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# Instrumented mouthguards in elite-level men's and women's rugby union: characterising tackle-based head acceleration events

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## ABSTRACT

**Objectives** To examine the propensity of tackle height and the number of tacklers that result in head acceleration events (HAEs) in elite-level male and female rugby tackles.

**Methods** Instrumented mouthguard data were collected from women (n=67) and men (n=72) elite-level rugby players from five elite and three international teams. Peak linear acceleration and peak angular acceleration were extracted from HAEs. Propensities for HAEs at a range of thresholds were calculated as the proportion of tackles/carries that resulted in an HAE exceeding a given magnitude for coded tackle height (low, medium, high) and number of tacklers. Propensity ratios with 95% CIs were calculated for tackle heights and number of tacklers.

**Results** High tackles had a 32.7 (95% CI=6.89 to 155.02) and 41.2 (95% CI=9.22 to 184.58) propensity ratio to cause ball carrier HAEs>30 g compared with medium tackles for men and women, respectively. Low tackles had a 2.6 (95% CI=1.91 to 3.42) and 5.3 (95% CI=3.28 to 8.53) propensity ratio to cause tackler HAEs>30 g compared with medium tackles for men and women, respectively. In men, multiple tacklers had a higher propensity ratio (6.1; 95% CI=3.71 to 9.93) than singular tacklers to cause ball carrier HAEs>30 g but a lower propensity ratio (0.4; 95% CI=0.29 to 0.56) to cause tackler HAEs>30 g. No significant differences were observed in female tacklers or carriers for singular or multiple tacklers.

**Conclusion** To limit HAE exposure, rule changes and coaching interventions that promote tacklers aiming for the torso (medium tackle) could be explored, along with changes to multiple tackler events in the male game.

### WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ At the elite (professional) level, the tackle has the highest injury rate of all contact events in rugby union, with most concussions occurring during this contact event.

⇒ There is a growing concern surrounding exposure to high-magnitude and repeated head acceleration events (HAEs).

⇒ Law trials and modifications can improve player safety by mitigating risk factors for head injuries and exposure to HAEs.

### WHAT THIS STUDY ADDS

⇒ An understanding of tackle characteristics, such as tackle height and the number of tacklers and how these factors influence HAE propensities in elite male and female rugby union players.

⇒ Tackle heights above the sternum of the ball-carrier had a greater propensity to result in HAEs>30 g for both male and female ball-carriers. Low tackle heights had a higher propensity to result in HAEs>30 g for male and female tacklers.

⇒ Tackles made by multiple players had a higher propensity to result in HAEs>30 g for male ball-carriers. Tackles involving a singular tackler had a lower propensity to result in HAEs>30 g for male tacklers. No significant differences were observed for tackle events that involved singular or multiple tacklers for female players.

### HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ These findings could contribute to developing improved coaching and officiating practice to help mitigate player exposure to HAEs.

⇒ To limit HAE exposure, rule changes and coaching interventions that promote tacklers aiming for the torso (medium tackle) could be explored, along with changes to multiple tackler events in the male game.

## INTRODUCTION

Rugby union is a contact sport that involves frequent high-intensity contact events (tackles, carries and rucks), resulting in a high injury risk.[1] There is growing concern around the relationship between head impacts and their potential short and long-term health risks.[2–4] A head acceleration event (HAE) is defined as 'an event/incident that gives rise to an acceleration response of the head caused by an external short-duration collision force applied directly to the head or indirectly via the body in sport, recreational, military, or other activities of interest'.[5]

Repetitive HAEs have identified as a potential contributor to concussive injury mechanisms and long-term brain health issues.[6–8] Current research has yet to identify a specific magnitude or threshold of HAEs that will result in immediate or delayed clinical presentation consistent with concussion. Still, it has been proposed that exposure to repetitive HAEs should be reduced as far as possible to improve player welfare.[9 10] Studies have used instrumented mouthguards (iMGs) to measure match HAE incidence and propensity in rugby players.[11–14] These studies highlighted tackle and carry as the match activities most likely to cause HAEs in male and female rugby players.[11 12 14 15] The tackle in rugby union has the highest reported risk for general injury.[1 16 17]

Analysing tackles resulting in a head injury has been common practice to identify law modifications and coaching interventions that may reduce their prevalence.[3 18–20] Such research has identified factors such as the height of tackles and upright body positions of players at the time of contact as risk factors for head injuries.[3 21 22] High tackles, where the tackler makes contact above the ball-carrier's sternum, often occur when the tackler is in an upright body position, resulting in a greater risk of head injury.[3 22] These findings led to trials of law modifications to reduce the legal tackle height at the community level by World Rugby[23–26] and their subsequent integration into community-level rugby in England by the Rugby Football Union.[27] Given the role of HAEs as a concussive injury mechanism, it is important to consider how law changes and trials may play a role in HAE exposure mitigation.[6–8] Other research has identified an increased injury risk when multiple tacklers are involved in the tackle.[17 28 29] Governing bodies such as the French Federation of Rugby (FFR) have trialled laws to reduce the number of tackers involved in a tackle, in combination with a reduced legal tackle height, resulting in decreases in head-to-head contact.[27] However, little is known about how these law modifications can impact on HAEs experienced by male or female players.

It is important to consider law modifications and other interventions that may reduce exposure to the frequency and magnitude of HAEs.[6] Identifying risk factors during the tackle, such as tackle height and a number of tacklers, presents an opportunity to gain insights into HAE aetiology. This study explored the propensity of HAEs sustained during the tackle event in elite male and female rugby matches by exploring tackle height and the number of tacklers involved in each tackle event.

## METHODS

### Study design and participants

A prospective observational cohort study was undertaken involving elite-level (professional) rugby union women (n=67) and men (n=72) players from European and international rugby competitions, including the Allianz Premier-15s (n=11), Gallagher Premiership (n=21), Top 14 (n=6) and United Rugby Championship (n=45), as well as Women's Autumn International Series in 2021 (n=13) and the Women's Rugby World Cup in 2022 (n=43). Video footage was obtained through Stats Perform (Chicago, Illinois, USA) and World Rugby.

All participants were equipped with custom-fit Prevent Biometrics (Prevent Biometrics, Minneapolis, Minnesota, USA) iMGs, following three-dimensional dental scans with a qualified dentist. These iMGs are equipped with triaxial gyroscopes and accelerometers, sampling at 3200 Hz with a measurement range of ±35 rad/s and ±200 g, respectively. Linear head kinematics collected at the iMG sensor location were transformed to the head centre of gravity.[11] Previous studies have validated the Prevent Biometrics iMGs, both in field and laboratory settings.[15 30–32] HAE were identified when the linear acceleration exceeded an 8 g trigger threshold on a single axis of the iMG accelerometer.[12] Time series data for HAEs were captured 10 ms before and 40 ms after the trigger event, with a recording threshold of 5 g at the head centre of gravity. The level of noise/artefact in each kinematic signal was classified by an in-house Prevent Biometrics algorithm as minimal (class 0), moderate (class 1) or severe (class 2). A 4-pole (2×2), zero-phase, low-pass Butterworth filter was applied to each kinematic signal. A 200 Hz, 100 Hz and 50 Hz cut-off frequency (−6 dB) were applied to class 0, class 1 and class 2 signals, respectively.[11] Each iMG device was manually synchronised to video footage for each match to ensure to-the-frame synchronisation for analysis.

Tackles and carries were analysed from 304 player matches (161 men, 143 women) across 28 matches. Proximity sensor readings were used to verify that the iMG was worn during each contact event. Video analysis identified 2266 tackles, defined as tackler involvements and 1426 carries with associated HAEs. Tackle involvements and carries were then analysed in accordance with Tooby *et al*[12] and Woodward *et al*,[11] categorising the contact event and its HAE stage (initial collision, secondary contact, ground impact or breakdown) for each tackler in the tackle event.

### Video analysis

All contact events in which the proximity sensors indicated the iMG was being worn were video verified and analysed via NacSport Scout Plus (V.7.0.0) by an experienced coder (3 years of rugby video analysis experience). The video had a minimum frame rate of 25 frames per second and 1080 p resolution. All contact events were coded using an adapted framework from existing analysis frameworks by Tucker *et al*,[20] Davidow *et al*[33] and Hendricks *et al*,[34] see table 1. The analysis framework was also adapted from law trial definitions by the FFR and World Rugby.[27] Intrarater reliability was conducted and Cohen's kappa calculated, see table 1, on a randomly selected match, 1-month post-initial analysis in line with previous research, where a value of 0.8 or above indicates near-perfect agreement.[35–37] All coded events were stored in an encrypted Microsoft Excel database and analysed using MATLAB (MATLAB_R2024a).

**Table 1** Analysis framework variables and descriptors for tackle and carry head acceleration event and non-instrumented mouthguards triggered events, with intrarater reliability scores

| Variable | Descriptor |
|---|---|
| Tackle height<br>Intrarater reliability: 0.91 | High – contact from the tackler is <u>above</u> the sternum, head/neck and shoulder/chest of the ball-carrier.<br>Medium – contact is <u>below</u> the sternum and <u>above</u> the waistband of the ball-carrier's shorts (torso).<br>Low – contact is <u>below</u> the waistband of the shorts (hip, upper leg and lower leg). |
| Number of tacklers<br>Intrarater reliability: 0.95 | Single – single tackler.<br>Multiple (2+) – two or more tacklers. |

## Statistical analysis

Given that multiple HAEs may occur during each contact event, the HAEs used in the calculations in this study were the maximum from the initial collision HAE stage.[11–13] Propensity was calculated across a range of peak linear acceleration (PLA) and peak angular acceleration (PAA) thresholds by dividing the number of tackle involvements that resulted in an HAE by the total number of tackle involvements that the individual was involved in while wearing the iMG, confirmed using the iMG infrared proximity sensor.[12] The total number of tackle involvements included the number of events resulting in an HAE, as well as the events that did not result in an HAE. Mean values across players and 95% CIs were calculated using a bootstrapping procedure, similar to Tooby *et al*.[12] HAEs were classified into lower (PLA<10 g and PAA<1.0 krad/s$^2$), medium (PLA>10 g and <30 g and PAA>1.0 krad/s$^2$ and <2.0 krad/s$^2$) and higher magnitude (PLA≥30 g and PAA≥2.0 krad/s$^2$) groups, to calculate a propensity ratio for tackle heights and number of tacklers for tackler and ball-carrier HAEs with statistical significance set at $p<0.05$ and non-overlapping 95% CIs.[12 14]

## RESULTS

### Tackle height

Figure 1 shows the propensity of high, medium and low tackle heights to result in an HAE exceeding a given range of magnitude thresholds for male and female ball-carriers and tacklers. In males, high tackles had a propensity of 4.1% and 8.7%, resulting in an HAE>30 g for the tackler and ball-carrier, respectively. In HAEs>30 g, medium tackles had a propensity of 4.0% for the tackler and 0.3% for the ball-carrier, while low tackles had a propensity of 10.1% for the tackler and 1.1% for the

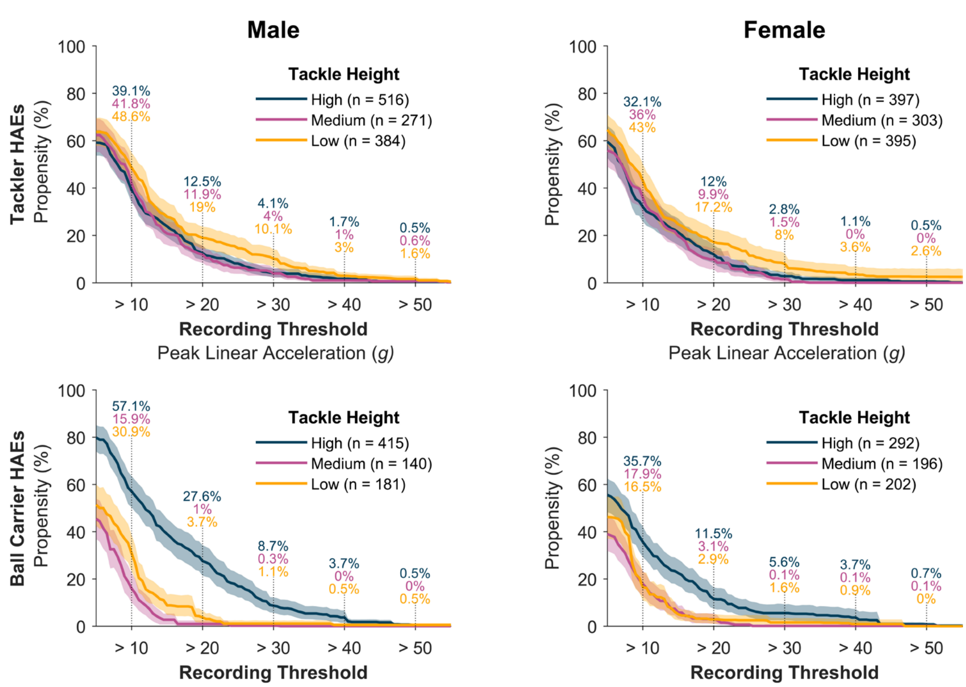


**Figure 1** The propensity of tackles at different tackle heights (high, medium or low) to result in an HAE across peak linear acceleration thresholds for male and female tacklers and carriers. Shaded regions indicate the 95% CI. The number of tackles at each tackle height is shown as n. Online supplemental figure 1 presents the results with a peak angular acceleration recording threshold. HAE, head acceleration event.

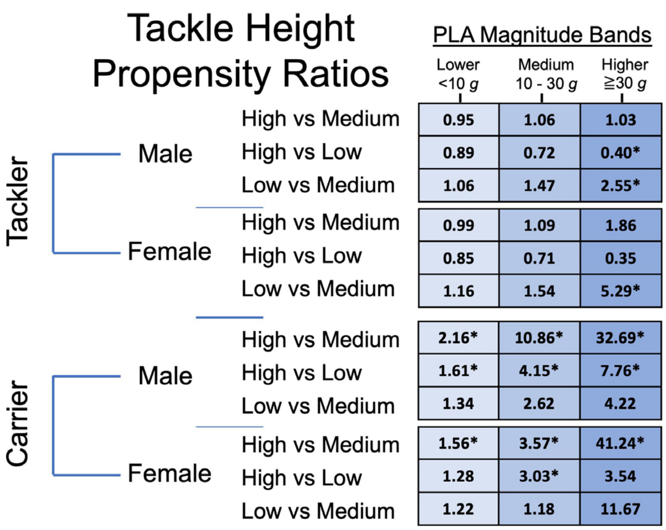


**Figure 2** Propensity ratios of male and female tackler and carrier HAEs caused by tackle heights within lower, medium and higher HAE magnitude bands. Comparisons between tackle heights are included, where *denotes statistical significance. Online supplemental figure 2 presents the results with peak angular acceleration magnitude bands. HAE, head acceleration event.

ball-carrier. In females, the propensity of high tackles to result in an HAE>30 g was 2.8% for tacklers and 5.6% for ball-carriers, while medium tackles had a propensity of 1.5% and 0.1% and low tackles had a propensity of 8.0% and 1.6%, respectively.

High tackles had a 32.7 (95% CI=6.89 to 155.02) propensity ratio to cause male ball carrier HAEs>30 g compared with medium tackles (figure 2). Similarly, female ball-carriers had a 41.2 (95% CI=9.22 to 184.58) propensity ratio to experience an HAE>30 g from a high tackle compared with a medium tackle. High tackles had a 0.4 (95% CI=0.30 to 0.54) propensity ratio to cause male tackler HAEs>30 g compared with low tackles. Low tackles had a 2.6 (95% CI=1.91 to 3.42) propensity ratio to cause male tackler HAEs>30 g compared with medium tackles. In female tacklers, low tackles had a 5.3 (95% CI=3.28 to 8.53) propensity ratio to result in HAEs>30 g compared with medium tackles.

### Number of tacklers in a tackle event

Figure 3 shows the propensity of singular and multiple tacklers involved in a tackle event to produce an HAE exceeding a given range of magnitude thresholds in male and female ball-carriers and tacklers. In males, 3.5% and 7.2% of tackles involving multiple tacklers caused HAEs above 30 g in tacklers and ball-carriers, respectively. Singular tacklers had an HAE>30 g propensity of 8.7% for the tackler and 1.2% for the ball-carrier.

In males, multiple tacklers had a significantly higher propensity ratio (6.1; 95% CI=3.71 to 9.93) (figure 4) to cause ball carrier HAEs>30 g than singular tacklers. Conversely, multiple tacklers had a significantly lower propensity ratio (0.4; 95% CI=0.29 to 0.56) to produce HAEs>30 g compared with singular tacklers for male tacklers. In female players, there were no significant differences between single tackler events and multiple tackler events for either the ball-carrier or tackler.

## DISCUSSION

This study is the first to explore how tackle height, and the number of tacklers influence the propensity of HAEs in the tackler and ball-carrier. Given the emphasis on HAE exposure reduction, it is important to explore these factors so that strategies can be targeted to reduce the incidence and magnitude of HAEs resulting from tackles in the sport.

### Tackle height

Our first important finding is that tackle height significantly affects HAE propensity and does so differently in the ball-carrier and the tackler. For ball-carriers, tackles above the sternum (high) had a greater propensity to result in HAEs>30 g compared with tackles at the torso (medium tackle) in male and female carriers, respectively. These findings align with previous head injury assessment (HIA) and concussion research, where tackles above the sternum of the ball-carrier have shown an increased risk of HIA removal and concussion. However, this was true for both ball carriers and tacklers.[3 20 28] This reinforces the potentially important role of tackle height laws in minimising the frequency of tackles above the sternum to mitigate ball carrier HAEs and head injuries to both players.

It is important to consider our finding that tacklers have a greater HAE propensity when tackling low compared with medium and high.[12] This contrasts with previous literature on HIA and concussion risk, which showed increased tackler injury risk when high tackles were made.[3 20 28] While not as pronounced as the differences found for the ball-carrier, the greater propensity for >30 g HAEs when making low compared with medium tackles are of interest because they suggest a difference in HAE versus HIA removal risk characteristics. The mechanism for this difference is unclear, but further exploration is required since interventions to reduce HIA and concussion incidence may not successfully reduce HAE incidence, and vice versa, particularly if the shift to reduce tackle height results in an increased frequency of low tackles.

The trade-off between these two risk factors, where high and low tackles affect ball carrier and tackler HAE risk differently, is important for the sport since the objective is the protection of both players. When considering HAE risk to either player, the lowest risk would be achieved from medium (torso) tackles, which were least likely to cause HAEs exceeding 30 g in both male and female tacklers and ball carriers. The greatest overall propensity was found from high tackles by virtue of the very large increase in ball-carriers HAE propensity, despite the relatively lower but increased propensity for tackler HAEs from low tackles.

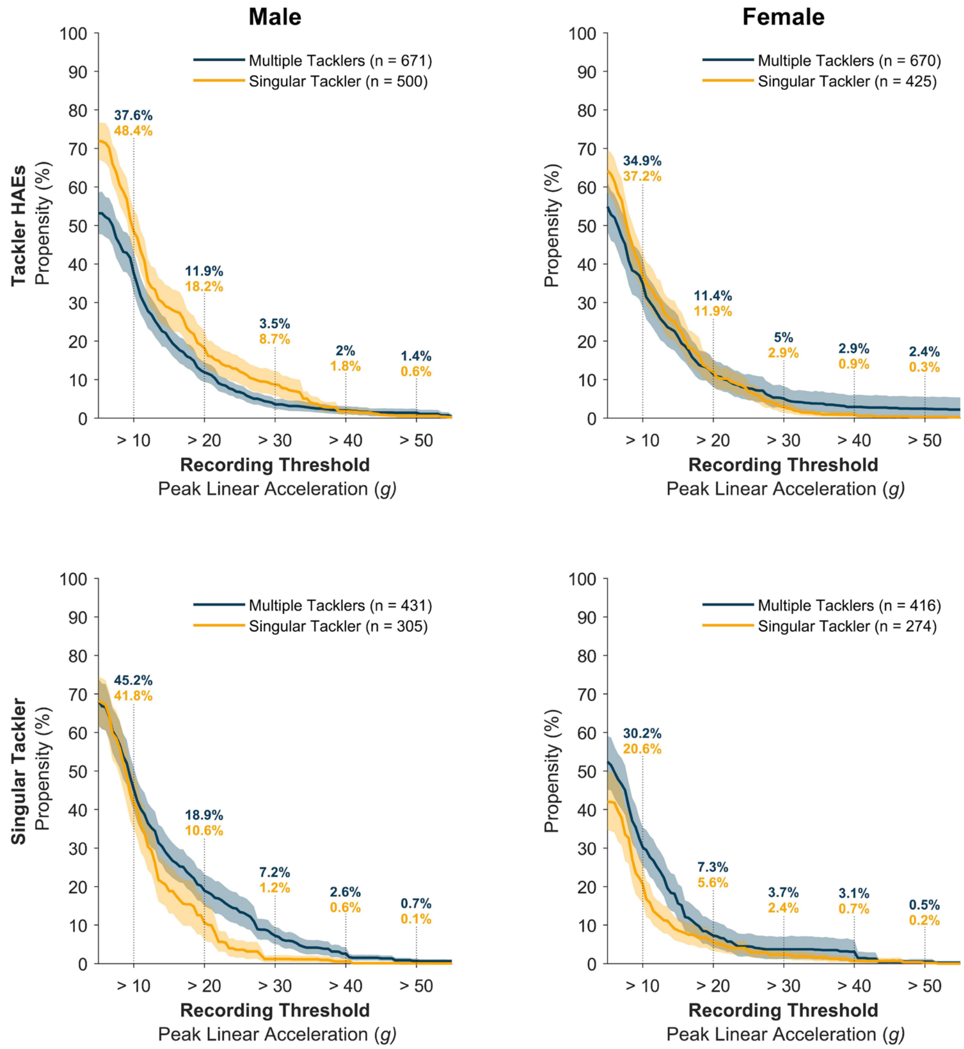


**Figure 3** The propensity of tackles to result in an HAE across peak linear acceleration thresholds for male and female tacklers and carriers where there were multiple (2+) tacklers or a single tackler. Shaded regions indicate the 95% CI. The number of multiple (2+) or singular tackler tackles is shown as n. Online supplemental figure 3 presents the results with a peak angular acceleration recording threshold. HAE, head acceleration event.

The findings strongly suggest that the target of law interventions or coaching education should focus on medium tackles, which would most effectively reduce HAE prevalence in both male and female tacklers and ball-carriers. This would also align with the reduced clinical outcome risk highlighted in previous concussion risk factor literature.[3 20]

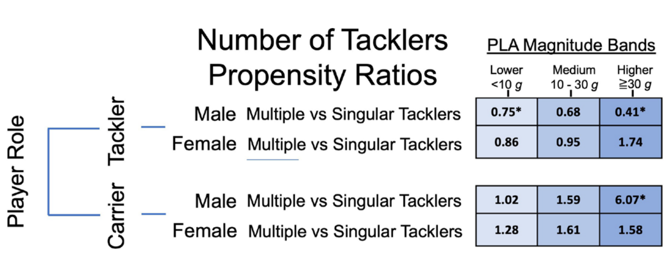


**Figure 4** Propensity ratios of male and female tackler and carrier HAEs caused by tackler numbers within lower, medium and higher HAE magnitude bands. Comparisons between tackler numbers are included, where *denotes statistical significance. Online supplemental figure 4 presents the results with peak linear acceleration magnitude bands. HAE, head acceleration event; PLA, peak linear acceleration.

## Number of tacklers

In a recent law trial, the FFR trialled a combination of lowering the legal tackle height and reducing the number of tacklers involved in the tackle event.[27] This trial focused on reducing the incidence of head-to-head contact between players while maintaining or improving enjoyment and participation. Previous literature has investigated the role of the number of tacklers in injurious events, finding that tackles involving multiple tacklers had a higher concussive injury risk than single-tackler events.[28 29] This is, in part, logically explained by an increase in the number of physical heads involved during each tackle. Our findings support these previous results, with multiple tacklers having a greater propensity to produce an HAE>30 g in male ball-carriers. In contrast, male tacklers had a lower propensity to experience HAEs when involved in tackles with multiple tacklers. This may be due to the differing dynamics of multiple tackler events. This was not explored in the current study; however, future research should investigate the interaction between other technical elements of multiple versus singular tackler events and HAE propensity. Overall, the results suggest that limiting the number of tacklers may benefit male ball carriers.

No significant differences were observed between multiple or singular tackler events in the female cohort. These sex differences, which require further exploration, may result from technical elements in the tackle that differ between male and female rugby players.

## Limitations

The data in this study was obtained from elite-level male and female rugby players and may not reflect the diversity in quality, quantity and level of rugby internationally, with all these factors potentially affecting HAE risk. Future research may investigate similar tackle characteristics and their propensities to result in HAEs at the community and age grade level of rugby. This study did not explore sociological or gendered factors affecting tackle technique and characteristics. Future research should explore tackle technique and factors that may modify tackle characteristics, including playing age and level, training history and conditioning.[38]

The filtering of head kinematics was conducted through in-house Prevent Biometrics algorithms.[12] A common open-source signal processing approach would be beneficial for cross-study comparison.[39] This study also used an iMG trigger threshold of 8 g. A prior simulation study suggested that false negatives may be influenced by a bias introduced through linear acceleration trigger mechanisms.[12 40] Furthermore, while this study investigated peak resultant head kinematics (PLA, PAA), these do not consider directionality and temporal data, which may play a critical role in injury risk and mechanism.[12 41] This study included data from a subset of matches in a playing season. Future research should consider HAEs throughout an entire playing season, including in a training environment, to account for potential variance and overall HAE exposure.

## CONCLUSION

This study is the first to explore how tackle height, and the number of tacklers influence the propensity of HAEs in the tackler and ball-carrier. Tackle height affects HAE propensity and does so differently in the ball-carrier and the tackler. For ball-carriers, tackles above the sternum (high) had a significantly greater propensity ratio to result in HAEs>30 g compared with tackles at the torso (medium tackle) in male and female carriers, respectively. Low tackles had a significantly greater propensity ratio to cause male and female tackler HAEs>30 g compared with medium tackles. The current study also identified that tackles involving multiple tacklers had a greater propensity to result in HAEs>30 g for male carriers. Conversely, for male tacklers, tackles involving a singular tackler had a greater propensity to result in HAEs>30 g. There were no significant differences in the number of tacklers and HAE exposure for female players. To limit HAE exposure, rule changes and coaching interventions that promote tacklers aiming for the torso (medium tackle) could be explored, along with changes to multiple tackler events in the male game.

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**Contributors** All authors conceptualised the research project. GT and JW designed the study. JW, GT, DMS and JT collected data for the study. JW, GT and JT were responsible for the analysis and interpretation of the results. JW drafted the manuscript and is the guarantor. All authors critically reviewed and edited the manuscript prior to submission.

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**Patient and public involvement** Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

**Patient consent for publication** Not applicable.

**Ethics approval** This study involves human participants and was approved by Ulster University's Research and Ethics Committee (UREC), University of Ulster (#REC-21-0061). Participants gave informed consent to participate in the study before taking part.

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**Data availability statement** Data are available upon reasonable request. Anonymous data are available at a reasonable request to the corresponding author.



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