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Original research

The association between tackle technique and head acceleration events in a cross-section of adolescent female rugby players☆,☆☆

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ABSTRACT

Objectives: Tackle technique is well researched in male rugby players, but not in female players. This study investigated the relationship between different tackle characteristics for the tackler and ball carrier and head acceleration event magnitude in adolescent female rugby players.
Design: A prospective cohort study that followed forty-one, 12–17-year-old female rugby players over 2 seasons.
Methods: Instrumented mouthguards and video analysis were used to quantify head acceleration events, by recording the peak linear and peak rotational acceleration that were associated with tackle events in both games and trainings.
Results: We found twice as many head acceleration events ≥8 g for the tackler (n = 1233) than the ball carrier (n = 694). Tackling the ball carrier at the shoulder/chest resulted in the highest peak rotational acceleration (1973.6 ± 85.6 rads rad/s2, mean ± SE) for the tackler, which was higher than tackling the ball carrier at the torso/hip (1609.7 ± 69.8, p = 0.0002). A face up tackle recorded a higher peak rotational acceleration for the tackler than a face down tackle (1958.8 ± 83.3, 1601.6 ± 64.2 rads rad/s2, $p < 0.0002$, Cohen's $d = 0.24$). For both the ball carrier and the tackler, an uncontrolled fall resulted in higher peak linear acceleration compared to a controlled fall (3.8 ± 2.7 g, $p < 0.005$, $d = 0.29$ and 4.2 ± 3.0 g, $p < 0.006$, $d = 0.30$ respectively).
Conclusions: Modifying tackle behaviours in female rugby may reduce head acceleration event magnitude associated with tackles and improve player safety.

Practical implications

- Instrumented mouthguards can provide an insight into the potential stress and strain the brain is exposed to during a rugby tackle and if we can reduce the head acceleration magnitude experienced by players, we can potentially reduce head injury risk associated with the rugby tackle.
- Changing tackle behaviours around face position (face up at pre-contact to face down at contact), and tackle height (torso and hip height rather than shoulder chest height) should help to reduce HAE magnitude for the tackler.

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- Coaching young female rugby players should incorporate best-practice falling techniques to reduce head acceleration forces during uncontrolled falls.

1. Introduction

Rugby players are exposed to a high number of collisions, placing them at a high injury risk.[1] The most common contact event in rugby is the tackle, which is the match event with the highest overall injury and concussion risk.[2–4] While a substantial body of literature explores tackle technique in male rugby players,[5–7] limited research exists on tackle technique in female players.[8,9,11]

In 2001, New Zealand Rugby introduced 'RugbySmart', a mandatory annual injury prevention course for all coaches which includes tackling recommendations. Since the programme began, injury rates in New Zealand have declined and player on-field tackle behaviours have improved.[12–14] However, most of this data was gathered on male rugby players[14] with the same information on female players lacking. Female rugby players have considerably different anatomy, body morphology, power development, neck control and rugby technical skill[15–17] compared to male players, which may affect tackle behaviours and subsequent injury prevalence. Females tend to join rugby union at a later age with less game knowledge and experience, therefore, learning the fundamentals of rugby union later than males.[8] Consequently, current tackling guidelines may not be suitable for female players.

Recent research on elite female rugby players has identified several tackle characteristics that result in more effective tackles such as tackler balance prior to contact, tackling the ball carrier at the torso, maintaining head contact with ball carriers' body, wrap and clamp of arms in tackle, active shoulder use and positive leg drive.[10] While these tackle behaviours are important for tackle success little is known about the safety of such characteristics. In particular, associations between tackle characteristics and head kinematics for the tackler and the ball carrier are currently unknown.

Collision events such as tackles can be measured using instrumented mouthguards (iMGs), which quantify head acceleration events (HAEs) by recording peak linear acceleration (PLA) and peak rotational acceleration (PRA). High-magnitude HAEs increase concussion risk due to stress and strain placed on the brain.[19,20] Previous research has found that young female rugby players are typically exposed to between 5 and 15 HAEs above a PLA of 10 g per player hour, compared to between 3 and 17 HAEs above 10 g for premier female players (adults playing in the top community-level competition).[21] In elite women's rugby the incident rate of an HAE above 10 g is approximately 6–16 events per player hour.[22] However, it is important to note that there is currently no established HAE threshold for concussion, and previous research has reported concussions occurring at low (30 g) and high (157 g) PLA magnitudes.[23,24] Furthermore, existing biomechanical injury threshold models are based on male populations and therefore may not directly translate to female athletes due to all the known and unknown differences between male and female athletes including differences in head centre of gravity. Optimal tackle technique may help reduce head acceleration forces for both the tackler and the ball carrier, lowering head injury risk. Therefore, the aim of this study was to investigate the relationship between different tackle characteristics (including initial point of contact, tackle approach and head position) for the tackler and ball carrier and HAE magnitude in adolescent female rugby players.

2. Methods

2.1. Participants

This prospective cohort study, which followed Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines, followed forty-one adolescent (12–17-year-old) female rugby players over 1283 h of trainings (22 ± 9 trainings per player per season) and 696 h of games (19 ± 8 games per player per season). Participants were recruited from two under-18 rugby teams in the Canterbury area of New Zealand during the 2022 and 2023 rugby seasons. Written informed consent and assent were obtained for all players. A detailed demographic breakdown is provided in Table 1. Ethical approval for all procedures and experimental design was obtained in full, from the University Ethics Committee (Ref: HEC2022-05).

On average, games were played 15-aside and for 70 min with 16 shorted tournament games between the two seasons; however, individual playing time varied greatly. Game exposure time was calculated as the time an individual player spent on field during a game. Training time was estimated from the standardised training session length of 90 min or 60 min.

2.2. Equipment

All players received a custom-fit HitIQ Nexus A9 iMG (HitIQ, Melbourne, Australia). The validity of the HitIQ Nexus A9 iMG has been demonstrated in previous studies both on-field[25] and within a laboratory setting.[26] A TRIOS 3 intraoral scanner (3Shape, Copenhagen Denmark) with CAD/CAM software was used to create a 3D scan of players' teeth, which was sent to HitIQ to produce the custom-fit iMG device. The HitIQ Nexus A9 iMG device contained three triaxial accelerometers (Analog Devices, USA, ADXL372) and a gyroscope (Bosch, Germany, BMG250). The iMG was set to trigger when an HAE exceeded ≥8 g threshold along any single axis (x, y, z).[27] The iMG recorded 20 ms before and 80 ms after the ≥8 g triggering event.

All game and training sessions were video recorded in high definition for the entirety of the session, using a primary side-on and secondary end-on mounted camera (Canon HFG50, Canon Inc., Japan), and a referee-mounted head camera (GoPro Hero, GoPro Inc., USA) in games if available. Footage was imported into Catapult Focus video analysis software (Catapult Sports, Melbourne, Australia) and synchronised with the iMG data using a clock flash captured in the video.[28] iMG events from all games and training sessions, for their entirety (including contact and non-contact training), were qualitatively analysed to identify key tackle components. The coding template for video verification and analysis was created with reference to World Rugby Laws, RugbySmart, previous research and consultation with experts in the sport science field.[29–31] Given that the present study is focused on improving tackle technique in community-level rugby players, the decision was made to align the analysis with the coaching resources that are most commonly available to, and promoted for use by, community-level players and coaches.

A tackle was defined as 'the ball carrier was held by one or more opponents and brought to the ground', constituting a successful tackle.[32] All iMG events ≥8 g were video-verified to determine true HAEs associated with a tackle event. Confirmed tackle-related HAEs were analysed to identify key tackle characteristics (initial point of contact, tackle approach, face position, head position and fall), HAE mechanism (direct contact to the player's head, indirect HAE without

Table 1
Participant characteristics for the 2022 and 2023 rugby seasons.

	2022		2023	
	n	Mean ± SD	n	Mean ± SD
Age (years)	18	14.4 ± 1.3	23	14.8 ± 1.3
Height (cm)	15	163.9 ± 7.9	23	167.0 ± 6.8
Body mass (kg)	15	64.3 ± 12.4	23	74.1 ± 17.6
Rugby experience (years)	18	3.8 ± 2.6	23	4.8 ± 3.1
Rugby playing position				
Forward	7	39%	15	65%
Back	11	61%	8	35%

Data are count (n), mean and standard deviation (SD), or percentage for rugby playing position. One participant completed two seasons of data collection; they are considered a separate participant in each season.

direct head contact or unknown) and head location of direct head impacts (front, back, side, top, chin, multiple or unknown; Fig. 2). Direct head contact is defined by the direct location of head contact on the player wearing the iMG device (head and neck, upper extremities, torso and hip, lower extremities, environment and unknown). However, indirect classification is limited by the assumptions of the video analysis when determining the type of indirect head acceleration (stabilising, jarring, rotation or whiplash). Tackles involving one or multiple tacklers were included in the analysis. In instances involving multiple tacklers, tackle approach and initial point of contact were recorded as "multiple" to indicate that more than one approach and point of contact were observed during the tackle event.

Initial point of contact was defined as the location on the ball carrier's body where the first point of contact was made by the tackler (Fig. 3). Tackle approach was defined as the direction from which the tackler approached the ball carrier, categorised as front-on, side-on, behind, unknown, or multiple (with multiple defined as more than one tackler approaching simultaneously). Face position was defined as the orientation of the tackler's face during the contact phase of the tackle (face up, face down, or unknown). Head position was defined as the position of the tackler's head relative to the ball carrier at the moment of contact (behind, beside, in front, above, or unknown). A fall was defined as a descent to the ground resulting from a loss or lack of support or intention, categorised into controlled, uncontrolled or unknown based off the body posture of the ball carrier; however, this classification is limited by the assumptions of the video analysis when determining whether body posture was controlled.

Overall tackle technique reflects whether a tackle adheres to the New Zealand Rugby-recommended criteria: torso/hip contact, a behind or side on tackle approach, a face up face position, and head position behind or beside the ball carrier.[14,33] Tackles meeting all four criteria (torso/hip initial point of contact, side on or behind tackle approach, face up face position, and behind or beside head position; Recommended) are compared with those that do not (Other Tackle Techniques). Table 2 shows the coding used for the tackles made.

Table 3
Data used to establish reliability of video verification coding template.

Category	Variable
Verified	Yes
	No
Match action	Tackler
	Tackled
	Breakdown
	Other
Mechanism	Direct
	Indirect
	Unknown

Coding template was designed from the original video verification and analysis, and the simplified video verification and analysis templates.

2.3. Data processing

The iMG data was processed through HitIQ in-house systems. Time series data for each axis of the three linear accelerometer sensors were resampled to 3200 Hz. Gyroscope data was up-sampled from 800 Hz to 3200 Hz. The normalised signal from the linear accelerometer was low pass filtered at 300 Hz using a 4th order 300 Hz low-pass Butterworth filter and linearly transformed to the centre of gravity of the head based on the 50th percentile hybrid III headform.[26]

2.4. Statistical analysis

A priori power analysis indicated that a total sample size of 36–40 participants would be required to detect moderate effect sizes ($d = 0.5$) with 80% power at this alpha level, accounting for the repeated measures design and between-subject comparisons.[34] With forty-one participants, our study exceeded this minimum requirement.

Inter-rater and intra-rater reliability was assessed for the video verification methods using percentage agreement. For inter-rater reliability

Table 2
Video verification and analysis coding definitions.

Category	Code	Definition
Verified	Yes	HAE was recorded by the mouthguard and can be visualised
	No	HAE was recorded by the mouthguard but did not occur or cannot be determined
Direct HAE: the player wearing the iMG had an HAE as a result of direct contact with their head and another player's body part or the environment	Head and neck	Direct head contact with another player's head or neck
	Upper extremities	Direct head contact with another player's upper extremities, including shoulder, arm and hand
	Torso and hip	Direct head contact with another player's torso or hip
	Lower extremities	Direct head contact with another player's lower extremities, including upper leg, knee, lower leg and foot
	Environment	Direct head contact with the environment, including the ground, ball, posts and tackle pad
	Direct unknown	Confirmation that direct head contact occurred; however, it is unclear what body part or environment the contact was with
Indirect HAE: the player wearing the iMG had an HAE that did not contain direct contact to the head e.g. a tackle as the waist causing acceleration of the head	Stabilising	Player maintains control of their head position
	Jarring	Sudden displacement of the head in a single plane of motion
	Rotation (L/R)	The player's head rotates around the sagittal axis (coronal plane)
	Whiplash (F/B)	The player's head rotates around the transverse axis (sagittal plane)
Head location: If a direct HAE, the location on the head (of the player wearing the iMG device) where direct contact occurred (see Fig. 2)		
Initial point of contact: First point of contact of the tackler during a tackle event recording an HAE (see Fig. 3)	Arm	Tackler makes contact with ball-carrier's arm or hand
	Shoulder	Tackler makes contact with ball-carrier's shoulder
	Torso and hip	Tackler makes contact with ball-carrier's torso or hip
	Lower leg	Tackler makes contact with ball-carrier's lower leg
	Upper leg	Tackler makes contact with ball-carrier's upper leg
	Head and neck	Tackler makes contact with ball-carrier's neck or neck
Collision approach: Approach of the player initiating the collision during an event recording an HAE	Behind	Tackler makes contact with ball-carrier from behind
	In front	Tackler makes contact in front of ball-carrier
	Side on	Tackler makes contact with ball-carrier's side
Head position: Head position of the player wearing the iMG and if they are making a tackle	Above	Tackler's head is higher than ball-carrier's body during contact
	Behind	Tackler's head is at the back of ball-carrier's body during contact
	Beside	Tackler's head is next to ball-carrier's body during contact
	Front	Tackler's head is in front of ball-carrier's body during contact
Face position: Face position of the player wearing the iMG and if they are making a tackle	Face up	Tackler's face is up during contact
	Face down	Tackler's face is down during contact

Multiple codes could be selected if applicable. If participant wearing the iMG was attempting a tackle their tackle code was selected. If participant wearing iMG was the ball carrier then the tackle code of the opposition who was tackling them was selected.

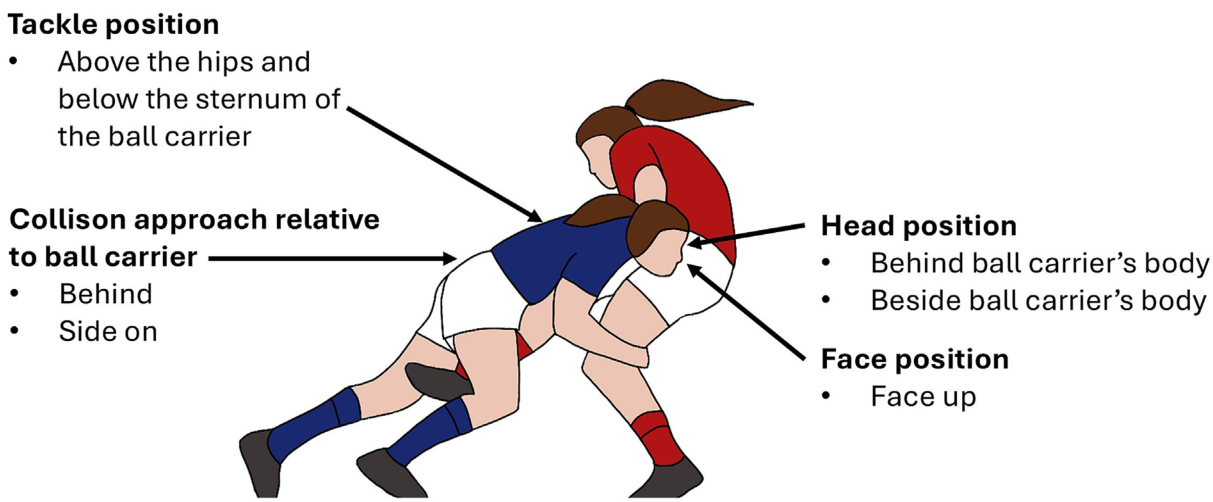

Fig. 1. Suggested tackle technique from New Zealand Rugby, RugbySmart Program and Rugby Toolbox resources.

two expert analysts coded the same four randomly selected rugby games separately, which were then compared, focusing on three categories, verified, match action and mechanism (Table 3). For intra-rater reliability, an expert analyst coded two rugby games twice, 6 months apart. Inter-rater and intra-rater reliability was assessed using percentage agreement.[35] We used positive predictive value (how well the device picks up true HAEs compared to false HAEs) and sensitivity (quantifies the amount of true HAEs the iMG device does not record) to measure the accuracy of our iMG recorded HAEs.[36–38] Across the 2022 and 2023 rugby seasons, there were 1927 recorded (1736 in games and 191 in trainings) HAE's ≥ 8 g during tackle events (1233 for the player making the tackle and 694 for ball carriers). Overall, intra-rater reliability was 94.4% and inter-rater reliability was 86.1%. Sensitivity and positive predictive value results were >90% and considered acceptable according to World Rugby recommendations.[39] Magnitude was recorded by the iMG device and reported as peak linear acceleration (PLA) and peak rotational acceleration (PRA).

Differences in the mean of the variables were estimated using a mixed modelling procedure (Proc Mixed) in the Statistical Analysis System (SAS, Version 9.4, SAS Institute, Cary North Carolina, USA). The

Table 4
The frequency and magnitude of head acceleration events for tacklers and ball carriers during the tackle event for different tackle characteristics in female adolescent rugby.

	Tackler			Ball carrier		
	Frequency (%)	PLA (g)	PRA (rad/s^2)	Frequency (%)	PLA (g)	PRA (rad/s^2)
Initial point of contact						
Head and neck	2 (0)	22.2 ± 9.1	1647.0 ± 1033.9	14 (2)	15.1 ± 3.5[a]	1274.7 ± 392.6[*]
Torso and hip[a]	630 (51)	18.4 ± 0.9	1609.7 ± 69.8	217 (31)	18.9 ± 1.1	1635.2 ± 105.6[*]
Shoulder	362 (29)	19.9 ± 1.0	1973.6 ± 85.6	307 (44)	20.2 ± 1.0	1912.9 ± 90.9[*]
Arm	0 (0)			3 (1)	38.9 ± 7.4	4548.8 ± 843.9
Upper leg	63 (5)	16.2 ± 1.7	1563.8 ± 189.9	21 (3)	21.8 ± 2.9	2078.8 ± 321.7[*]
Lower leg	61 (5)	19.3 ± 1.8	1924.5 ± 191.7	114 (16)	17.8 ± 1.4[a]	1696.4 ± 141.1[*]
Multiple	10 (1)	22.8 ± 4.1	1678.9 ± 463.1	18 (3)	19.3 ± 3.1	1630.9 ± 346.4[*]
Unknown	105 (9)	18.6 ± 1.4	1791.6 ± 147.3	0 (0)		
Tackle approach						
Front on	547 (44)	18.8 ± 0.7	1705.9 ± 78.7	252 (36)	20.2 ± 0.9	1833.9 ± 104.9
Side on[a]	154 (13)	16.9 ± 1.1	1665.3 ± 129.9	71 (10)	19.6 ± 1.6	1788.7 ± 184.6
Behind[a]	480 (39)	18.8 ± 0.7	1748.3 ± 81.6	329 (48)	18.8 ± 0.8	1788.7 ± 94.0
Multiple	5 (0)	24.6 ± 6.0	2472.7 ± 678.7	36 (5)	16.1 ± 2.3	1363.6 ± 256.1
Unknown	47 (4)	17.9 ± 1.9	1907.4 ± 225.4	6 (1)	15.6 ± 5.5	1317.3 ± 620.9
Face position						
Face up[a]	325 (25)	19.8 ± 0.8	1958.8 ± 88.3[^]			
Face down	821 (63)	17.9 ± 0.6	1601.6 ± 64.2			
Unknown	154 (12)	19.9 ± 1.0	1939.2 ± 115.9[^]			
Head position						
Above	63 (5)	18.1 ± 1.6	1892.1 ± 177.2			
Beside[a]	488 (40)	18.8 ± 0.7	1700.5 ± 73.6			
In front	95 (8)	20.7 ± 1.3	1799.4 ± 146.0			
Behind[a]	448 (36)	18.0 ± 0.7	1699.2 ± 75.7			
Unknown	139 (11)	19.1 ± 1.1	1878.3 ± 122.9			
Overall tackle technique						
Recommended	112 (9)	19.1 ± 1.3	1847.6 ± 150.8	7 (1)	15.3 ± 5.1	1508.3 ± 574.5
All other techniques	1121 (91)	18.5 ± 0.5	1716.5 ± 64.8	687 (99)	19.3 ± 0.6	1782.2 ± 73.4

Data are frequency (%) or least squares means ± SE. A tackle was defined as 'the ball carrier was held by one or more opponents and brought to the ground'.[32] Initial point of contact is defined as 'the first point of contact of the tackler on the ball carrier'. Data were collected in both game and training sessions. Multiple defines events where there was more than one characteristic associated with the event.

[a] New Zealand Rugby suggested tackle technique; Recommended overall tackle technique is when the tackle involved all recommended techniques for the tackle.

[*] Significantly different to arm initial point of contact within group ($p < 0.006$).

[^] Significantly different to face-down face position ($p < 0.01$).

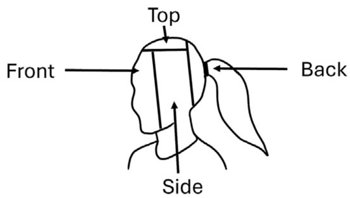

Fig. 2. Head locations of direct head impacts to the ball carrier, indicating location of front, back, side, top and chin.

fixed effects for the tackler and ball carrier were initial point of contact, tackle approach, face position, head position, mechanism and their interactions and the random effects were subject, team and residual variance. Data are presented as least square means and standard errors along with between group mean change and 95% confidence intervals. Cohen's effect size (d) was used to calculate practically meaningful differences between tackle characteristics and head acceleration values. Effect sizes of <0.19, 0.20–0.60, 0.61–1.20 and >1.20 were considered trivial, small, moderate and large, respectively.[40] Proc Freq in SAS was also used to calculate the frequencies of the various characteristics of the tackle event for the tackler and ball carrier. The p value for each statistic was calculated for the between group comparisons and we used an alpha level of $p < 0.05$ for significance in the study. Finally, Bonferroni corrections were applied where multiple comparisons were made.

3. Results

Of the HAEs recorded for players making a tackle, only 9% ($n = 112$) included all four recommended tackling characteristics (Fig. 1). We observed no significant change in the magnitude of HAEs when the tackler was using all four of the recommended tackle characteristics compared to using all other tackle techniques (0.6 ± 2.7 g, 131.1 ± 292.8 rad/s^2, mean ± 95% confidence interval, Table 4). The tackler most often tackled the ball carrier at the torso/hip, while the shoulder/chest area was the second most common initial point of contact and led to the highest PRA for the tackler (Table 4). Tacklers had a face-down position in 63% of tackles, which has lower PRA by 357.2 ± 187.8 rad/s^2 ($p = 0.0002$ Cohen's $d = 0.24$) compared to face-up position (Table 4). The tackle approach and tackler head position had no effect on the magnitude of tackler HAEs (Table 4).

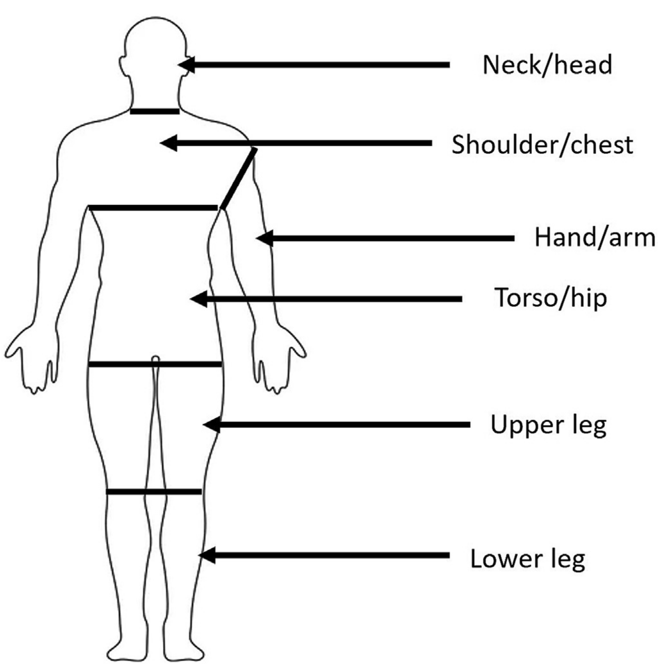

Fig. 3. Initial point of contact of the tackler with reference to the ball carrier's body, indicating location of tackles made to the neck/head, shoulder/chest, hand/arm, torso/hip, upper leg and lower leg.

When the ball carrier was tackled by the tackler at their arm area the ball carrier received the highest PLA and PRA which was significantly higher than most other tackle characteristics (Table 4). The tackle approach of the tackler had no effect on the magnitude of PLA and PRA for the ball carrier.

Compared to direct HAEs, indirect HAEs produced lower PLA for the ball carrier (Table 5). Direct head contact with the tackler's head and another player's head or neck resulted in the highest PLA for the tackler (26.0 ± 1.6 g), significantly higher than direct head contact with any other identified surface. Similarly direct head contact with the tackler's head and another player's head or neck resulted in the highest PRA for the tackler (2310.9 ± 184.9 rad/s^2) which was significantly higher than direct head contact with the torso or hip.

The ball carrier was exposed to higher PLA when their head made direct contact with another player's head or neck (25.3 ± 1.9 g), or the environment (e.g., ground; 22.3 ± 1.2 g, Table 5). Such impacts for the ball carrier resulted in significantly higher PLA than impacts with the torso or hip (14.6 ± 3.1 g, $p = 0.0001$, $d = 0.33$) or upper extremities (17.3 ± 1.4 g, $p = 0.0001$, $d = 0.13$).

The player making the tackle most often made direct contact with their own chin or the front of their head (Table 6). Tackles where the tackler experienced an HAE due to direct contact of their chin (19.9 ± 1.0 g) or multiple areas (more than one head location; 23.7 ± 2.4 g) resulted in the highest PRA which was significantly higher than contact with the front, back, left or right sides of their head. For the ball carrier, direct head contact with the back of their head resulted in the greatest PLA (23.9 ± 1.5 g) which was significantly higher than contact in the same area for the tackler (5.0 ± 3.7, $p = 0.008$, $d = 0.37$).

For both the ball carrier and the tackler, an uncontrolled fall resulted in significantly higher PLA compared to a controlled fall (3.8 ± 2.7 g, $p = 0.005$, $d = 0.29$ and 4.2 ± 3.0 g, $p = 0.006$, $d = 0.30$ for the ball carrier and tackler respectively, Table 7).

4. Discussion

To our knowledge, this is the first study to quantify the HAEs associated with different tackle characteristics in adolescent female rugby players. Tackle technique recommendations used in this study and others[10] were developed based on male rugby athletes with little consideration for how female anatomy and morphology may alter optimal tackle technique.[14,41] Indeed, we found no reduction in the magnitude of HAEs between young female tacklers who used all of the recommended tackle characteristics and tacklers who did not (Table 4), which may suggest some tackle characteristics may not lower HAE magnitude in this cohort. Further research is clearly needed to understand the relationship between tackle characteristics and head impact loading.

4.1. The effect of tackle characteristic on HAEs of the tackler

We found that the tackler utilised all four recommended tackle technique elements (Fig. 1) in only 9% of recorded HAEs. Many female rugby players begin participating in rugby at a later age compared to males; subsequently, they learn the fundamentals of tackling over a shorter period which may result in less tackling experience compared to males.[8] The lack of tackling experience may have contributed to the low percentage of tackle events that fully incorporated all elements of the recommended tackle technique, or the recommended tackle techniques may not be suitable for young female players. However, it is important to acknowledge that this study only reports tackle events with an HAE above 8 g and lower-magnitude events were not captured. These unreported tackles may have demonstrated all four

Table 5
The frequency, and magnitude of head acceleration events for the different mechanisms associated with tackle events in female adolescent rugby.

	Tackler			Ball carrier		
	Frequency (%)	PLA (g)	PRA (rad/s²)	Frequency (%)	PLA (g)	PRA (rad/s²)
Direct (i.e. HAE with direct head contact)	**926 (75)**	**18.8 ± 0.5**	**1725.7 ± 65.0**	**343 (50)**	**20.6 ± 0.7**	**1825.03 ± 91.2**
Environment	75 (6)	19.4 ± 1.5†	1735.5 ± 177.5	120 (17)	22.3 ± 1.2	1866.9 ± 142.3
Head and neck	69 (6)	26.0 ± 1.6	2310.9 ± 184.9	50 (7)	25.3 ± 1.9	2353.6 ± 216.4
Upper extremities	277 (22)	18.7 ± 0.9†	1868.4 ± 99.1§	83 (12)	17.3 ± 1.4^,†	1706.8 ± 169.5
Torso and hip	388 (32)	17.2 ± 0.8†	1478.5 ± 86.7†	18 (3)	14.6 ± 3.1†	1067.4 ± 356.4†
Lower extremities	104 (8)	18.5 ± 1.3†	1800.5 ± 153.0	67 (10)	19.7 ± 1.6	1764.2 ± 187.5
Direct unknown	13 (1)	21.3 ± 3.6	1966.2 ± 418.4	5 (1)	17.4 ± 5.9	1058.4 ± 673.5
Indirect (i.e. HAE with no direct head contact)	**153 (12)**	**17.0 ± 1.1**	**1743.4 ± 129.2**	**287 (41)**	**17.7 ± 0.8***	**1735.1 ± 98.3**
Stabilising	24 (2)	15.1 ± 2.7†	1654.4 ± 309.2	31 (4)	13.2 ± 2.4^,†	1550.3 ± 272.9
Jarring	83 (7)	17.0 ± 1.4†	1720.3 ± 169.7	146 (21)	18.4 ± 1.1†	1731.7 ± 130.1
Rotation (L/R)	27 (2)	18.6 ± 2.6	1930.4 ± 292.3	54 (8)	17.7 ± 1.8†	1743.5 ± 208.2
Whiplash (F/B)	19 (1)	16.8 ± 3.0†	1671.6 ± 347.5	56 (8)	18.3 ± 1.8†	1839.7 ± 204.6
Unknown	**154 (13)**	**18.9 ± 1.1**	**1742.4 ± 128.8**	**64 (9)**	**18.6 ± 1.7**	**1754.3 ± 193.5**

Data are frequency (%) or least squares means ± SE. Direct HAEs are when the player wearing the iMG device experiences a head acceleration event (HAE) due to direct contact to their head. Indirect HAEs are when the player wearing the iMG device experiences a head acceleration event (HAE) but there is no direct contact with their head e.g. they are tackled at waist height resulting in a "whiplash" motion of the head resulting in a HAE. Data were collected in both game and training sessions.
* Significantly different to direct head contact ($p < 0.01$).
^ Significantly different to environment within group ($p < 0.008$).
† Significantly different to head and neck within group ($p < 0.008$).
§ Significantly different to torso and hip within group ($p < 0.008$).

recommended technique elements and may therefore reflect safer tackles; however, further research is required to elucidate this point.

World Rugby and New Zealand Rugby tackle guidelines recommend that the tackler maintains a "head up, eyes forward" (face up) position while entering a tackle, followed by an ear-to-body[42] or cheek-to-cheek position[43] after initial contact with the ball carrier, while keeping the "eyes up".[44] Research on elite female rugby players has shown an ear-to-body tackle position is effective; however, less than half the tackles observed in the study adopted this technique.[10] World Rugby[39] suggests that the tackler uses a face-up position during the pre-contact phase as it allows the tackler to maintain eye contact with the ball carrier and position their head correctly at the time of contact, whereas an ear-to-body position following the initial contact is thought to reduce the likelihood of the tackler's head being left in a loose and vulnerable position.[42]

Although New Zealand Rugby and World Rugby both emphasise the tight coupling of the tackler's head to the ball carrier's body to reduce head injury risk, the recommendation to maintain an "eyes up"[44] position may inadvertently increase head rotational acceleration risk, as this posture is often associated with a face-up position, especially in younger populations with less training experience. In the current study we found 64% of tacklers used a "face-down" position. It is important to acknowledge we only report tackle events with an HAE above 8 g; therefore, lower magnitude events may have used a different face position. Our results showed a face-up position during the initial point of contact resulted in significantly higher PRA compared to the face-down position (Table 4). A face-down position creates a rigid structure from the head, down the neck and into the spine, allowing for increased control and stability of the cervical spine and head,[45] which may reduce head acceleration. Based off these findings we recommend teaching players to adopt a face-up position during the pre-contact phase, then transition to a face-down position at the point of contact. Tackle recommendations by World Rugby and New Zealand Rugby should emphasise the importance of not only head-to-body contact with the ball carrier but a face-down position during the tackle contact phase to ensure a stable cervical spine and reduce HAE risk.

We found high tackles (i.e. contact with another player's head and neck region) resulted in the highest individual PLA magnitude for the tackler (22.0 ± 9.1 g). However, only two high tackle events were observed in this study, limiting the ability to draw definitive conclusions. Further research is required to confirm the relationship between tackle height and PLA magnitude. Notably, high tackles have also been shown to be less effective of tackle success[10] and support proposals to lower the tackle height in grassroots rugby.[46]

Our results suggest that the majority of HAEs (75%) experienced by the tackler are due to direct contact to their head (Table 5). Of these direct head impacts, the most frequently impacted head region was the chin (27%), resulting in high magnitude PRA (Table 6). During the video analysis process, it was observed that a significant proportion of direct chin impacts were associated with a whiplash motion of the head. The resultant fast and strong rotation of the head contributes to an increased concussion risk, as the rotation of the cerebrum around

Table 6
The frequency, peak linear acceleration (PLA) and peak rotational acceleration (PRA) of mechanisms associated with direct head acceleration events in female adolescent rugby.

	Tackler			Ball carrier		
	Frequency (%)	PLA (g)	PRA (rad/s²)	Frequency (%)	PLA (g)	PRA (rad/s²)
Top	11 (1)	23.4 ± 4.0	1827.0 ± 433.4	12 (3)	18.3 ± 3.8	1378.7 ± 415.2
Front	225 (24)	19.1 ± 1.0	1618.1 ± 101.2†	79 (23)	21.9 ± 1.6	1907.9 ± 164.4
Chin	251 (27)	19.9 ± 1.0	2067.2 ± 96.2	84 (25)	19.2 ± 1.6	2081.3 ± 159.1
Back	101 (11)	18.9 ± 1.4	1570.2 ± 146.2†	89 (26)	23.9 ± 1.5*	1886.4 ± 154.1
Left	96 (10)	15.9 ± 1.5^	1356.7 ± 151.8^,†	23 (7)	20.1 ± 2.8	1727.7 ± 300.1
Right	163 (18)	17.4 ± 1.2	1513.3 ± 117.4†	33 (10)	17.9 ± 2.3	1626.8 ± 251.2
Multiple	33 (4)	23.7 ± 2.4	2235.7 ± 250.9	5 (1)	17.8 ± 5.9	975.7 ± 641.2
Unknown	46 (5)	19.2 ± 2.0	1876.8 ± 213.9	18 (5)	15.5 ± 3.1	1083.3 ± 338.9*

Data are frequency (%) or least squares means ± SE. Multiple is defined as a direct head acceleration event to more than one head location. Data was collected in both game and training sessions.
* Significantly different between tackler and ball carrier ($p < 0.05$).
^ Significantly different to multiple within group ($p < 0.006$).
† Significantly different to chin within group ($p < 0.006$).

Table 7
The frequency and magnitude (PLA and PRA) of controlled or uncontrolled falls associated with head acceleration events in the tackle event for the ball carrier and tackler in female adolescent rugby.

	Tackler			Ball carrier		
	Frequency (%)	PLA (g)	PRA (rad/s^2)	Frequency (%)	PLA (g)	PRA (rad/s^2)
No fall	726 (59)	18.5 ± 0.6	1744.0 ± 70.7	207 (30)	19.2 ± 0.9	1884.8 ± 113.4
Uncontrolled fall	103 (8)	21.7 ± 1.3*	1987.3 ± 155.4	270 (39)	20.6 ± 0.9*	1873.1 ± 101.2
Controlled fall	329 (27)	17.5 ± 0.8	1619.8 ± 94.4	150 (21)	16.7 ± 1.1	1543.9 ± 130.7
Unknown fall	75 (6)	19.0 ± 1.6	1719.2 ± 179.9	67 (10)	19.6 ± 1.7	1611.6 ± 189.5

Data are frequency (%) or least squares mean ± SE. Fall: a descent to the ground resulting from a loss or lack of support or intention. Data was collected in both game and training sessions.
* Significantly different to controlled fall.

the brain stem produces both shear strain and tensile strain on the brain.[20] Research suggested an increase in neck strength increases the muscle's ability to generate adequate preparatory and reactive forces required to counter head accelerations,[47,48] which may help reduce the acceleration associated with whiplash related HAEs; however, there is conflicting research on the benefits of neck strengthening for rugby players.[49]

When the tackler has more than one head impact during the tackle (coded as multiple impacts) they suffer the highest PRA (Table 6). We speculate that this may be due to an inability of the tackler to control their head movement after the initial head impact, which leaves them vulnerable to higher external forces impacting their head during subsequent HAEs. A lack of neck strength in young female athletes[50] may also allow a gap between the tackler's head and the ball carrier's body during the tackle event, increasing the chance of tackler head movement during the tackle. Direct impact to the tackler's chin during a tackle also resulted in significantly high PLA and reinforces the need for the tackler to position their head behind or to the side of the ball carrier with no space between their head and opponent's body.

4.2. The effect of tackle characteristic on HAEs of the ball carrier

HAEs were less frequent for the ball carrier, supporting previous literature, which suggests the tackle event may be safer for the ball carrier compared to the player(s) performing the tackle.[51] While less frequent (n = 3), tackles made to the ball carrier's hand/arm region resulted in the highest PLA and PRA. All these tackles involved the tackler using the ball carrier's arm as a fulcrum to spin the ball carrier around before the ball carrier hit the ground. Such a movement would increase the velocity of the ball carrier's head prior to contact with the ground increasing the impact forces. Coaches should discourage these 'grab-and-spin' type tackles.

Half of the ball carrier HAEs were from direct contact with the head (Table 3), specifically to the back of the head (Table 6). In many cases, contact to the back of the head occurred as the ball carrier was tackled to the ground, often resulting in the back of the head hitting the ground in an uncontrolled manner. Adolescent female rugby players have less head and neck control compared to older athletes,[18,52] which may contribute to increased head acceleration magnitudes when ball carriers are tackled to the ground.

Uncontrolled falls resulted in the highest PLA for the ball carrier and tackler (Table 7). Research suggests females rely on visual information in order to pre-activate neck musculature and control their head during an impact.[53] Therefore, when a female cannot see an impending impact, they may be less able to pre-activate and prepare their muscles, contributing to less neck stabilisation and higher head accelerations.[53] Improving players' body awareness and ability to anticipate tackle outcomes may contribute to reduced head acceleration magnitudes while teaching players how to fall correctly and absorb the energy from a tackle may help reduce indirect HAEs and head contact with the ground.

The current study has several limitations. We have only reported tackle events with a head acceleration exceeding 8 g; therefore, lower-magnitude tackles using the recommended technique may not have triggered an iMG recording and were not included in the analysis. This may have biased our results by overestimating tackle severity and misrepresenting tackle effectiveness. Additionally, we have only reported on successful tackles where the ball carrier was brought to the ground and have not reported on unsuccessful tackle attempts, which means we may have missed some important iMG data. We acknowledge that unsuccessful tackle events may also result in large head acceleration events; however, we chose to use World Rugby's definition of a tackle which is when the ball carrier is held by one or more opponents and is brought to the ground, alongside staying in line with the definitions used in the current literature. We have only reported on players in a single team, not all the players on the rugby field. Utilising iMG units for all players on the field would provide valuable insights into how both the ball carrier and tackler respond to the same tackle event. Additionally, data from both games and trainings have been utilised in the current study. Training environments typically involve lower overall intensity and reduced collision magnitude, which may lead to an underestimation of true head acceleration risk compared to match conditions. However, research suggests that training tackle intensity should replicate game intensity to optimise skill development, technical proficiency, and decision-making and to prepare the player for on-field demands.[54] Therefore, we wanted to include training and game tackle events to understand if training tackle events match game demands. The underlying tackle technique and associated biomechanics are present in both contexts and hold comparable head acceleration risk. Future analysis of this data set should examine whether differences in technique between game and training settings influence the level of risk placed on the head during tackle events. Finally, players in the current study were drawn from two different rugby teams; therefore, factors such as coaches' training programme and focus may have affected the incidence and magnitude of HAEs between the seasons.

5. Conclusion

Tacklers experienced high PLA magnitude when using a face-up position during a tackle and much lower PLA magnitude occurred when using a face-down position. We recommend tackle guidelines should emphasise a face down head position at the time of contact for the tackler to reduce the risk of high magnitude HAEs. Ball carriers were exposed to high HAE magnitudes when the tackler contacted their arm area. Uncontrolled falling in either the tackler or ball carrier resulted in higher HAEs; therefore, development of effective falling techniques should be prioritised in female rugby to reduce high-magnitude HAEs. Modifying tackle behaviours in this way may contribute to an overall reduction in accumulated HAE exposure, thereby promoting a safer playing environment for all players.

CRediT authorship contribution statement

Nicole Spriggs: Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Stefan Henley:** Methodology, Investigation, Data curation, Writing – review & editing. **Natalia Kabaliuk:** Conceptualization, Methodology, Writing – review & editing. **Danyon Stitt:** Conceptualization, Investigation, Writing – review & editing. **Annette G. Heward-Swale:** Investigation, Writing – review &

editing. **Congyu Xu:** Investigation, Writing – review & editing. **Kevin Mangan:** Investigation, Data curation, Writing – review & editing. **Rich S.W. Masters:** Conceptualization, Writing – review & editing. **Tracy R. Melzer:** Conceptualization, Formal analysis, Resources, Writing – review & editing. **Arindam Basu:** Formal analysis. **Tim Anderson:** Conceptualization, Writing – review & editing. **Deborah Snell:** Writing – review & editing. **Adrian Clark:** Writing – review & editing. **Keith Alexander:** Conceptualization, Writing – review & editing. **Sinéad Moylett:** Formal analysis. **Michael J. Hamlin:** Conceptualization, Formal analysis, Resources, Data curation, Supervision, Funding acquisition. **Nick Draper:** Conceptualization, Methodology, Resources, Data curation, Supervision, Funding acquisition.

Confirmation of ethical compliance

This research complied to the ethical standards set by Lincoln and Canterbury Universities. Ethical approval for all procedures and experimental design was obtained in full, from the University Ethics Committees (Ref: HEC 2021/26, HEC2022-05).

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