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Original research

‘Mind your head’, tackle characteristics associated with concussions in rugby league: A case-control study

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A B S T R A C T

Objectives: Identify tackle characteristics associated with concussions in male professional rugby league.
Design: Case-control study.
Methods: Tackles resulting in 196 clinically diagnosed concussions and 6592 non-concussive tackles were analysed, from the men's rugby league Super League between 2018 and 2022. Eleven tackle characteristics were coded for each tackle, and Firth penalised logistic regression models were employed to identify influential variables through forward stepwise selection. Three multivariate models were produced; all (i.e., ball-carrier and tackler), tackler, and ball-carrier concussions.
Results: Of the 196 concussions, 70 % occurred to the tackler and 30 % to the ball-carrier. Initial impact location on the ball-carrier was identified as a predictor in all models, specifically the shorts, upper- and lower-leg (OR 9.1–12.3, compared to shoulder) for tacklers and head/neck (OR 66.1, compared to shoulder) for ball-carriers. Tackler head placement in front of the ball-carrier (OR 8.5, compared to away from the body) and a ball-carrier leading arm in any position (OR 4.8–22.1, compared to no leading arm) provided the greatest odds of a tackler concussion. For player's body position the greatest risk of concussion for all players was observed when both players were falling/diving (OR 8.8, compared to both players upright). One (OR 4.9, compared to two) and four (OR 3.7, compared to two) defender tackles provide the greatest odds for all concussions.
Conclusions: Concussion prevention strategies should aim to reduce head impacts by deterring initial contact with the ball-carrier's head/neck. Tackle technique should prioritise making initial impact with the torso and avoid the head being in front of the ball-carrier and any leading arms.

Practical implications

- Tackle interventions should target initial impact with the ball-carriers' head or neck to reduce ball-carrier concussions, e.g., stricter officiation of the laws, greater sanctioning or mitigation through law change.
- Tackler body position should not be a focus when aiming to reduce concussion as being upright and bent at the waist have similar risks.
- Tackle technique interventions should focus on appropriate head placement, not in front of the ball-carrier, to avoid direct impact to the head of the tackler.

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1. Introduction

Rugby league is a high intensity intermittent contact sport.[1] The incidence of injury during matches in rugby league's Super League (the elite professional men's competition in Europe) is reported as 71.0 injuries per 1000 h.[2] The majority of these injuries are the result of the tackle (61 %), of which there are over 600 per match.[3] The documented rate of concussion, largely as a consequence of tackles, has increased from 4.6 per 1000 hours[2] to 11.7 per 1000 player hours in recent seasons (2015–2022).[4] Considering the potential negative long-term effects of sport-related concussion,[5] identifying risk factors is a critical next step for the development of successful prevention strategies.[6]

Limited information is currently available on the tackle characteristics that result in concussive events in rugby league, and this information could be used to inform prevention strategies such as law changes or coaching interventions. A preliminary analysis conducted using 20 concussions in the Australasian National Rugby League (NRL), showed that 83 % (16) of concussions for both ball-carriers and tacklers were a result of tackles to the upper torso or head, with all ball-carriers (11) concussed through initial contact in this zone.[7] More recently, risk factors resulting in head injury assessments (HIAs) were identified over two seasons in the NRL, identifying the tackler to be 1.74 times more likely to require a HIA than the ball-carrier (0.99 HIAs/1000 tackles vs. 0.57 HIAs/1000 tackles).[8] Both the tackler (1.38 HIAs/1000 events) and ball-carrier (1.17 HIAs/1000 events) were at greatest risk when the tackler was upright, with a 3.2-fold higher risk when compared to the tackler bent at the waist. Coupled with the observation that impact with the head, shoulder, and knee are more likely to result in HIAs compared to other body parts, these findings are consistent with previous research in rugby union[9,10] and suggest that tacklers should bend at the waist keeping their head around the torso of the ball-carrier to minimise HIA risk. However, the analysis focused on body position and impacting body part, and a greater understanding of other factors could be beneficial. Therefore, a more comprehensive assessment of rugby league tackle characteristics that are associated with concussion is required to better inform targeted prevention strategies.

Therefore, to further elucidate the characteristics of tackles that are associated with concussion risk, the aim of this study is to identify the tackle characteristics associated with clinically diagnosed concussions in the men's Super League between 2018 and 2022. The goal of this analysis is to recognise the tackle characteristics that predict concussion

Table 1
Number of coded cases and controls for each variable.

Variable		All cases (n [% of total])	Ball-carrier cases (n [% of total])	Tackler cases (n [% of total])	Control (n [% of total])
Total		196	57	139	6592
Ball-carrier leading arm	No leading arm	55 [28]	27 [47]	28 [20]	3273 [50]
	Ball carrying arm	61 [31]	11 [19]	50 [36]	1251 [19]
	Non-ball carrying arm	44 [22]	7 [12]	37 [26]	1051 [16]
	Bump position	24 [12]	8 [14]	16 [12]	700 [11]
	Hand off	12 [6]	4 [7]	8 [6]	317 [4]
Ball-carrier movement	Straight at defender	74 [38]	19 [34]	55 [40]	1546 [24]
	Straight away from defender	26 [13]	11 [19]	15 [10]	1862 [28]
	Step towards defender	45 [23]	11 [19]	34 [24]	1875 [28]
	Step away from defender	30 [15]	11 [19]	19 [14]	965 [15]
	Arcing run	21 [11]	5 [9]	16 [12]	344 [5]
Match activity	Line tackle	144 [72]	36 [63]	108 [78]	5342 [81]
	Set piece	6 [3]	3 [5]	3 [2]	464 [7]
	Off the ball	9 [5]	6 [11]	3 [2]	145 [2]
	Try scoring	8 [4]	5 [9]	3 [2]	64 [1]
	Kick off	15 [8]	3 [5]	12 [8]	176 [3]
	Drop out	5 [3]	0 [0]	5 [4]	51 [1]
	Unstructured	9 [5]	4 [7]	5 [4]	350 [5]
Number of tacklers	1v1	59 [30]	16 [28]	43 [31]	890 [14]
	1v2	76 [39]	26 [46]	50 [36]	2279 [35]
	1v3	49 [25]	15 [26]	34 [24]	3178 [48]
	1v4	12 [6]	0 [0]	12 [9]	245 [4]
Initial impact location on ball-carrier	Head/neck	78 [40]	54 [94]	24 [18]	984 [15]
	Shoulder	49 [25]	2 [4]	47 [32]	2784 [35]
	Chest	15 [8]	0 [0]	15 [11]	1156 [18]
	Abdomen	6 [3]	0 [0]	6 [4]	460 [7]
	Shorts	35 [18]	0 [0]	35 [26]	857 [14]
	Upper leg	9 [5]	1 [2]	8 [6]	214 [3]
	Lower leg	4 [2]	0 [0]	4 [3]	137 [2]
Tackler arrival	1st tackler	136 [69]	32 [56]	104 [74]	3275 [50]
	2nd tackler	48 [24]	22 [39]	26 [19]	2237 [34]
	3rd tackler	11 [6]	3 [5]	8 [6]	1030 [16]
	4th tackler	1 [1]	0 [0]	1 [1]	50 [1]
Ball-carrier-tackler body position	Upright - upright	55 [28]	20 [35]	35 [25]	1988 [30]
	Upright - bent at waist	36 [18]	2 [4]	34 [24]	1115 [17]
	Upright - falling/diving	10 [5]	0 [0]	10 [7]	445 [7]
	Bent at waist - upright	11 [6]	8 [14]	3 [2]	677 [11]
	Bent at waist - bent at waist	49 [25]	9 [16]	40 [29]	1510 [23]
	Bent at waist - falling/diving	7 [4]	0 [0]	7 [5]	484 [7]
	Falling/diving - upright	5 [3]	3 [5]	2 [1]	62 [1]
	Falling/diving - bent at waist	4 [2]	3 [5]	1 [1]	179 [2]
	Falling/diving - falling/diving	19 [10]	12 [21]	7 [5]	132 [2]
Tackler head placement	Front			76 [56]	1098 [17]
	Back			37 [27]	1792 [27]
	Side			23 [17]	2485 [38]
	NA			0 [0]	1212 [18]
Inconclusive		78			823

in rugby league thus creating target areas for future concussion prevention interventions,[11,12] rather than providing a causal framework to suggest why concussions occur.[13]

2. Methods

This study was carried out using data from the top level of men's European rugby league (i.e., Super League) during the 2018–2022 seasons. Over this period, match concussions were reported by a health care professional as a part of the recognised medical standards.[14] A concussion report was completed and provided to the Rugby Football League (RFL) within 24 h of a player being removed from the field of play with a concussion or suspected concussion. Concussions were identified in players who were immediately and permanently removed from the field following the display of Category 1 concussion signs/symptoms, or after being permanently removed from play following an off-field assessment conducted when a player displayed Category 2 signs/symptoms, or other symptom reports consistent with a suspected concussion.[14] The RFL used the concussion reports to identify the concussive events on video and these clips were then provided to the research team for subsequent, retrospective video analysis. If a player was not immediately removed from the field (i.e., prior to the completion of the following set of six tackles), was checked on-field by a member of the medical team but cleared to continue playing, or the concussive event could not be identified, no video was provided by the RFL for the research team to analyse. With the exception of shirt number and team, no personal information (i.e., name, position, age) regarding the concussed player or match was provided to the video analysis team. Ethics approval was granted by Leeds Beckett University.

An analyst with 3 years' experience coded all tackle events using Hudl Sportscode (V12.4.24, Hudl, Lincoln, Nebraska, United States). A coding window comprising 11 variables informed and developed based on previous research,[15–17] was applied to each tackle video clip. The coded variables were; role of concussed player, match activity, number of tacklers, tackler arrival, ball-carrier body position, tackler position, impact location on ball-carrier's body, ball-carrier movement, ball-carrier leading arm, tackler head location and tackle penalties awarded by the referee. Full definitions of each variable are provided in Supplement 1. Assessment of intra-rater reliability identified tackler head placement to be of substantial agreement (k = 0.79), and all other variables to be almost perfect to perfect agreement (k = 0.84–1). If the footage of the concussive event was unclear (e.g., the contact was obstructed) the event was excluded. The remaining concussive events formed the case dataset.

A total of 7415 control tackles which did not include a concussive incident were also coded by the same analyst from 10 randomly selected games from the same competition. A tackle was defined as '*any event where one or more tacklers attempted to stop or impede the ball carrier whether or not the ball carrier was brought to ground*'.[8] Two matches from each of the five seasons that provided the cases were randomly sampled to provide a representation of the total dataset. Based upon the previous research this was deemed to provide a sufficient number of controls, exceeding the number and ratio included by previous studies to account for rare events and any variation between seasons.[8,18]

All analyses were conducted in RStudio (V.4.2.0, R Foundation for Statistical Computing, Vienna, Austria). Firth penalised logistic regression (*logistf* package) was applied to identify the most influential tackle characteristics (match activity, number of tacklers, tackler

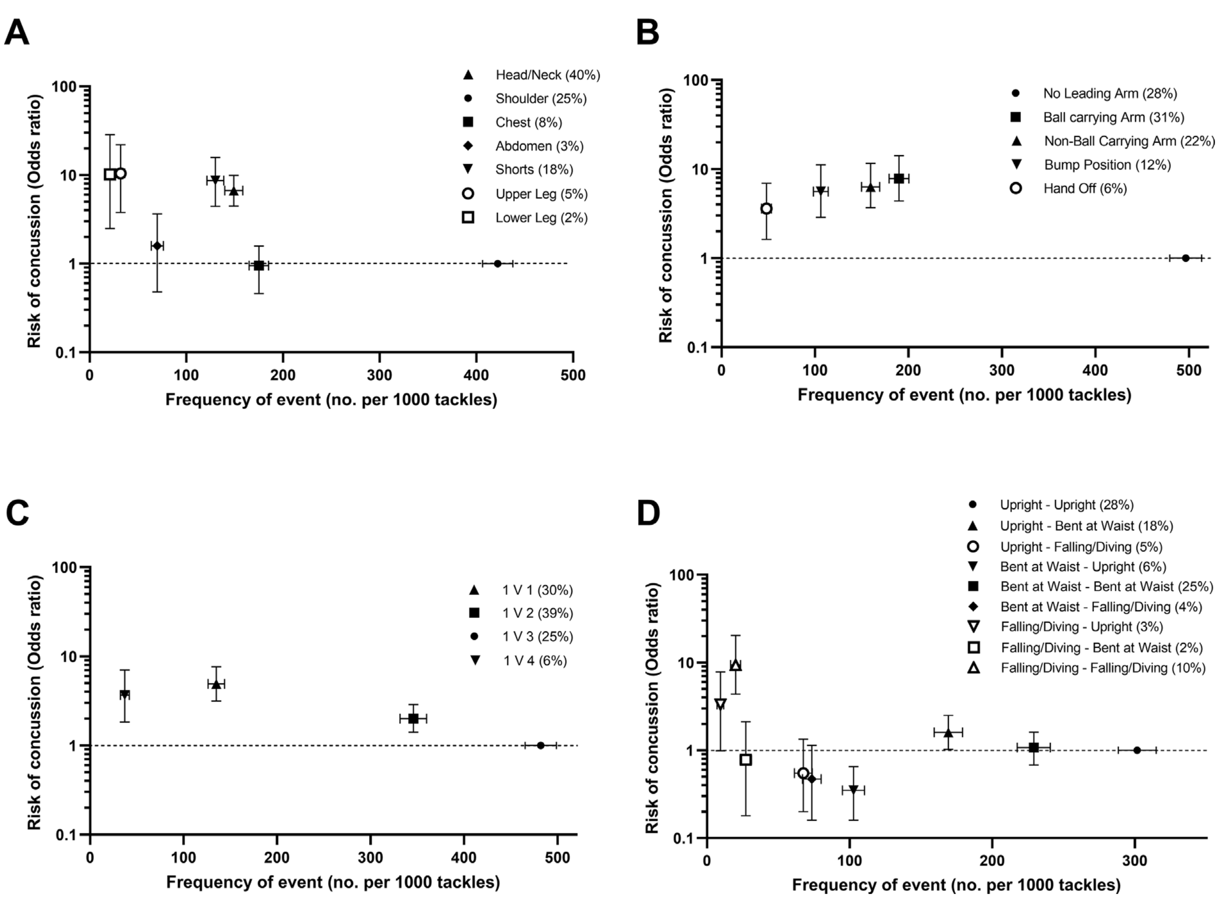

Fig. 1. The association between tackle characteristics and all concussions when compared to the most common characteristic for A) tackle impact zone location on the ball-carrier, B) carrier leading arm, C) number of defenders in the tackle and D) carrier-tackler body position. The x-axis shows the frequency of the tackle characteristic occurring per 1000 tackles and the y-axis the odds ratio compared to the most frequently occurring characteristic. Error bars represent 95 % CIs. The dashed line represents an odds ratio of 1. The percentage of concussions attributed to each characteristic is displayed in the legend.

arrival, height of ball-carrier, height of tackler, impact location on ball-carrier, ball-carrier movement, ball-carrier leading arm and tackler head location) that resulted in a concussion using a forward stepwise selection procedure.[19,20] Model performance was assessed through Bayesian Information Criterion, with variables manually added one at a time until the model fit could not be improved. Collinearity of the predictor variables in the final model was assessed with a variable inflation factor ≥10 deemed to demonstrate substantial collinearity. No substantial collinearity was identified. Three models were produced; all concussions, tackler concussions only, and ball-carrier concussions only. For each variable the most frequently occurring category was the reference point, with odds ratios (ORs) providing the likelihood of each category resulting in a concussion against the reference point. The *emmeans* and *parameters* package was used to extract ORs and 95 % confidence intervals (95 % CI) from the models and perform statistical comparisons using a bootstrapping approach with 1000 samples.[21,22] ORs, the frequency of each category occurring (per 1000 tackles), and their 95 % CI were plotted to provide a comparison of the risk of concussion from the tackle characteristic and the regularity of the event occurring within a match.[18] Differences from the reference characteristic were deemed significant if the CI did not cross 1.

3. Results

Overall, 274 concussions (20.7/1000 game-hours) occurred in the Super League between 2018 and 2022. A total of 78 concussive events could not be analysed because the player was not immediately removed from the field of play (n = 34) or the view was obstructed (n = 44), leaving 196 tackle concussions for analysis. Of the control tackles 6592 were deemed appropriate for analysis. More concussions were sustained by tacklers (n = 139; 70 %) than ball-carriers (n = 57; 30 %). Twenty penalties (10 %) were awarded for tackles causing concussions, with 18 (9 %) for contact with the head, one (<1 %) late tackle and one (<1 %) tip tackle. From the 6592 control tackles, 21 (<1 %) penalties were observed (18 [<1 %] for contact with the head and 3 [<1 %] late tackles), a rate of one illegal tackle penalty every 353 tackles. Table 1 shows the number of events for each tackle variable stratified by cases and controls.

For all concussions (ball-carrier and tackler), tackle impact location on the ball-carrier's body, ball-carrier leading arm, number of defenders in the tackle, and ball-carrier-tackler body position interaction were identified as important tackle characteristics relating to concussion (Fig. 1). For tackle impact zone location on the ball-carrier, lower leg (OR 10.2; 95 % CI 2.5–28.4), upper leg (10.5; 3.8–22.0), shorts (8.6; 4.4–15.74), and head/neck (6.7; 4.5–9.9) contacts were significantly more likely to cause a concussion than contact at the shoulder reference point. All variations of a ball-carrier leading arm resulted in significantly greater odds of a concussion compared to no leading arm, with the ball-carrying arm the highest (7.8; 4.4–14.5). The 1v3 tackles (i.e., 1 ball-carrier and 3 tacklers) were the most common tackle type in the control cohort. A tackle with one tackler had greater odds (4.9; 3.1–7.6) of resulting in a concussion than a tackle with three tacklers. In comparison to the reference value of both tackler and ball carrier upright, tackles involving falling/diving ball carriers and falling/diving tacklers had significantly higher odds of concussion (9.4; 4.4–20.4), whilst ball-carrier bent at waist and tackler upright (0.5; 0.2–0.7) had significantly lower odds of a concussion.

Fig. 2 shows the variables associated with tackler concussions, which were tackler head placement, carrier leading arm, number of players in the tackle, and tackle impact zone location on the ball-carrier. Tackler

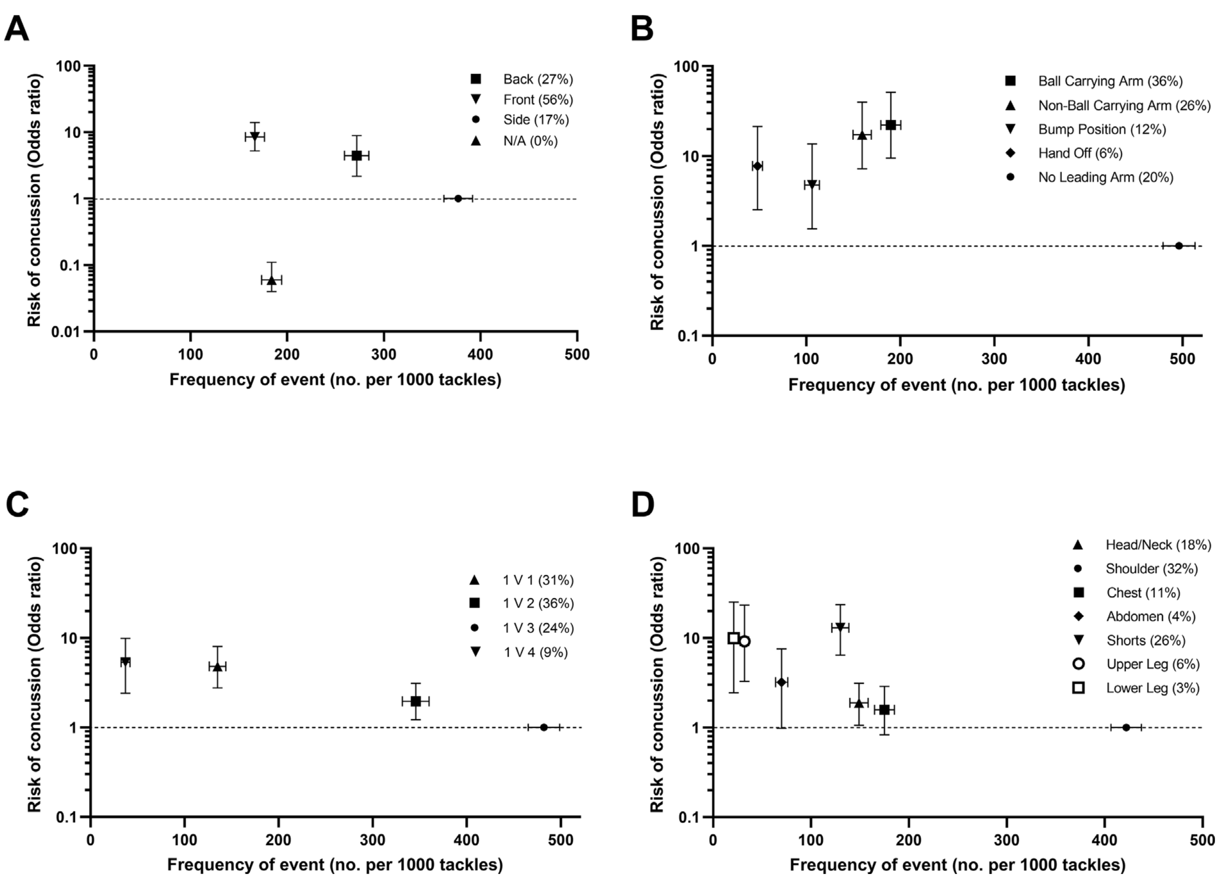

Fig. 2. The association between tackle characteristics and tackler concussions when compared to the most common characteristic for A) tackler head placement, B) carrier leading arm, C) number of players in the tackle and D) tackle impact zone location on the ball-carrier. The x-axis shows the frequency of the tackle characteristic occurring per 1000 tackles and the y-axis the odds ratio compared to the most frequently occurring characteristic. Error bars represent 95 % CIs. The dashed line represents an odds ratio of 1. The percentage of concussions attributed to each characteristic is displayed in the legend.

head placement was the first variable included in the model with both front (8.5; 5.2–14.0) and back (4.5; 2.2–9.0) head placements having significantly greater odds of a concussion compared to the side. No tackler concussions were observed when the head did not make clear impact with the ball-carrier (N/A) although this non-impact tackle occurred at a rate of 184 per 1000 tackles in the controls, the second lowest of all head positions. All ball-carrier leading arm types produced significantly greater odds of a concussion to the tackler than no leading arm. Of these, ball-carrying leading arm (22.2; 9.5–51.3) and non-ball-carrying leading arm (17.2; 7.2–39.9) produced the greatest odds of a concussion compared to no leading arm. With respects to number of tacklers, tackles involving four (5.4; 2.4–9.9), one (4.8; 2.8–8.0) and two (2.0; 1.2–3.1) tacklers all had significantly greater odds of a concussion than the reference of three tacklers. Tackle impact zone location on the ball-carrier was the final variable selected for the model with impact zones on the ball-carrier of lower leg (9.9; 2.5–25.2), upper leg (9.2; 3.3–23.2), and shorts (12.9; 6.4–23.5) having significantly higher odds of a tackler concussion than the shoulder tackle impact location.

Only two variables were associated with increased risk of a ball-carrier concussion (Fig. 3). Tackle impact zone location on the ball-carrier initially selected, with concussions only occurring in three tackle impact locations; head/neck (n = 54; 94 %), shoulder (n = 2; 4 %), and upper leg (n = 1; 2 %). In terms of rate of occurrence, head/neck contact was the third highest tackle impact location on the ball-carrier (149 per 1000 tackles in the controls), and resulted in 94 % of ball carrier concussions, with a significantly higher OR (66.1; 24.5–399.2) compared to an initial impact location of the shoulder of the ball-carrier. No ball-carrier concussions occurred when initial impact was made to the chest, abdomen, shorts or lower leg of the ball-carrier, however, due to the Firth penalisation for sparse data ORs of 0.4 (0.2–2.4), 1.0 (0.3–6.5), 1.3 (0.4–8.4) and 13.6 (1.5–120.2) were reported. The second variable of importance was the ball-carrier-tackler body position. When both players were falling/diving the odds of concussion were significantly greater (13.1; 5.0–37.8) than when both players were upright. However, this situation where both players were falling/diving was one of the least frequently occurring events (20 per 1000 tackles in the control cases). No concussive events were recorded for the ball-carrier when the ball-carrier was upright or bent at the waist and the tackler was falling/diving, with the respective OR reported as a result of Firth's penalisation found to be 0.4 (0.1–4.7) and 0.4 (0.1–4.3).

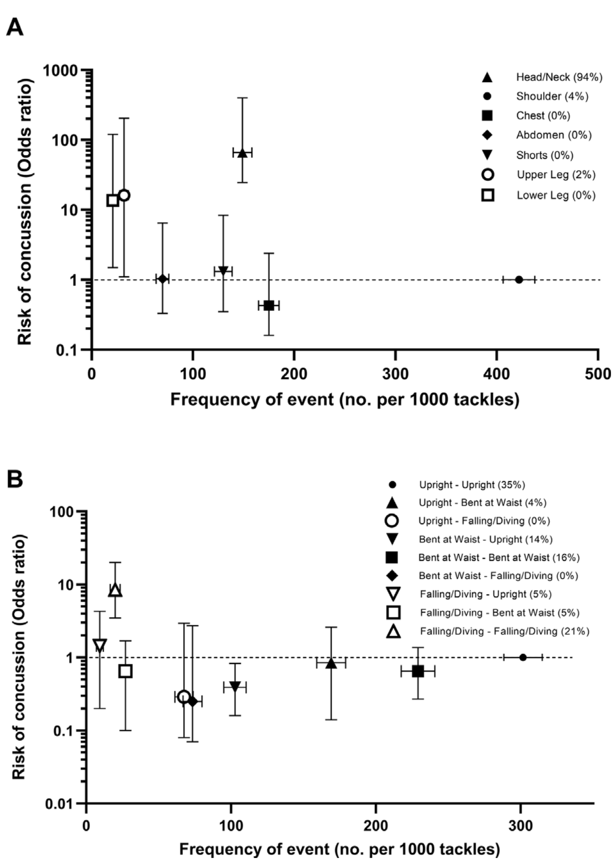

Fig. 3. The association between tackle characteristics and ball-carrier concussions when compared to the most common characteristic for A) tackle impact zone location on the ball-carrier and B) ball-carrier-tackler body position. The x-axis shows the frequency of the tackle characteristic occurring per 1000 tackles and the y-axis the odds ratio compared to the most frequently occurring characteristic. Error bars represent 95 % CIs. The dashed line represents an odds ratio of 1. The percentage of concussions attributed to each characteristic is displayed in the legend.

4. Discussion

This study provides the most comprehensive analysis to date of tackle characteristics associated with clinically diagnosed concussions in rugby league. Of the 196 concussions, 70 % occurred to the tackler and 30 % to the ball-carrier. Concussions to either player in the tackle were associated with four variables: tackle impact location on the ball-carrier, ball-carrier's use of a leading arm, the number of players in the tackle, and the ball-carrier-tackler body position. Characteristics associated with tackler concussion were similar, with the addition of head placement and exclusion of ball-carrier-tackler body position from the predictive model. Only two variables were identified as significant for ball-carrier concussions, namely tackle impact zone location on the ball-carrier's body and ball-carrier-tackler body position interaction. These findings may contribute to the identification of the factors concussion prevention strategies should target such as law changes to reduce the frequency of the identified highest risk situations and coaching interventions that promote safer tackle technique, thus reducing concussions in rugby league.

The observation that more concussions occurred to the tackler than the ball-carrier is consistent with previous reports that HIAs during men's rugby league are 1.7 times more likely in tacklers than ball-carriers.[8] Furthermore, the current findings are similar to those reported in men's rugby union, with an approximately 70 %/30 % split between tackler and ball-carrier.[18] Given the relatively greater risk to the tackler, and the differences in identified tackle risk factors for tackler concussions (Figs. 2 & 3), concussion prevention strategies may need to be tailored specifically to each player's role in the tackle.

As more concussions occur to the tackler, prioritising strategies focused on the protection of the tackler have the potential to significantly reduce overall concussions, should these interventions prove effective. The tackler, however, has a duty of care for both themselves and the ball-carrier and therefore all interventions, whether they prioritise the reduction of ball-carrier or tackler concussions, will have implications on the overall performance and risk of the tackle. As such, law interventions deterring the tackler from dangerous tackle types may have some benefit in protecting the tackler from injury, but will be more likely to have greater protective effects for the ball-carrier,[23] whose concussion is almost exclusively the result of initial impact to the head/neck when being tackled. The tackler must also have appropriate competence to execute safe and effective tackle technique within the laws, to ensure they execute their duty of care for themselves and the ball carrier.[24] Further research should explore the quality of tackle technique and its implications for tackler concussion to inform coaching practices that promote tackler safety, especially for initial impact at the shorts, upper leg or lower leg.

Tackle impact location on the ball-carrier was the only characteristic identified in all three models, highlighting its potential importance in concussion prevention. Initial impact with the head/neck, shorts, upper leg and lower leg created the greatest risk for concussion for both tacklers and ball-carriers. When considering role, impacting the lower body (i.e., shorts, upper leg and lower leg) of the ball-carrier created the highest risk of a concussion for tacklers, in support of previous research that has shown that head impacts with the ankle, knee, or hip are more likely to cause head injuries in rugby codes.[8,10,18,25] The ball-carrier is at greater risk when there is initial impact to the head/neck. Indeed, this contact is almost exclusively responsible for ball carrier concussions in this study (94 %). In rugby league, under law 15.1.b. "When effecting or attempting to effect a tackle makes contact with the head or neck of an opponent intentionally, recklessly, or carelessly" a penalty should be awarded.[26] However, the prevalence observed for the ball carrier's head/neck being the initial impact location during tackles (149 per 1000 tackles), combined with the finding that only 18 penalties were awarded for contact to the head in the 984 initial head/neck contact control tackles suggests that sanctioning of this law violation needs reviewing. Therefore, to target ball-carrier concussions, interventions that address initial contact to the head or neck of the ball-carrier such as stricter enforcement of law 15.1.b., greater sanctioning by match officials or lowering the height of the tackle in law could be considered with the shoulder, chest, and abdomen providing a potentially safer tackle zone.[23]

Although the previous literature evaluating the body position of players suggests that head injuries are more likely to occur when the tackler is upright,[8,10] the findings of this study differ. The greatest odds of concussion occurred when both players were falling/diving. The falling/diving mechanism could be initiated voluntarily by attempting to score a try, surrendering to a tackle or a tackler losing their footing as they project into a tackle, or involuntarily such as a ball-carrier who is already in the act of being tackled or a player slipping. This could result in a possible lack of control, preventing the ability to anticipate head impact, avoid contact or result in a sudden change in body position which other players in the tackle cannot adjust to. It is acknowledged that some of these events such as slipping or scoring a try are inherent in the game and may not be preventable and may not be considered a modifiable risk factor. Furthermore, due to their low frequency of occurrence mitigation of such risk will have minimal impact.

In contrast, Gardner et al.[8] suggest that when considering HIAs in the NRL, the safest tackle type is when both players are bent at the waist. However, the current findings identified similar odds of concussion when the tackle height interaction involved any combination of players being upright or bent at the waist. For example, when comparing both players in an upright body position to both players bent at the waist for all concussions the OR = 1.0 (Fig. 1). Differences in the findings could be a result of the definition used for the video analysis or the interpretation by the analyst and inter-rater reliability of such criteria should therefore be considered when comparing between studies. Alternatively, other factors which may be associated with being bent at the waist, such as the point of impact with the opponent's body whilst bent, may increase the risk of concussion in tacklers when adopting a lower body position. Therefore, given the results of the present study, tackler body position may be less important than ensuring tackles are within the laws of the game to protect the ball-carrier (i.e., no contact with the head).

The tacklers' head position was identified as the first variable when predicting tackler concussions. A tackler head impact to the front of the ball-carrier's body posed the greatest odds of concussion. This type of head placement is the least frequent in match play (167/1000 tackles), suggesting it may not be favoured by players. Previous research has identified one-on-one tackles where the defender drops their head into contact, ending up in front of the ball-carrier results in significantly greater peak linear and angular head accelerations compared to tackle types where the head is positioned away from the ball-carrier or outside/on their shoulder.[27] Findings in rugby union also suggest that placing the head in front of the ball-carrier creates the greatest risk of injury.[28] Coaching interventions should address appropriate tackler head position, with suggestions that placing the head up and forward upon approach to the tackle to be able to adjust for ball-carrier movement, whilst making shoulder contact with the ball-carrier's mid-torso and positioning the head to the side of the ball-carrier will help to avoid direct impact to the tackler's head and reduce head accelerations.[27,29]

A leading arm of the ball-carrier was also identified as a predictor of concussions for the tackler. Contact by the tackler with any type of the ball-carrier's leading arm resulted in greater odds of concussion compared to not impacting a leading arm. Whilst leading arms, bump positions, and hand offs may protect the ball-carrier, there is little understanding of the ball-carrier leading arm position on performance outcomes in rugby league. In rugby union, fending has been shown to improve the ball carrier's chance of offloading,[29] tackle breaks,[30] and injury prevention for the ball-carrier.[31] However, a large number of tackler HIAs (67 %) that occur as a result of fends in rugby union have been attributed to illegal actions (i.e., not using the palm of the hand to fend).[32] Unlike rugby union, rugby league does not have explicit laws regarding the ball-carrier's leading arm position.[26] To inform law changes and coaching practices, further understanding of the performance, protective, and safety benefits for the ball-carrier compared to the risks for the tackler is required.

The current study identified the most frequently occurring tackle type (1 ball-carrier v 3 tacklers) had the lowest odds of concussion, with all other tackle types having greater risk especially four and one defender tackles. It is possible that one defender tackles are associated with higher concussions due to greater tackler speed and energy transfer between the tackler and the ball-carrier as they occur in open play with no prior reduction in ball carrier speed as a result of a previous defender engaging in the tackle.[10,18] Whilst subjective analysis of player speed and acceleration has been conducted in rugby union,[18] further research is required to understand the role of player speed on concussion by using objective measures, such as global positioning systems. This is especially important when considering that speed, when assessed subjectively, was identified as the most important variable for predicting concussion in rugby union.[18] As for 1v4 tackles, these resulted in the greatest risk for head injury for the tackler in a single tackle event (Fig. 2). The process of several players engaging in a single tackle is complex, with defenders simultaneously or sequentially attempting to stop the carrier. In theory, each arriving player should increase concussion risk, since more heads are exposed to the injurious event of head impact. Whilst restricting the number of defenders that can engage in a tackle would limit the potential for head contacts, the characterisation of all players in the tackle (i.e., how tacklers join and their relative impact locations) could be a risk factor rather than the number of defenders involved. Further causal understanding of these potential confounders such as speed into the tackle, phase number, and tackle height, would support law changes limiting tackler number or inform technique when multiple defenders are involved.

This study provides the most comprehensive assessment to date of the tackle characteristics associated with concussions in rugby league, however, it is not without limitations. First, data could be missing as a result of the reliability of the reporting method to identify concussive events. Whilst match day medical staff approximate a time of the event in the match, it is not always identified from the video footage, and some events were removed from the case sample. It is also possible that even more concussive events were missed at the time of injury. Players may also suffer from concussive symptoms following the game, making it difficult to identify the exact concussive event, therefore these were also not included in this study. Limited camera angles from matches can result in obstructions that prevent the coding of tackle characteristics, prompting their removal and reducing the case sample size. Consequently, Firth's penalised regression was used to adjust for sparse data bias. However, odds ratios for variables with both few cases and controls may still be observed to have inflated point estimates and 95 % CIs, e.g., lower leg impact in the ball-carrier model.[33] The forward stepwise approach for variable selection is a commonly applied methodology, however, the main limitation to this approach is the final model does not always guarantee the best possible variable subset. The forward stepwise approach was selected following an initial exploration of methods, and in the future, datasets that include a greater number of cases, and thus a more equally balanced dataset, may wish to apply this and other methods such as random forest. Finally, the incidence rate (i.e., the number of concussions per a given number of tackles) and proportion (i.e., the proportion of concussive tackles within each sub-type of a characteristic) of concussion mechanisms could not be directly reported. Whilst case-control studies provide a pseudo-rate that can be used to obtain an incidence rate and proportion it requires knowledge of the case sampling fraction (i.e. the proportion of the control tackles [the sample] taken from the total number of tackles [the population]). However, due to there being no tackle data available for the 2018–2020 seasons, all tackle events would have had to have been coded removing the efficiency of the case-control study design. To avoid the extrapolation of the data for the uncoded tackles and the resultant uncertainty in the findings by assuming the number of tackles was equal to the average per game in the control cohort, odds ratios were used to provide an estimate of the risk ratio within this study.

5. Conclusions

Tacklers sustain a greater number of concussions compared to the ball-carrier. Tackle impact zone location on the ball-carrier, ball-carrier leading arm, the number of tacklers, ball-carrier-tackler body position, and tackler head position were identified as predictors of concussion in rugby league. Further research is required to evaluate the optimal ball-carrier and tackle technique, including the impact of the ball-carrier's leading arm on concussion risk to both the ball-carrier and tackler. The current findings suggest that reinforcement or modification of the current laws to address initial impact with the ball-carriers head or neck may be required. There is limited justification to enforce a change to the tackler's body position, as suggested by previous research. Appropriate tackle technique should also be reinforced with tacklers aiming to make contact between the shoulder and the abdomen with the head placed to the side or away from the ball-carrier.

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CRediT authorship contribution statement

Cameron Owen analysed the data and wrote the manuscript. Cameron Owen, Kevin Till, Andrew Gardner, James Brown, Matt Cross, Sharief Hendricks, Rich Johnston, Gemma Phillips, Keith Stokes, Ross Tucker, and Ben Jones were involved in the conceptualisation of the study and reviewing of the manuscript for approval.

Confirmation of ethical compliance

Ethics approval was granted from Leeds Beckett University Ethics Committee.

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Consent to participate and publish

The Rugby Football League provided consent for the results to be published prior to the study commencement.

Declaration of interest statement

Cameron Owen's research fellowship is funded by the Rugby Football League. Kevin Till is employed in a consultancy capacity by Leeds Rhinos. Andrew Gardner has a clinical practice in neuropsychology involving individuals who have sustained sport-related concussion (including current and former athletes). He is a contracted concussion consultant to Rugby Australia, and has received grant funding from the NSW Sporting Injuries Committee, the Brain Foundation (Australia), an Australian-American Fulbright Commission Postdoctoral Award, a Hunter New England Local Health District, Research, Innovation and Partnerships Health Research & Translation Centre and Clinical Research Fellowship Scheme, and the Hunter Medical Research Institute (HMRI), supported by Jennie Thomas, and the HMRI, supported by Anne Greaves. He has current philanthropic support from the Nick Tooth Foundation. He acknowledges unrestricted philanthropic support from the National Rugby League (NRL). Matt Cross is employed by Premiership Rugby. Gemma Phillips is employed in a consultancy capacity by the Rugby Football League and Hull Kingston Rovers. Keith Stokes is employed by the Rugby Football Union. Ross Tucker is employed in a consultancy capacity by World Rugby. Ben Jones is employed in a consultancy capacity by Premiership Rugby, Rugby Football League, and Leeds Rhinos.

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Data availability

The datasets (deidentified participant data) generated during and/or analysed are available from the corresponding author on request.

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