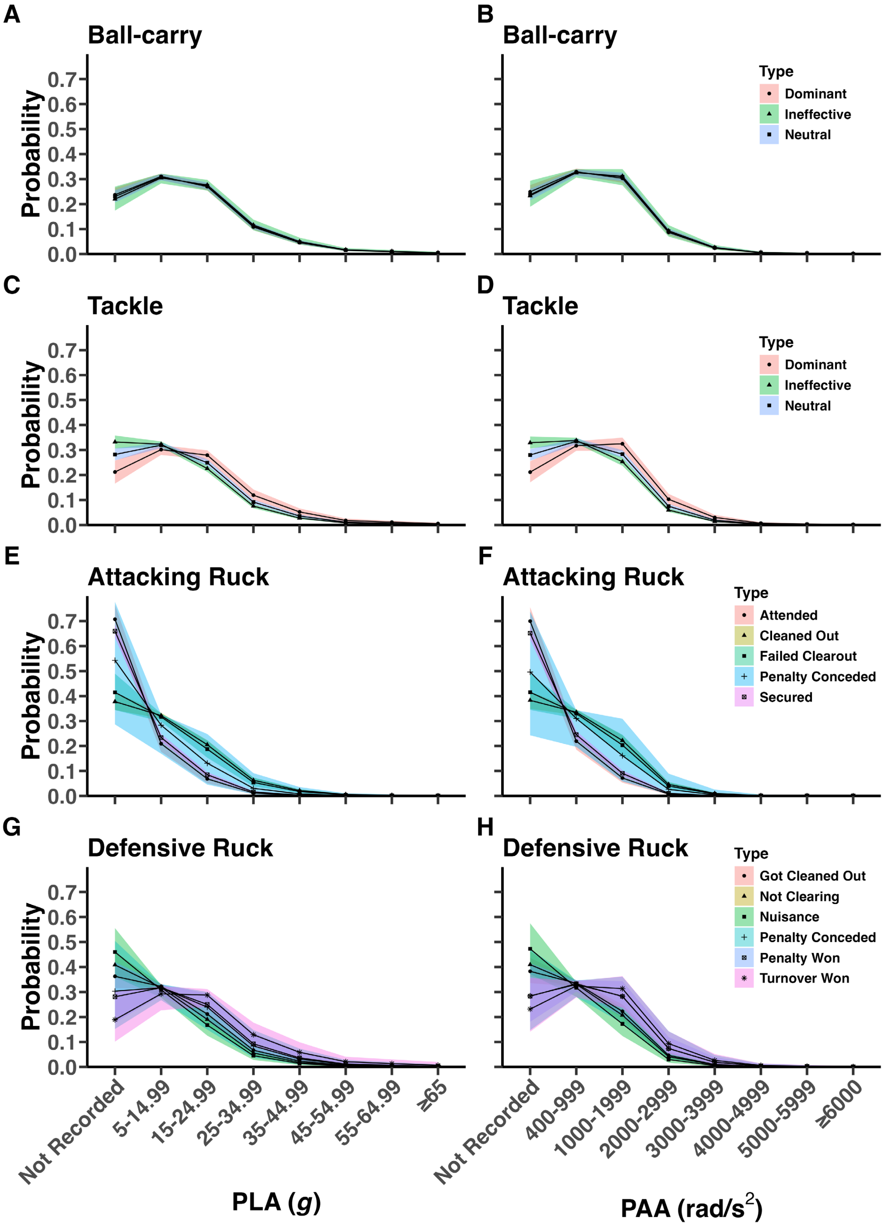

FIGURE 2 | The probability of a HAE_{max} occurring across a range of PLA and PAA magnitude ranges during a ball carry (A, B), tackle (C, D), attacking (E, F), or defensive ruck (G, H), assessed as the characteristics of each event type. Colored bands represent 95% confidence intervals.

The importance of differentiating between attacking and defensive rucks is shown by the contact event type analysis. Within attacking rucks, the event *secured* and *attended* had the lowest probabilities for the recorded HAE_{max} magnitude ranges and constituted almost 75% of all attacking ruck occurrences (Figure 2, Table S2). Conversely, some defensive ruck types (e.g., *turnover won*) had probability profiles overlapping those of tackles and ball carries. Although there is less certainty in the estimates of defensive ruck types due to the lower sample size relative to attacking rucks (Table S2), it is logical that contact types such as *turnover won* would involve an element of physical contact, thereby increasing the probability of larger magnitude HAE_{max} occurring. Similarly, within attacking rucks, it is reasonable to believe that contact-event types, such as *got cleaned out* and *failed clearout*, could have a greater physical element than *secured* or *attended*. Indeed, the results support this assumption with respect to the HAE_{max} probability profiles. Future studies should consider the contact element of rucks in greater detail (i.e., with different labelling) to better understand the elements of this contact event that are more likely to be associated with higher magnitude HAE_{max}, and that may therefore be targets of injury prevention initiatives.

Despite differences when breaking events down by contact type, the probability profiles between positions were similar, irrespective of contact type, which is in contrast to how positional groups have previously been described, identifying clear physical and physiological differences [30]. Importantly, although the probabilities of HAE_{max} were similar, players are involved in different numbers of contact events per match due to positional demands (e.g., forwards are involved in

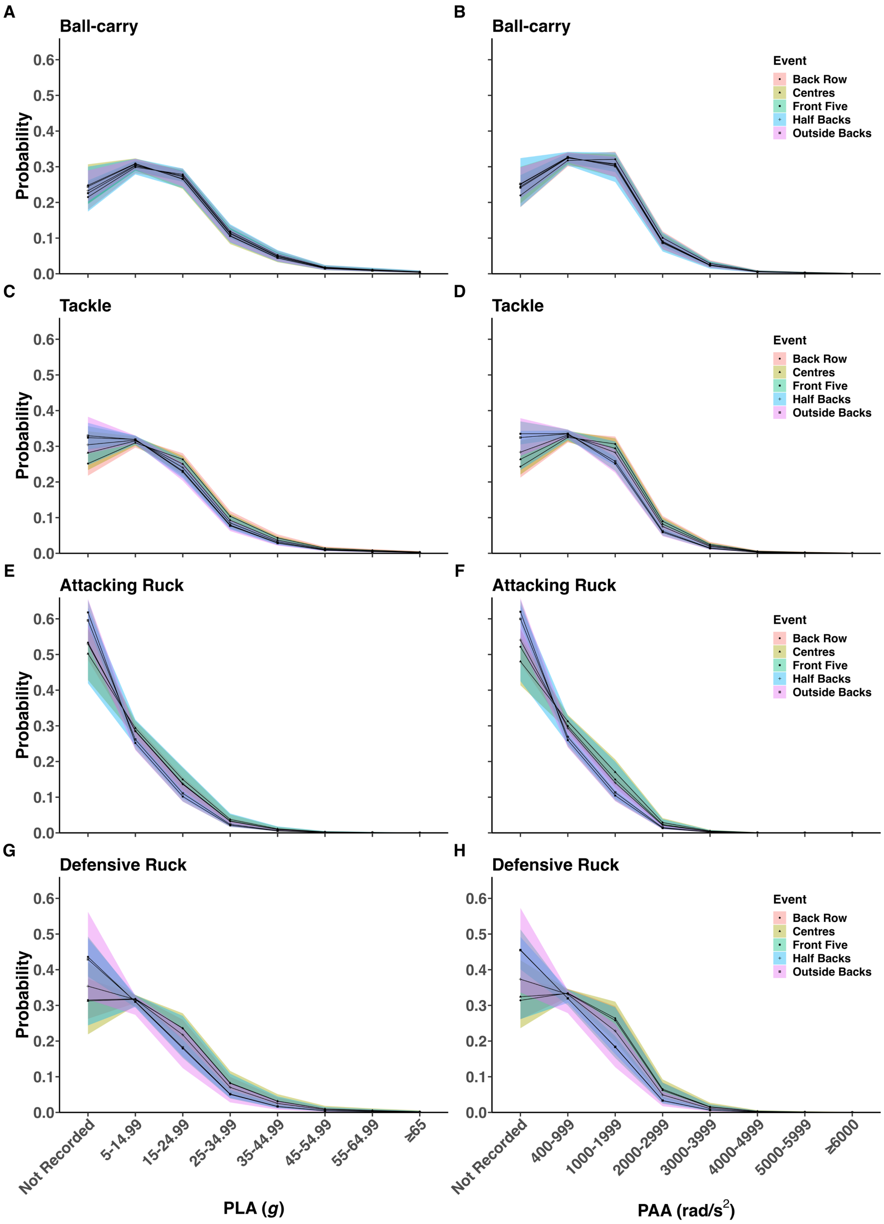

FIGURE 3 | The probability of a HAE_{max} occurring across a range of PLA and PAA magnitude ranges during a ball carry (A, B), tackle (C, D), attacking (E, F), or defensive ruck (G, H), interacted with positional group. Colored bands represent 95% confidence intervals.

approximately double the number of tackle events than backs per match [1]), so the absolute HAE exposure for each contact event will differ between positions. Indeed, in senior community [20] and senior professional male [15] rugby union players, research has demonstrated a greater incidence of HAEs in forwards than backs. Given that the cumulative exposure to head accelerations across a playing career may have consequences for long-term brain health [9], future research should build upon the probability profiles by including details of the absolute exposure to each contact event. However, researchers should be aware that the current probability profiles only provide the maximum HAE within a contact event and therefore are not suitable for estimates of the overall cumulative load. Until iMG technology advances to the extent where false negatives are not systematically present (i.e., the trigger threshold is not an issue), it will not be possible to assess cumulative load across all magnitude ranges accurately [31].

An important feature of this study is the inclusion of a *not recorded* HAE_{max} category. Probabilities in this category ranged from 0.233 (95% CI 0.213–0.255) for ball-carry PLA to 0.579 (95% CI 0.552–0.606) for attacking ruck PLA. A *not recorded* HAE_{max} represents an in vivo HAE that did not exceed the trigger threshold at the iMG location (i.e., the teeth). However, PLA values greater than 8g trigger threshold may have been experienced at the head CoG. A previous study simulating head accelerations across different impact locations revealed that a 10*g* trigger threshold is only exceeded in 24.7% of head impact locations following a 10*g* head impact at the head CoG, whereas 86.0% and 99.9% of impact locations exceeded a 10*g* trigger threshold following 20 and 30*g* head CoG impacts, respectively [18]. Consequently, it is reasonable to assume that lower in vivo HAE magnitudes are more likely to result in a *not recorded* HAE_{max}. The magnitude of linear acceleration has also been shown to be proportional to angular acceleration [18, 32], and therefore, these

HAE_{max} are also likely to be relatively lower in angular acceleration. However, the exact values of these *not recorded* data remain unknown. Further research utilizing lower linear trigger thresholds or incorporating angular trigger thresholds may be beneficial to improve our understanding of the *not recorded* data.

4.1 | Limitations

While providing novel insights, this study has some limitations. The first is selection bias, which is present in the form of volunteer bias (only players who volunteered to wear iMGs were included) and nonrandom sampling (a convenience sample of volunteers from two competitions was used). It is therefore possible that the sample in this study (207 out of a possible 779 players across both competitions) is not fully representative of the population of male professional Southern Hemisphere rugby union players. Second is the use of the maximum PLA and PAA as estimates of in vivo HAEs for each contact event. The use of peak resultant head kinematics does not consider directionality and temporal data which may also be important for injury risk. The inclusion of the *not recorded* category allowed for only one data point per contact event (i.e., it is only known that data is missing). Therefore, to ensure observations were equally weighted within this probability-based analysis, the highest recorded PLA and PAA were selected for each contact event. This does not provide the full picture for contact events that results in multiple HAEs. Researchers should be aware that evaluating other characteristics may provide different results to those in this study. Furthermore, although data from iMGs have previously been validated, kinematic filters and proximity sensors have yet to undergo individual validation. Moreover, iMGs are subject to false negatives [15]; therefore, potential resultant missing values could have influenced the probability estimations. Finally, the method used to link HAE_{max} data to video analysis data may have been subject to error. As a 10s window was used [15], it is possible that some HAE_{max} may have been misattributed.

5 | Perspective

Findings from the present study demonstrated that as HAE_{max} magnitude increased the probability of occurrence decreased resulting in relatively small probabilities at higher magnitudes. However, currently there are no clinical studies determining the threshold over which HAEs are potentially deleterious, particularly with respect to long-term exposure. Players who play regularly during their career could still have a significant exposure to higher HAE_{max} which may have clinical significance. Indeed, recent research in American Football players demonstrated that the long-term exposure to nonconcussive HAE is more strongly associated with chronic traumatic encephalopathy in later life, than with concussive events [9]. In the present study, experiencing a HAE_{max} was associated with the contact events that players participated in and the roles they performed within these contact events, not their actual playing position. Thus, researchers, policy makers, and practitioners should focus more closely on specific aspects of different contact events when exploring HAE mitigation strategies. The reported probabilities of HAE_{max} occurrence in this study can be used to evaluate future HAE reduction strategies in professional rugby union players and to guide practitioners in planning and player monitoring (e.g., during concussion return to play).

Author Contributions

G.R., B.J., and L.S. conceptualized the research project and designed the study. G.R. and J.T. collected the data. G.R. and T.S. analyzed the data while all authors were involved in the interpretation of the results. G.R. and T.S. drafted the manuscript. All authors critically reviewed and edited the manuscript prior to submission.

Ethics Statement

Institutional ethics approval was received, and participant informed consent obtained (REF: 108638).

Conflicts of Interest

G.R. role is part-funded by World Rugby. T.S. role is part-funded by Premiership Rugby. C.O. is part-funded by the Rugby Football League. L.S., É.F., and D.S. are employed by World Rugby. C.R. is employed by South Africa Rugby Union. K.R. is employed by the New Zealand Rugby Union. K.S. is employed by the Rugby Football Union. J.T. role is part-funded by the Rugby Football League, Premiership Rugby, and World Rugby. R.T. is employed by World Rugby as a consultant. B.J. is employed by Premiership Rugby and Rugby Football League as a consultant and has received funding from Prevent Biometrics and World Rugby.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, G.R., upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.