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Training and Match-Related Head Acceleration Events in Top Level Domestic Senior Women's and Men's Rugby Union: A Multi-League Instrumented Mouthguard Study

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ABSTRACT

The aim of this study was to investigate the difference in head acceleration event (HAE) incidence between training and match-play in women's and men's players competing at the highest level of domestic rugby union globally. Players from Women's (Premiership Women's Rugby, Farah Palmer Cup) and Men's (Premiership Rugby, Currie Cup) rugby union competitions wore instrumented mouthguards during matches and training sessions during the 2022/2023 seasons. Peak linear (PLA) and angular (PAA) acceleration were calculated from each HAE and included within generalized linear mixed-effects models. The incidence of HAEs was significantly greater in match-play compared to training for all magnitude thresholds in both forwards and backs, despite players spending approximately 1.75–2.5 times more time in training. For all HAEs (PLA > 5 g and PAA > 400 rad/s^2), incidence rate ratios (IRRs) for match versus training ranged from 2.80 (95% CI: 2.38–3.30; men's forwards) to 4.00 (3.31–4.84; women's forwards). At higher magnitude thresholds (PLA > 25 g; PAA > 2000 rad/s^2), IRRs ranged from 3.64 (2.02–6.55; PAA > 2000 rad/s^2 in men's backs) to 11.70 (6.50–21.08; PAA > 2000 rad/s^2 in women's forwards). Similar trends were observed in each competition. Players experienced significantly more HAEs during match-play than training, particularly at higher magnitude thresholds. Where feasible, HAE mitigation strategies may have more scope for HAE reduction if targeted at match-play, particularly where higher magnitude HAEs are the primary concern. However, the number of HAEs associated with different training drills requires exploration to understand if HAEs can be reduced in training, alongside optimizing match performance (e.g., enhancing contact technique).

1 | Introduction

Rugby union is a contact sport played globally by both men and women [1]. In contact sports, there is concern regarding the potential long-term effects of repetitive head impacts on brain health [2, 3]. Accordingly, it is important for stakeholders to understand the contexts in which head accelerations most commonly occur (e.g., training vs. competition). Such information can be used by researchers and policymakers to appropriately design and implement mitigation strategies [4, 5]. Furthermore, coaches and practitioners may wish to use this data to guide player load management strategies. Finally, this research may provide players with a greater understanding of the head accelerations associated with the activities involved in their sport.

Instrumented mouthguards (iMGs) have been implemented within rugby union to approximate head acceleration events (HAEs) [6]. However, the focus has been primarily on quantifying and characterizing HAEs during match-play [7–9]. A study in amateur men's players identified that the proportion of HAEs experienced during training compared to matches was 35% [7]. Nevertheless, HAEs have not been quantified within an elite training setting. There are differences in physical characteristics [10], greater training loads [11], collision intensities [12] and incidence of head injuries [13] at higher levels of competition compared to amateur settings. Therefore characterizing HAE exposure from training in elite players is a significant gap in the literature. Moreover, there has yet to be any study quantifying HAEs in training in women's players at any playing level. Therefore, the aim of the present study was to quantify and compare the incidence of HAEs in training and match-play in women's and men's players competing at the highest level of domestic rugby union, across a range of competitions globally.

2 | Methods

2.1 | Study Design

A prospective observational study was conducted in rugby union players from two semi-professional women's and two professional men's rugby union competitions who partook in the World Rugby deployment of iMGs (Prevent Biometrics; Minneapolis, MN, USA) during the 2022/2023 seasons. These included the highest level of domestic women's competition in England (Premiership Women's Rugby) and New Zealand (Farah Palmer Cup), and the highest level of domestic men's competition in England (Premiership Rugby) and South Africa (Currie Cup). Players wore iMGs during both rugby training and match-play. For each competition, iMG data were used to determine the HAE incidence in forwards and backs during training and matches. Incidence was expressed using two different exposure time denominators: *per typical match* or *typical training week*, which was based on median match playing and training times, respectively; and *per hour*, which allowed overall comparison with normalized exposure time. The number of players, training sessions, matches and total min per competition and positional group are detailed in Table 1. Ethics approval was received from the University Ethics Committee (REF: 108638).

2.2 | Instrumented Mouthguards

All players underwent 3D dental scans and were provided with custom-fit iMGs (Prevent Biometrics; Minneapolis). The iMG contained an accelerometer and gyroscope that sampled at 3200 Hz with measured ranges of ±200 g and ± 35 rad/s. The 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 [14].

A discretized period of kinematics (−10 and + 40 ms from the 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 (Equation 1). The head was assumed to be a rigid body, therefore angular acceleration values were not transformed. 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 from all HAEs were initially filtered by Prevent Biometrics using a four-pole, zero phase, low-pass Butterworth filter with a 200 Hz cut-off frequency. Linear acceleration was directly measured by the accelerometer and angular acceleration was calculated by Prevent Biometrics via differentiation of the angular velocity signal recorded by the gyroscope. Another in-house Prevent Biometrics algorithm classified HAEs based on the level of noise in the signal, events classified the level of noise remaining in each signal as low ($n = 70635$), moderate ($n = 4153$), or severe ($n = 1542$). An additional filter was applied by Prevent Biometrics to HAEs classified with moderate and severe noise with 100 and 50 Hz cut-off frequencies, respectively. Peak linear acceleration (PLA) and peak angular acceleration (PAA) values were calculated by extracting peak resultant values from each HAE. Following this processing, only HAEs which exceeded both 5 g and 400 rad/s^2 were used in the analysis, in order to ensure that HAEs included in the data set were a result of contact events, based on previous recommendations [9, 15]. The use of this threshold and Prevent Biometrics' algorithm resulted in a positive predictive value of 0.99 in a previous rugby union study [9], therefore HAEs were not directly video verified for false positives:

$$\overrightarrow{a_{\mathrm{h}}} = \overrightarrow{a_{\mathrm{m}}} + \vec{\alpha} \times r_{\mathrm{mh}} + \vec{\varpi} \times \left(\vec{\varpi} \times r_{\mathrm{mh}}\right) \tag{1}$$

The relative acceleration equation, where $\overrightarrow{a_{\mathrm{h}}}$ is the linear acceleration at the head CoG with respect to time, $\overrightarrow{a_{\mathrm{m}}}$ is the linear acceleration at the iMG sensor location with respect to time, $\vec{\alpha}$ is the angular acceleration with respect to time, r_{mh} is the position vector from iMG sensor location to the head CoG, and $\vec{\varpi}$ is angular velocity with respect to time. The transformation vector (r_{mh}) was (−0.082, 0.009, −0.065) in meters.

TABLE 1 | The number of players, player matches (PM)/training weeks (PTW), total hours, median training/playing time (interquartile range; IQR) and HAEs (all, > 25 g, > 2000 rad/s^2) for training and matches per position and competition. W = women's competition, M = men's competition.

					HAEs		
	Players	Player matches/ player training weeks	Total player hours	Median playing/ weekly training time (IQR)	All recorded	PLA > 25 g	PAA > 2000 rad/s^2
Matches (forwards)							
Women's: all competitions	269	1038 (PM)	892	58 (27–80)	12 930	1173	1142
Premiership Women's Rugby (W)	114	577 (PM)	505	60 (27–80)	7620	705	727
Farah Palmer Cup (W)	155	461 (PM)	387	56 (27–76)	5310	468	415
Men's: all competitions	238	1567 (PM)	1306	56 (24–77)	38 305	4795	3592
Premiership Rugby (M)	143	1097 (PM)	933	57 (26–80)	27 653	3460	2558
Currie Cup (M)	95	470 (PM)	373	52 (22–70)	10 652	1335	1034
Matches (backs)							
Women's: all competitions	180	684 (PM)	687	74 (40–80)	6187	633	637
Premiership Women's Rugby (W)	71	355 (PM)	357	80 (40–80)	2992	259	294
Farah Palmer Cup (W)	109	329 (PM)	329	71 (45–80)	3195	374	343
Men's: all competitions	141	863 (PM)	848	72 (40–80)	14 770	1838	1658
Premiership Rugby (M)	81	564 (PM)	563	73 (42–80)	10 459	1328	1164
Currie Cup (M)	60	299 (PM)	285	71 (28–80)	4311	510	494
Training (forwards)							
Women's: all competitions	156	358 (PTW)	538	143 (132–162)	914	42	36
Premiership Women's Rugby (W)	31	68 (PTW)	84	113 (99–138)	162	9	12
Farah Palmer Cup (W)	125	290 (PTW)	454	144 (133–166)	752	33	24
Men's: all competitions	141	359 (PTW)	503	129 (114–138)	2429	168	127
Premiership Rugby (M)	90	239 (PTW)	335	128 (122–138)	1834	124	94
Currie Cup (M)	51	120 (PTW)	168	149 (97–153)	595	44	33
Training (backs)							
Women's: all competitions	92	190 (PTW)	286	144 (134–166)	401	18	25
Premiership Women's Rugby (W)	18	36 (PTW)	38	138 (113–138)	41	0	1
Farah Palmer Cup (W)	74	154 (PTW)	248	162 (141–166)	360	18	24
Men's: all competitions	58	111 (PTW)	144	126 (112–135)	394	27	40
Premiership Rugby (M)	39	79 (PTW)	105	128 (114–135)	316	23	35
Currie Cup (M)	19	23 (PTW)	39	97 (97–125)	78	4	5

Note: A player match is the product of the number of matches in the study and the number of players participating in them within each position-competition group (e.g., 269 women's forwards who participated in 1038 matches between them). Player training week is the product of the number of training weeks involved in the study and the number of players participating in them within each position-competition group (e.g., 141 men's forwards who participated in 359 training weeks between them). Total player hours is the accumulated total number of hours played/trained across all players within each position-competition group.

2.3 | Training Data

Due to the limited number of camera angles typically used to film rugby union training, it was not possible to visually inspect if all players were wearing their iMGs at all appropriate times during training (e.g., as a minimum iMG on-teeth during contact and off-teeth during the rest period within a drill). However, in a subsample of players from Premiership Rugby (men, $n=17$, 11 forwards, 6 backs across 3 clubs) and Premiership Women's Rugby (women, $n=24$, 16 forwards and 8 backs across 3 clubs), video footage was available in which each player was identifiable throughout a training session. Across 17 training sessions and 71 player-training-session observations, for all drills in which an iMG was worn, players only removed their iMG in between training activities or when they were not directly involved in the training activity in which there was the potential for contact (e.g., subbing in and out, or between repetitions during a training drill). Based on these findings, it was assumed that all players wore their iMG during training activities in which they were at risk of being involved in a contact event. However, given that the subsample was from a single country, it is possible that these practices were not ubiquitous across all competitions.

For each competition, weekly training video footage was requested from all participating clubs. Video data for a given training session were included in the study if an accurate start timestamp was provided, and the content of all drills could be discerned (i.e., no drills were undertaken off camera). For each training session, the start and stop times and contact level (classified using the rugby football union's definitions of contact training, unpublished) of each drill were coded by two experienced analysts, reaching a total of 325 h of video footage analyzed. Only iMG data occurring on the date of the training session, between the start and stop times of each session were included in the training dataset. Accelerometer, gyroscope and proximity sensor data recorded by iMGs were synchronized to video footage and visualized using Matlab (MathWorks, UK, version R2023a). Three authors visually inspected proximity sensor data to determine whether players wore their iMG for each drill. A player's data were only included if they wore an iMG in all training drills on a given day with the exception of non-contact training.

Players typically only wore their iMGs during the main training days of the week during which contact training is typically undertaken (i.e., no training sessions 24 h prior to a match, or the first training session after a match within 48 h). Therefore, only data from the main training days of the week were included in the study. The total number of training weeks and minutes for each competition used in the final analysis are detailed in Table 1.

2.4 | Match-Data

Video analysis provided by Opta (StatsPerform, Chicago, IL, USA) were used to identify match exposure for each player-match. Only iMG data recorded by players participating in the match, on the date of the match, and between each player's start and stop playing time were included in the match dataset. Accelerometer, gyroscope, and proximity sensor data were synchronized to Opta data for each match, which contained timestamps of all contact events (tackles, ball carries, rucks, mauls, and scrums). Proximity sensor data were used to identify whether the iMG was being worn for each contact-event and only player matches where the instrumented player wore their iMG for at least 90% of their contact events were included to ensure iMG adherence and minimize false negatives [8, 9].

2.5 | Statistical Analysis

To quantify and compare the HAE incidence in training and match-play for women's and men's players, generalized linear mixed models assuming a Poisson distribution were used. Sex, type (training or match play), position (forward or back) and the logarithm of minutes played were included as fully factorial fixed effects allowing slopes of HAEs accumulation per minutes to be estimated for each sex, type, and position combination. Random slopes for the number of HAEs per minute of exposure time were added for each athlete and allowed to vary between training and match play. A random effect for the week, clustering players within matches and training weeks together was also included. All statistical analyses were completed in R (version 4.3.2) using the *glmmTMB* [16] and *emmeans* [17] packages.

Incidence was estimated with a predicted function using each generalized linear mixed model using the various denominators. These denominators included *per typical match* or *per typical training week*, whereby the median minutes played per player-match and median minutes trained per week were used, respectively; and *per training hour* or *per match hour*, to allow comparison using a normalized exposure time. Median minutes played (used for the *per typical match* denominator) was calculated using playing time provided for each player-match in Opta data, while median minutes trained (used for the *per typical training week*) was calculated using only those players with two or more sessions in the training week. These median exposure times were calculated separately for forwards and backs, and men's and women's players and are provided in Table 1.

In addition to different denominators, incidence was expressed using different thresholds. Firstly, the incidence of *all HAEs* (i.e., those measured by the iMG which exceeded both 5 g and 400 rad/s^2) was used to estimate the exposure of HAEs exceeding those usually measured from non-contact events [9, 15]. Additionally, the incidence was calculated using higher HAE thresholds: separately, HAEs exceeding 25 g, and HAEs exceeding 2000 rad/s^2 were used to capture the incidence of higher magnitude HAEs. Thresholds beyond this did not reach model convergence. Incidence rate data are visualized in Figures 1 and 2, and provided in numerical form in Table S1.

Incidence rate ratios were used to compare rates between training and match play within positions and sexes (e.g., men's forwards *incidence per match hour* vs. men's forwards *incidence per training hour*). Results are presented as means (95% confidence intervals). In situations where very limited data were present around the median number of minutes played, or very few HAEs were present, confidence intervals were likely to be inflated.

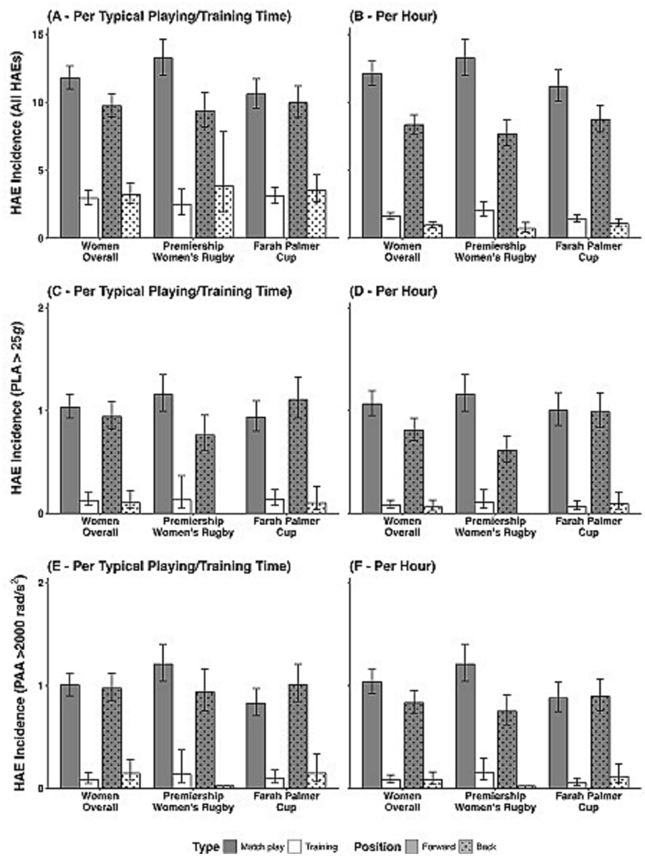

FIGURE 1 | Head acceleration event incidence for all women's players and in each women's competition per median training/playing time (A, C, E) and per hour (B, D, F). Position is represented by the absence (forwards) or presence (backs) of dots. NB: No HAEs for PLA > 25 g and only one HAE > 2000 rad/s^2 were recorded during Premiership Women's Rugby training, therefore robust confidence intervals could not be calculated.

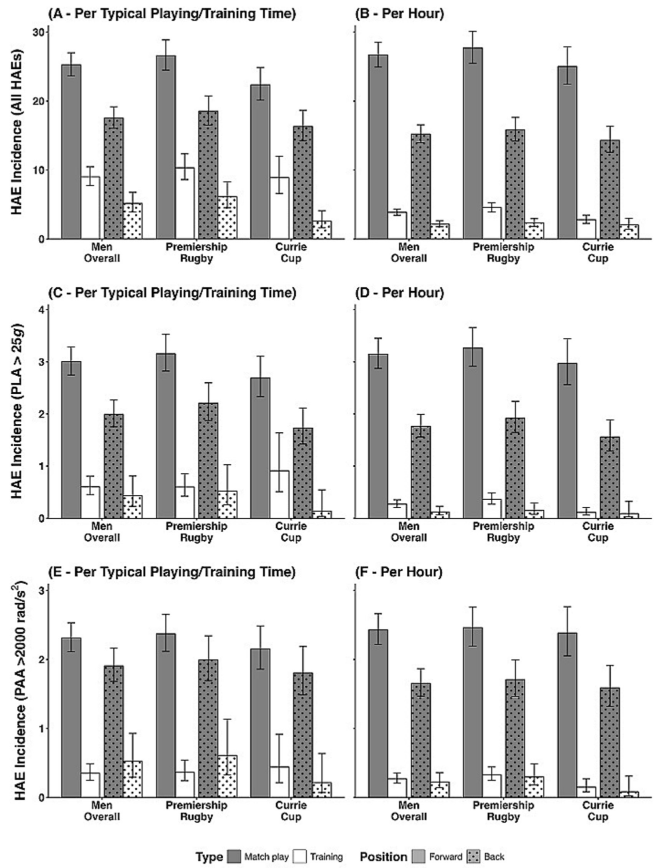

FIGURE 2 | Head acceleration event incidence for all men's players and in each men's competition per median training/playing time (A, C, E) and per hour (B, D, F). Position is represented by the absence (forwards) or presence (backs) of dots.

Comparisons were deemed significantly different if confidence limits did not overlap or did not contain one [18].

3 | Results

3.1 | Incidence of HAEs in Women's Training and Match-Play

The HAE incidence for players was significantly greater in a typical match compared to a typical training week for all magnitude thresholds (Figures 1 and 2; A,C and E). For *all HAEs*, differences between a typical training week and a typical match, as measured by incidence rate ratios (Table 2), ranged from 2.80 (2.38–3.30; men's forwards) to 4.00 (3.31– 4.84; women's forwards). At higher magnitudes, incidence rate ratios were larger, ranging from 3.64 (2.02–6.55; HAEs > 2000 rad/s^2; men's backs) to 11.70 (6.50–21.08); HAEs > 2000 rad/s^2; women's forwards depending on the HAE threshold, sex and positional group (Table 2). When normalized per hour, differences between training and match-play were greater than per typical training week/match, ranging from 6.88 (6.01–7.88; all HAEs; men's forwards) to 14.24 (7.62–26.62; PLA > 25 g; men's backs). Similar trends were seen in individual competitions. Figure 3 depicts all head kinematic values for training and match-play for women's and men's players.

4 | Discussion

The aim of the present study was to quantify and compare the incidence of HAEs in training and match-play in women's and men's players competing at the highest level of domestic rugby union, across a range of competitions globally. The HAE incidence for players was significantly greater in a typical match compared to a typical training week for all magnitude thresholds, with incidence rate ratios ranging from 2.80 (2.38–3.30; all HAEs; men's forwards) to 11.70 (6.50–21.08); HAEs > 2000 rad/s^2; women's backs depending on the HAE threshold, sex and positional group. These ratios increased when training and match-play were normalized per hour. Similar trends were observed in individual competitions. Where feasible, mitigation strategies designed to reduce players' HAE exposure may have greater scope to do so if targeted at match-play (e.g., rules changes and player match/HAE limits), particularly where higher HAE magnitudes are of primary concern.

In both women's and men's players, HAE incidence for forwards and backs was significantly greater in a typical match than in a typical training week (Figures 1 and 2; A,C and E), despite

TABLE 2 | Incidence rate ratios (confidence intervals) for training compared to match-play per median training/playing times and per hour. Training is used as the reference value; for example, HAEs exceeding 25 g were 5.25 times more numerous in a typical match than in a typical training week in Premiership Rugby forwards, while the incidence of HAEs per hour was 9.03 higher during match-play than training in that competition.

	Per typical weekly training/playing time		Per hour training/match-play	
	Forwards	Backs	Forwards	Backs
Sex				
Women's				
All HAEs	4.00 (3.31–4.84)	3.03 (2.37–3.87)	7.41 (6.31–8.70)	8.76 (6.91–11.11)
PLA > 25 g	8.20 (4.87–13.82)	9.04 (4.18–19.55)	13.39 (8.28–21.67)	13.24 (6.28–27.90)
PAA > 2000 rad/s^2	11.70 (6.50–21.08)	6.65 (3.42–12.93)	12.49 (7.80–20.00)	9.88 (5.17–18.88)
Men's				
All HAEs	2.80 (2.38–3.30)	3.40 (2.56–4.51)	6.88 (6.01–7.88)	7.02 (5.65–8.71)
PLA > 25 g	4.98 (3.68–6.73)	4.64 (2.43–8.87)	11.60 (8.77–15.35)	14.24 (7.62–26.62)
PAA > 2000 rad/s^2	6.60 (4.65–9.36)	3.64 (2.02–6.55)	8.98 (6.78–11.89)	7.34 (4.54–11.86)
Competition				
Premiership Women's Rugby (W)				
All HAEs	5.30 (3.63–7.76)	2.43 (1.18–4.99)	6.37 (4.84–8.39)	10.58 (6.54–17.13)
PLA > 25 g	8.92 (3.13–25.41)	NA	10.59 (4.98–22.52)	NA
PAA > 2000 rad/s^2	8.87 (3.20–24.55)	NA	7.72 (4.06–14.68)	NA
Farah Palmer Cup (W)				
All HAEs	3.42 (2.76–4.24)	2.82 (2.09–3.80)	7.77 (6.33–9.53)	8.05 (6.06–10.70)
PLA > 25 g	7.07 (3.98–12.54)	11.13 (4.19–29.55)	14.92 (7.98–27.91)	10.54 (4.65–23.90)
PAA > 2000 rad/s^2	8.84 (4.61–16.96)	6.87 (2.98–15.86)	17.46 (8.55–35.65)	7.81 (3.71–16.43)
Premiership Rugby (M)				
All HAEs	2.58 (2.11–3.14)	2.69 (1.95–3.70)	6.08 (5.16–7.15)	6.76 (5.23–8.74)
PLA > 25 g	5.25 (3.64–7.58)	3.83 (1.90–7.69)	9.03 (6.62–12.34)	13.07 (6.46–26.45)
PAA > 2000 rad/s^2	6.53 (4.31–9.92)	2.91 (1.53–5.52)	7.48 (5.44–10.27)	5.76 (3.43–9.70)
Currie Cup (M)				
All HAEs	2.52 (1.84–3.44)	6.31 (3.90–10.20)	8.93 (7.06–11.29)	7.01 (4.71–10.42)
PLA > 25 g	2.95 (1.62–5.38)	12.65 (3.13–51.07)	26.09 (14.02–48.53)	17.70 (4.74–66.13)
PAA > 2000 rad/s^2	4.87 (2.31–10.23)	8.43 (2.79–25.49)	15.99 (8.66–29.50)	19.31 (5.07–73.56)

Note: No HAEs for PLA > 25 g and only one HAE > 2000 rad/s^2 were recorded during Premiership Women's Rugby training. Therefore, incidence rate ratios were not calculated for this competition at these thresholds.
Abbreviations: M, men's competition; W, women's competition.

players spending approximately 1.75–2.5 times more time training (Table 1). When normalized per hour (e.g., approximately half of the median training times, Table 1), HAE incidence rate ratios ranged from 7.41 (6.31–8.70; all HAEs in forwards) to 13.39 (8.28–21.67; PLA > 25 g in forwards) in women's players, and from 6.88 (6.01–7.88; all HAEs in forwards) to 14.24 (7.62–26.62; PLA > 25 g in backs) in men's players In practical terms, this means that players in the present study would have to train between approximately 7–14 h to experience a similar number of HAEs in training as in an hour of match-play, depending on their sex and position. This is far greater than the median training times of the teams in the current study (97–149 mins, Table 2).

At higher HAE magnitude thresholds (PLA > 25 g; PAA > 2000 rad/s^2), the difference between training and match-play increased (Table 2). However, it is important to note that the absolute number of HAEs experienced by players decreased (Figure 1), confirming previous findings in elite-level match-play [8, 9]. For example, although HAE incidence for women's forwards was 8.20 times greater at PLA > 25 g in a typical match than a typical training week (Table 2), in absolute terms, on average forwards had only 0.13 HAEs in a typical training week (median of 129 min training time) and 1.04 HAEs during a typical match (median of 58 min of match-play) at this magnitude threshold. Nevertheless, across a competitive season or a playing

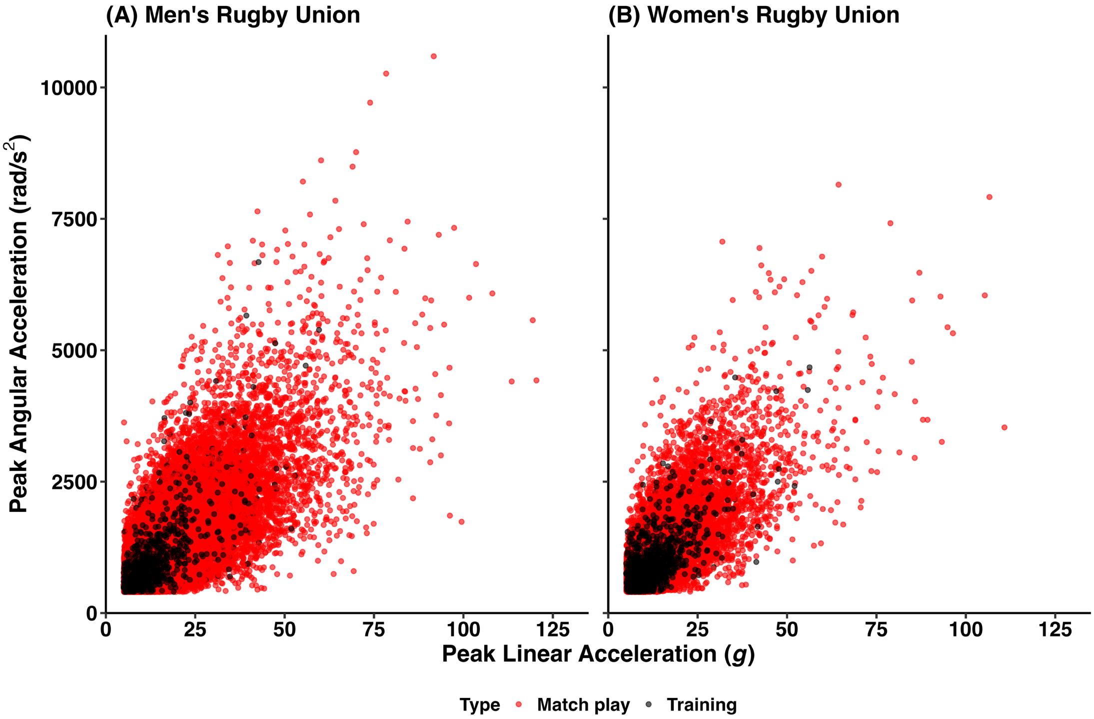

FIGURE 3 | Head kinematic values during training (black dots) and match-play (red dots) for men's and women's players.

career, these differences would have a significant impact on player exposure. The clinical relevance of exposure to HAEs at different magnitude threshold ranges needs to be determined before conclusions can be made regarding the pertinence of these findings to player safety.

In the present study, for most competitions and playing positions, significantly more data (2–9-fold more) were collected from match-play than from training (Table 1). In a recent study investigating iMG usage in professional rugby, iMG managers (appointed practitioners responsible for the collection and analysis of iMG data in sports teams) reported that players did not habitually wear mouthguards during training (instrumented or otherwise) [19]. This represented a major barrier to players wearing iMGs, and player and staff engagement with iMG data. Furthermore, in the present study, the quality of the training video data provided by teams in certain competitions was not always of a standard that could be used. Due to the limited data, incidence rate ratios could not be calculated for Premiership Women's Rugby at higher thresholds as there was only 1 HAE > 2000 rad/s^2 and no HAE > 25 g, while the incidence rate ratio confidence limits calculated for Currie Cup backs were very wide (Table 2). Further research is therefore required to understand if the HAE incidence estimations in the present study accurately represent these two playing populations.

The differences between training and match-play identified in this study have important implications for player welfare policy. In other collision sports, for example, American Football, research has demonstrated significant associations between retrospective estimations of cumulative head impacts throughout players' careers and chronic traumatic encephalopathy [3] and neurocognitive impairments in later life [20]. Thus, interventions to reduce player exposure to HAEs are of high priority. In contact sports such as American Football and ice hockey, observational studies have identified training activities (e.g., full-contact [21]) and match actions (e.g., longer closing distances [22], contact technique [23], and illegal contacts [24]) that result in higher magnitude HAEs. Recently in rugby union, Roe et al. [8] observed that tackling, followed by ball carrying, had the highest probability of resulting in a HAE regardless of magnitude. To date, however, the evaluation of policy changes to enhance player safety with respect to head injury has primarily focused on concussion. For example, rule changes such as the "targeting rule" in the NFL [25] and the outlawing of body checking in youth ice hockey [26], have reduced concussion incidence, while in rugby union, changes to the tackle height in semi-professional [27] and amateur [28] players did not. It has yet to be ascertained whether such interventions would have had a significant impact on HAE incidence in these populations.

In intervention design, an important initial step is to develop an understanding of the problem requiring intervention and identify the factors that are most amenable to change [29]. In the present study, on average, both women's and men's rugby union players experienced a significantly greater number of HAEs during match-play than training. Therefore, interventions targeting match-play, such as reduced maximum match limits for players in a season and/or law change to change the frequency and/or nature of match contact events may have greater scope for reducing long-term player HAE exposure than those targeting training (restricting the time spent on selected training activities). However, to support the design of such interventions additional research is required to determine the most feasible and appropriate ways to do so (e.g., investigating the HAE causal mechanisms on which to intervene [5], assessing the appropriateness and feasibility of rule changes while considering player and fan viewpoints, optimal match limits [30] and training activity exposure [31]). Moreover, the acute and chronic clinical significance of HAE exposure has not been prospectively determined. These are important considerations for whether policy changes should target activities that result in HAEs of specific magnitudes, or HAEs overall.

4.1 | Limitations

Although this study provides novel insights, it has some limitations. The first of these, consistent with similar studies [7–9], is sampling bias. This is present in the form of non-random sampling (a convenience sample from each competition was used) and volunteer bias (only players who volunteered were included). The generalizability of the results in the present study is conditional on the sample of players being representative of the population more broadly. For example, those that volunteered to wear an iMG may have done so because they are involved in more contact events, which could bias the findings by overestimating HAE incidence. Given that the wearing of iMGs during matches and contact training has recently been mandated, future research should aim to include a broad range of players, playing positions, ages and other potentially important factors. Additionally, the number of training sessions in the data set was much lower than the number of matches, particularly in Premiership Women's Rugby and Currie Cup men's backs. Therefore, HAE incidence estimates in training may not be fully representative of these playing populations. Furthermore, due to players not habitually wearing iMGs during certain training sessions (match-day + 2, match-day−1), only data from the main training sessions of the week were available. Although contact training is not typically undertaken in sessions other than those quantified in the present study, it is possible that players may have experienced some HAEs during these other training sessions. Moreover, the subcomponents of training were not investigated in this study, nor were the mechanisms of HAE. It is likely that certain activities within training (e.g., full-contact training) contribute more to HAE incidence than others. Thus, it is important that future research investigates the HAEs associated with different training activities to determine if mitigation strategies targeting training may also be appropriate and feasible. However, careful consideration is warranted to ensure that strategies to reduce HAEs in training do not interfere with the preparation of players, particularly given the importance of technical proficiency for safe tackling and ball-carrying in match-play [32]. Finally, attempts were made to model higher HAE magnitudes thresholds in accordance with other rugby union literature [8]. However, due to the lack of data in training versus matches for both men (e.g., >40 g; 1685 HAEs in match-play and 23 in training) and women (e.g., >40 g; 399 in matches and 9 in training), models did not converge. Future research may require larger data sets and advanced statistical models to cater for the rarity of these events in training.

4.2 | Perspective

This is the first study to quantify the differences in HAE incidence between training and match-play in women's and men's players competing at the highest level of domestic competition. The HAE incidences for women's and men's players were significantly greater in match-play compared to training for all magnitude thresholds in both forwards and backs, despite players spending longer (approximately 1.75–2.5 times more) in training than in matches. Differences in HAE incidence ranged from 2.80 to 11.70 times greater in matches than in training, depending on the HAE threshold, sex and positional group; and were even larger when training and matches were compared per hour. Given that long-term exposure to HAEs in rugby union players is a health concern, mitigation strategies targeting match-play may have greater scope to reduce HAE exposure, although future research is required to determine the most feasible and appropriate ways to do so. Furthermore, the number of HAEs associated with different types of training drills also needs to be explored to understand if HAEs can be reduced in training, alongside optimizing match performance (e.g., enhancing contact technique).

Author Contributions

G.R., L.S., M.C., K.S., and B.J. conceptualized the research. G.R., D.S., J.T., and S.Hu. collected the data. J.T., T.S., G.R., S.Hu., R.W., and L.M. analyzed the data while all authors were involved in the interpretation of the results. G.R. drafted the research paper and all authors contributed equally to the writing beyond this point.

Conflicts of Interest

T.S. role is part-funded by Premiership Rugby. G.R. role is part-funded by World Rugby. J.T. role is part-funded by the Rugby Football League, Premiership Rugby and World Rugby. C.O. is part-funded by the Rugby Football League. B.J. is employed by Premiership Rugby and Rugby Football League as a consultant and has received funding from Prevent Biometrics and World Rugby. M.C. is employed by Premiership Rugby. L.S., É.F. and D.S. are employed by World Rugby. C.R. is employed by the South African Rugby Union. K.R. is employed by New Zealand Rugby. S.H. is funded by the Rugby Football Union. K.S. and S.K. are employed by the Rugby Football Union. R.T. is employed by World Rugby as a consultant. S.H., R.W., and L.M. have no conflicts of interest.

Data Availability Statement

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

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Supporting Information

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