Impacting the rugby tackle: risk factors and mechanisms for concussion and musculoskeletal tackle-related injury – a systematic review and Delphi consensus to inform intervention strategies for risk reduction

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ABSTRACT

Objective

To (1) systematically review the literature to identify which match-related risk factors and mechanisms of rugby tackle events result in musculoskeletal injury; concussion; head injury assessments; and head impacts or head accelerations; and (2) identify the perceived importance and feasibility of potential intervention strategies for tackle-related injury reduction in the rugby codes.

Design

A systematic search was performed using PRISMA guidelines. Risk factors/mechanisms associated with tackle injuries across the rugby codes were extracted. After extraction, 50 international rugby experts participated in a Delphi poll. Via content analysis, expert-recommended risk factors/mechanisms were developed. In round two, experts rated all risk factors and mechanisms for importance to injury risk. In round three, the feasibility of law changes, coach and player education and training as interventions to reduce injury risk for each injury risk factor/mechanism deemed important during round two were rated.

Data sources

PubMed [MEDLINE], Scopus, SPORTDiscus [EBSCOhost] and CINAHL.

Eligibility criteria

Eligible studies included cohort, observational and cross-sectional designs, that included male or female rugby union, league, or sevens players.

Results

Thirty-seven eligible studies were identified, with 138 injury risk factors/mechanisms extracted. 70% of the studies were rated ‘high quality’, with 30% moderate quality. Thirty-eight new risk factors/mechanisms were recommended by the expert group, eight being identified as important and highly feasible for modification by an intervention strategy. ‘The tackler placing their head on the incorrect side of the ball carrier’ was described as the most important mechanism, with ‘training’ and ‘coach/player education’ thought to be highly feasible interventions.

Conclusion

Numerous risk factors or mechanisms associated with tackle-related injury appear important and modifiable, helping to guide interventions to reduce injury risk in the rugby tackle.

What is already known on this topic?

- The tackle is the most common cause of injury across the rugby codes, and a large body of work has assessed risk factors and mechanisms within the tackle that lead to negative tackle outcomes including musculoskeletal injury, concussion, head impacts and head acceleration events.

What are the new findings?

- There are a wide range of risk factors and mechanisms which were significantly associated with negative tackle outcomes, including 25% from the pre-contact phase, 53% from the contact phase, and 13% from the post-contact phase.
- Less than 20% of injury risk factors and mechanisms achieved consensus on being highly important to causing musculoskeletal injury (n = 10 risk factors), or concussion or head accelerations (n = 16 risk factors) during the tackle.
- Training and coach and player education were the most highly rated means of mitigating the risk factor and mechanism across a variety of factors. Only eight risk factors achieved consensus in how they could be modified, with seven being from the contact phase of the tackle and six being related to tackle technique.

How might this study affect research, practice, or policy?

- Our findings inform injury prevention initiatives in rugby to target risk factors in the contact phase of the tackle.
- Current coach and player educational resources with respect to tackle technique (e.g., Tackle Ready) should be evaluated to see whether they incorporate the risk factors highlighted in this study.
- Future studies are needed to empirically assess the effectiveness of interventions at addressing the highly important and modifiable risk factors identified by this consensus.

INTRODUCTION

Rugby union, rugby league and rugby sevens (collectively referred to as 'rugby' hereafter) are team collision sports with a relatively high injury risk [1–3], with previous epidemiological research finding rugby has an injury risk three times higher than other collisions sports [4] Of the injury-associated events in rugby, the tackle occurs the most frequently [5–7] and is the greatest cause of injury [1,8–12]. For example, in men's rugby, 29-39 injuries per 1000 hours occur when being tackled, with 10-20 injuries per 1000 hours when tackling [1,9,11,13]. Furthermore, tackles are also responsible for the highest incidence of concussions in rugby, with 5 concussions per 1000 hours in women's rugby union [14], 12 in men's rugby union [11], 8.3 in men's rugby sevens [1], 15.5 in men's rugby league [15], with these numbers increasing over time with better concussion detection [16]. There are also concerns that repetitive head accelerations could be linked to neurodegenerative disease risk [17–19].

The aetiology and mechanisms of injurious tackle events [20–25], as part of the 'sequence of injury prevention' model have been explored [26]. These studies attempted to identify characteristics of the inciting injury with the goal of informing preventive measures for prominent injury types (i.e. concussion)[7] . Characteristics associated with tackle-related injuries identified via video analysis, include, but are not exclusive to head-to-head collision [20,24], head to shoulder/arm collision [28], twisting of the ball carrier's legs [24] and the tackle occurring in the blind vision area of the ball carrier [29]. Whilst understanding injury mechanisms are informative from a mechanical perspective, consulting expert practitioners and researchers to guide the next stages of injury prevention research for the tackle is a fundamental stage in the process of prevention, to better understand the context and increase potential effectiveness of preventive measures [30–33].

Due to the dynamic nature of tackles, it is well-established that injuries can occur for a multitude of reasons [34–36]. The primary means of understanding tackle injuries and associated mechanisms in rugby has been via video analysis during matches. To date, video analyses of tackle injury risk factors and mechanisms during matches have not been synthesised. A synthesis of the video analyses of tackle injury mechanisms in rugby literature along with expert practitioner and researcher consultation may inform a comprehensive understanding of associated injury mechanisms and risk factors, and help identify potential injury prevention strategies [37]. Therefore, the aims of the study are to firstly systematically review the literature to identify which match-related risk factors and mechanisms of rugby

tackle events result in musculoskeletal injury; concussion; head injury assessments; and head impacts or head accelerations. Secondly, using the identified injury risk factors and mechanisms, the study aims to establish prevention strategies for tackle-related injury reduction in rugby based on expert opinion of their feasibility and potential impacts.

Methods

Part one: Systematic review of injury mechanisms and/or risk factors within rugby tackle events

The review adhered to the Preferred Reporting Systematic Reviews and Meta-Analyses (PRISMA) statement. This review was amalgamated with an existing pre-registered review Prospero, Record ID 359080) and registered with the Open Science Framework (https://osf.io/79zb4). Institutional ethics approval was obtained (ref: 112841) from Leeds Beckett University Research Ethics Committee.

Search strategy

A systematic search of electronic databases (PubMed [MEDLINE], Scopus, SPORTDiscus [EBSCOhost] and CINAHL), performed from earliest records to 24/01/2023, which was updated on 23/10/2024. Search terms were built from previously published rugby sport science and medicine reviews (38). The search strategy combined rugby ("rugby league", "rugby union", "rugby sevens", rugby") AND tackle event ("tackle", "tackle event", "tackle-based", "collision", "ball carry") with terms covering topics related to injury within rugby tackle events ("injury", "mechanisms" OR "risk factors" OR "concussion" OR "sports related concussion" OR "brain injury" OR "mild traumatic brain injury" OR "mTBI" OR "traumatic brain injury" OR "TBI" OR craniocerebral trauma" OR "head injury" OR "head contact" OR "head impact" OR "head acceleration" OR linear acceleration" OR rotational acceleration" OR 'angular acceleration". The searches were completed for the title and abstract fields only. Searches were limited to the English language.

Study Eligibility Criteria

All studies involving a cohort, observational or cross-sectional design were considered to meet eligibility criteria for inclusion in this review. Both men and women or boy and girl cohorts in rugby union, league, or sevens were included. There were no restrictions placed on the level of competition or age of cohorts used. Studies were excluded from the review if they were

conference abstracts, systematic reviews, thesis dissertations, editorials, expert opinions, letters to an editor, or case studies. Studies were also excluded if they (i) did not examine tackle events separately from other match activities (e.g., the study grouped injurious tackle, ruck and maul events together), (ii) mechanisms and/or factors were not assessed for association with injury, direct head impacts, head accelerations or concussion risk, (iii) injury mechanisms or factors assessed were not within the match (i.e., training load, sleep quality etc), (iv) the assessed tackle events were not within match-play (i.e., lab-based), (v) there were no comparators between the injury risk factors and mechanisms (e.g., injury vs non-injury events or contact location 1 vs contact location 2), and (vi) the study included injury data derived from non-validated secondary sources (e.g., data collection via internet reports).

All citations identified within the initial search were imported into an online database used for managing the screening of abstracts for systematic reviews (Rayyan: https://rayyan.qcri.org). Duplicates were removed from the results of the search, and the resulting studies abstracts were screened independently by two researchers (MH and RJ) against the eligibility criteria. Studies which did not meet the criteria resulted in removal. The remaining studies full texts were then screened against the criteria for inclusion within the review. On first review, 98% of the included or excluded studies were agreed by the two researchers. The disagreements were resolved through discussion between the two researchers, and no further reviewers were needed. The title and authors of the papers reviewed were not masked to the researchers.

Quality Assessment

The lead author (MH) used the Newcastle Ottowa Scale (NOS) for cohort, case-control, and cross-sectional studies to assess the quality of the included studies [39]. The reliability of the NOS for cohort and case-control studies has fair to good inter-rater reliability and validity [40]. This tool was used as it is an appropriate alternative to other available tools to assess risk of bias and could be used across the included study types. The methodological quality of studies was divided into three groups based on the number of stars awarded: *low (0 to 3 stars), moderate* (4 to 6 stars), and *high* (7 to 9 stars) [39]. These ratings were checked for accuracy by a second author (RJ).

Data Extraction

A data extraction table was generated by the lead author, who then extracted the following from the included studies:: *(i) theme one - sample demographic:* sport, cohort type, sample size

(including injury incidence) *(ii) theme two - study methodology:* study aims, study design, injury definition, statistical analysis, injury type, tackle direction, reported limitations *(iii) theme three-research findings:* match-related variables which were significant and associated with injury risk with statistical data. Once complete, the table was reviewed and agreed by the authorship team (MH, RJ, BJ). Each extracted variable was classified and grouped as either an injury risk factor or mechanism. An injury risk factor was defined as any aspect of the tackle situation which modified the risk of injury to the athletes. Examples of risk factors for injury in the tackle include the velocities of the players prior to the contact, the height and direction from which the tackler(s) contacted the ball carrier, and the posture of the tackler(s) and ball carrier at the time of impact [24]. An injury mechanism was determined as how injuries happen within an inciting event [27]. Each injury mechanism was then categorised into phases of the tackle (i.e., pre-contact, contact post-contact [41,42], for ball carrier and tackler injuries. In addition, when extracting the data, the effect measures were reported as either risk ratios (RR), relative risk ratios (RRR), odds ratios (OR), Phi and Cramer's V, Cohen's *d* effect sizes (ES) or as a Gini-index score. The extracted data were cross-checked by another member of the authorship team (RJ).

Part two: Consensus on future research priorities in rugby tackle injury reduction

Expert panel

A group of 181 experts on the tackle were invited to participate, which included 127 males and 54 females. The invited experts included research (i.e., professor, research fellow), sport science (i.e., applied sport scientist, strength, and conditioning coach), medicine (i.e., chief medical officer, team doctor, physiotherapist), governance (i.e., director of rugby), player (i.e., international player) or coaching (i.e., head coach, academy coach) experts. A minimum of ten experts in total were required for reliable results, with greater numbers improving reliability [43]. Experts were considered eligible if they had been a professional within the five years prior to January 2023 in either research, sport science, medicine, governance, coaching, or playing with at least 5 years full-time experience or equivalent. For a player to be included in the expert panel, they must either (1) have been a current international player at the time the invitations to participate were issued or (2) have retired as an international player in the last five years or (3) be a professional player (non-international) actively be involved in sport science or medicine (e.g., PhD candidate, lecturer, medical doctor). All participants were recruited by a purposeful sampling technique [44]. Knowledgeable and experienced

individuals within rugby tackle events were approached from a wide representation of national governing bodies across male and female rugby codes, as well as elite players and practitioners from an international sample.

Round one

A revised version of the results from the systematic review was developed by three of the authors (MH, RJ, BJ). Experts were asked to read the revised version of the results from part one, outlining the injury risk factors and mechanisms that were identified for musculoskeletal injury, concussion, head injury assessment, head impact events and head acceleration events. The revisions were undertaken where needed to describe the direction of risk factors or mechanisms more clearly (i.e., 'high tackler speed' was changed to 'the tackler travelling at high speed is associated with a higher risk of injury during a tackle'). In addition, when appropriate, variables were grouped together if they described the same mechanism (i.e., shortening steps, watching target, straight back etc. were grouped as 'tackle technique'). Online software (Qualtrics, Provo, USA) was used to ask the experts to rate the importance of the injury risk factor increasing the risk of injury using a Likert scale (1: very low; 2: low; 3: medium; 4: high; 5: very high). The Likert ratings were combined (i.e., low = 1 and 2; medium = 3; high = 4 and 5) [45]. Consensus was defined at ≥70% agreement of high importance [46–48]. Experts were asked to provide additional injury risk factors or mechanisms that they believed to be important [37,45], which were subsequently analysed using inductive manifest content analysis [49]. In this type of analysis, researchers observe any patterns of what has been suggested by the expert group and describe what they say [46], staying as true to the expert suggestions as possible. Participants were given two weeks to respond to the questionnaire for each round.

Round two

Experts received the 'expert-identified' tackle injury risk factors and mechanisms [49] along with the descriptive results from round one (i.e., the mean Likert score of the importance of the risk factor and the percentage of responses for each category) for those risk factors upon which the experts had not reached consensus.

After ratings were received, the data were collated. For any 'expert-identified' risk factors and mechanisms that did not achieve consensus, they were redistributed along with their descriptive results for an additional round of ratings. This ensured that *all* risk factors and mechanisms that

did not reach consensus had gone through two rounds of scoring. The percentage of experts that rated each injury risk factor or mechanism as low (1-2), medium (3) and high (4-5) were calculated along with the median rating and the interquartile range of the ratings

The combined 'expert-identified' and 'systematic review' risk factors and mechanisms which reached consensus of high importance during this round were included in round three along with those risk factors that had already reached consensus in round one. At the end of round two all injury risk factors identified from the systematic review and via experts that had not reached a consensus with respect to being 'highly important' were removed.

Round three

Experts received a list of all the injury risk factors and mechanisms that had reached consensus as highly important during rounds one and two. Experts were then asked to rate the feasibility of modifying the risk factor or mechanism via i) law change, ii) coach and player education, iii) training, or iv) other [50] using a Likert scale (1: very low; 2: low; 3: medium; 4: high; 5: very high). 'Law change' was defined as altering the rules and regulations that govern rugby. 'Coach and player education' refers to programs, initiatives and resources designed to enhance the knowledge, skills and understanding of both coaches and players. 'Training' was defined as the preparation of players for physical and mental demands of rugby. The experts were given an opportunity to suggest other interventions that might be appropriate for a specific injury risk factor or mechanism. The percentage of experts that rated each intervention's feasibility as not applicable/low (0-2), medium (3) and high (4-5) were calculated. The median rating and interquartile ranges of the feasibility ratings were also calculated. In addition to this, experts were offered an opportunity to provide details of the interventions they recommended if they rated an intervention a 'high'. Using thematic content analysis, these detailed interventions suggested by the expert group were then summarised by MH and RJ [37,51]. An overview of the Delphi methodology can be found in figure 1.

INSERT FIGURE 1 HERE

Figure 1. An overview of the systematic review and 3 round Delphi methodology

Equity, diversity and inclusion

The author group consisted of two female and eleven male researchers at differing career stages with diverse backgrounds, with the aim to offer different perspectives in all male and female rugby codes at various playing levels. The study included both male and female participants in all rugby codes at different playing levels.

Patient and public involvement

The public was involved in the study's recruitment; the experts recruited for part two could share the recruitment information with others who meet the criteria for the expert panel. There was no other patient or public involvement in the production of this research.

RESULTS

Part one: Systematic review of injury mechanisms and/or risk factors within rugby tackle events

Identification of studies

The systematic literature search found 1173 studies and after screening, 37 studies met the inclusion criteria (figure 2). The descriptive details of each study included in the review are highlighted in supplementary table 1. This also includes the studies which were added from the updated systematic review. In total, 179,482 tackles were analysed in the studies. Of the 37 studies selected for review, eight were from Australia [21,25,52–56], seven from South Africa [23,28,57–61], seven from Ireland [62–67], six from the United Kingdom [22,24,52,68–70], four from Japan [71–74] two from New Zealand [75,76], one from France [77] and one from Canada [78]. There were 27 studies in rugby union [22,28,52,57–59,59,61–64,66–68,72,73,75–77,79,80] and ten in rugby league [21,24,25,53–55,69,81]. No rugby sevens studies were included in the final review. Thirty four studies included men only, two included women only [55,78] and one study included both male and female [82].

INSERT FIGURE 2 HERE

Figure 2. PRISMA flow diagram for the literature selection process for systematic review

Quality Assessment

Of the 37 studies which were included in the final review, 70% (n=26) were rated as 'high quality' and 30% (n=11) were rated 'moderate' quality'. For case-control studies, the most common reason for being downgraded was not ascertaining the exposure (4/22 studies). In the cohort studies, ten of 13 studies were downgraded on the comparability of cohorts based on the design or analysis. The two cross sectional studies were both downgraded for ascertaining the exposure or highlighting confounders within their analysis. The results of the quality assessment can be found in the supplementary table 2.

Study Properties

A summary of the properties of each included study and injury occurrences reported is included in the supplementary table 3. Of the 37 studies, 29 collected data retrospectively from matches and/or training [22–25,28,52,53,55,56,58–62,64,65,68–75,78–80] using video analysis. Eight studies collected data prospectively throughout a season, or over several seasons [21,54,57,66,76,77,81,82]

Twelve studies investigated concussion injuries [23,53,55,58,70,71,73,74,77–80], three investigated head injury assessment (HIA) [56,66,67], and eight included head impact events (HIE) [54,60,62–65,81,83]. One study, which was identified in the updated systematic review, included head acceleration events (HAE) [82]. Eleven included any injury resulting from a tackle [21,22,24,28,52,57,59,61,68,69,75]. One study investigated cervical injuries [80] and one analysed upper body injuries only [71]. Twenty-nine studies included both ball carrier and tackler injuries [21–23,28,52–55,57–63,65,67,67–69,71,73,75,77,79–81], with two analysing tackler injuries only [64,72] and one investigating ball carrier injuries only [24].

The number of concussions/HIAs included in the studies ranged from 10 [23] to 388 [77] and the number of head impact events included ranged from 31 [63] to 1448 [54]. The studies which included head injury assessment had a range from 34 [73] to 464 [79]. Studies which included all musculoskeletal injuries ranged from 28 [75] to 579 [61] injuries. Injury incidence was not reported in seventeen studies [22,24,54,60,62–65,68,69,72,75,78,79,81–83] Concussion was reported per 1000 playing-hours in seven studies [23,58,70,71,77,80,84], ranging from 5.8 - 14.8 [58]. Four studies reported per 1000 tackle events [66,67,74,84]. For all musculoskeletal injury studies, six studies reported per 1000 playing hours [28,57,59,61,80] and ranged between 5.8 to 82 per 1000 playing hours [61,80] and two per 1000 tackle events [21,52], which ranged between 4.6 to 12 per 1000 tackle events.

Different approaches were adopted for the injury definitions within the included studies. For studies which included all injuries, several studies (n=10) used definitions from a consensus statement [85] on injury definitions in rugby union [22,24,57–59,61,69,71,80]. Seven studies used the temporary or permanent removal of the player from the game as the definition for injury [55,62,64–67,76] and one study permitted on-field treatment to be included within the injury sample [63]. Two studies only included an injury if it led to a player missing a subsequent match [52,75]. Broad injury definitions (e.g., any tackling injury sustained by a player) were also used [21,68]. Four concussion or HIA related studies used a ‘clinically diagnosed concussion’ as the injury definition [23,53,74,79]. In addition, two other concussion or HIA related studies used ‘suffered or was suspected to suffer a head impact’[56,72,73]. One concussion related study used the term ‘suspected concussion’ [84]. Suspected concussion is defined using the criteria: 1) the on-field indications for permanent removal from World Rugby's Head Injury Assessment protocol; 2) observable signs from the concussion recognition tool; 3) clear indicators of a concussion from World Rugby's concussion guidance document

and 4) criteria from the 2019 consensus definitions of video signs of concussion in professional sport and has been content validated using experienced clinicians [86]. The display of category 1 concussion symptoms or after being removed from play following a HIA showed category 2 symptoms was also used as a concussion definition in one study [70]. Two studies used wearable sensors with video analysis to confirm a HIE, but no clinically diagnosed injury was used [54,81] with one only using video to confirm the HIE [60]. One study did not report an injury definition [77] .

Risk factors and mechanisms associated with tackle injury.

The initial systematic review found 122 rugby tackle injury risk factors and mechanisms; these were included in the Delphi Poll. A further 16 risk factors and mechanisms were identified via the updated search performed 638 days later but were not included in the Delphi Poll due to the timing of when the systematic review update took place.

Eighty-one (59%) were specific to concussion, HIA or HIE, 52 (38%) were associated with all injury types and five (3%) were associated to musculoskeletal injuries only. Sixteen (11.6%) were categorised as injury risk factors, 40 injury mechanisms (29%) were during the pre-contact phase, 66 injury mechanisms (49%) during the contact phase and 16 injury mechanisms (12%) during post-contact. The injury risk factors and mechanisms found from the review, including the code, study cohort, tackle type or direction and reported association with risk are shown in the supplementary tables 4-6.

Part 2: Consensus on future research priorities in rugby tackle injury prevention

Expert panel

Of the 181 identified experts, 50 (28%) agreed to participate in the study. The participating experts were from multiple nations (United Kingdom n=11, Australia n=13, South Africa n=17, New Zealand n=8, Italy n=1). The expert's roles were categorised into elite player (n=10), sports medicine (n=17), sport science (n=7), coaching (n=11), research/academic (n=4) and governance (n=1). The expert group consisted of 36 men and 14 women; 43 were involved in men's rugby, with 7 involved in women's rugby. 30 experts had a role rugby union, 6 in rugby sevens and 14 in rugby league. The average number of years of experience within their respective roles were 11.9 ± 6.4 years. The response rates for the Delphi poll were 28% (n=50/181; round one), 54% (n=27/50; round two, part one), 34% (n=17/50 round two, part two), 42% (n=21/50; round three).

Consensus on the importance of tackle injury risk factors and mechanisms

In round one, the expert group suggested a total of 38 tackle injury risk factors and mechanisms in addition to those reported in the systematic review (part one). After round two, 26 (16 concussion, 10 musculoskeletal) injury risk factors or mechanisms were rated as high importance with 45 rated as moderate or low importance (table 7a, table 7b and 8). Of the risk factors or mechanisms rated as high importance, 65% were from the systematic review and 35% from expert suggestions. In addition, 33% of the injury risk factors and mechanisms were found to have low importance, of these, 75% were from the literature and 25% were from the expert group. '*The tackler placing their head on the incorrect side of the ball carrier increases the risk of injury'* was rated the highest for concussion related injury mechanism with 100% of the expert group rating it as highly importance. *A physical deficit sustained during the match increases the risk of injury* was the highest rated for musculoskeletal injuries, with 85% of the expert group rating it as high importance.

Table 7a. Ratings of importance for each risk factor or pre-contact mechanism associated with concussion, HIA, HIE following round two of the Delphi poll. Risk factors in bold reached consensus as 'highly important'.

	Median importance (IQR)	Low	Medium	High
Injury Risk Factors				
A player's experience and ability to control their own body during a tackle increases the risk of injury.	**4 (0.0)**	**13%**	**6%**	**81%**
A physical deficit due to an undiagnosed head injury sustained during the match increases the risk of injury during a tackle.	**4 (1.0)**	**11%**	**7%**	**81%**
A fatigued player unable to execute appropriate technique during a tackle increases the risk of injury.	**4 (0.5)**	**15%**	**7%**	**78%**
A fatigued player exhibiting poor decision making during a tackle increases the risk of injury	**4 (0.0)**	**11%**	**11%**	**78%**
A player with limited experience of tackle type selection during match-play increases the risk of injury during a tackle.	**4 (1.0)**	**8%**	**22%**	**70%**
A player who exhibits highly aggressive and/or physical play during a match increases the risk of injury during a match.	3 (1.0)	0%	63%	38%
A player with relatively greater exposure to contact events during a match increases the risk of injury during a tackle.	3 (0.3)	6%	69%	25%
An increase in intensity during a match increases the risk of injury during a tackle.	3 (1.0)	38%	50%	13%
A physical deficit sustained during the match increases the risk of injury during a tackle.	2 (0.9)	63%	31%	6%
The final quarter of a match increases the risk of injury during a tackle.	2 (0.3)	88%	6%	6%
A tackler with low body mass compared to the ball carrier increases the risk of an injury during a tackle.	2 (1.0)	81%	15%	4%
The longer a player is playing in the match, the higher the risk of injury during a tackle.	2 (1.0)	63%	37%	0%
Poor pitch conditions increase the risk of injury to a player during a tackle.	2 (1.0)	81%	19%	0%
A player coming into a match as a substitute, reduces the risk of an injury to that player within a tackle event.	1 (1.0)	96%	4%	0%
Injury Mechanism - Pre-contact				
The tackler or ball carrier not being aware of incoming contact increases the risk of injury during a tackle.	**4 (1.0)**	**4%**	**15%**	**81%**
The ball carrier or tackler travelling at high speed increases the risk of injury during a tackle.	**4 (0.0)**	**7%**	**15%**	**78%**
A tackler's view being obscured prior to contact increases the risk of injury during a tackle.	3 (1.0)	0%	56%	44%

The ball carrier being unbalanced or off their feet prior to contact increases the risk of injury during a tackle.	2 (1.0)	56%	31%	13%
The tackler hesitating prior to contact increases the risk of injury during a tackle event.	3 (1.3)	44%	31%	25%
The ball carrier attempting to evade the tackler with a diagonal run or sidestep increases the risk of injury to the tackler during a tackle.	2 (0.0)	81%	11%	8%

Table 7b. Ratings of importance for each risk factor or contact/post-contact mechanism associated with concussion, HIA, HIE following round two of the Delphi poll. Risk factors in bold reached consensus as ‘highly important’.

Injury Mechanism - Contact				
The tackler placing their head on the incorrect side of the ball carrier increases the risk of injury during a tackle.	**5 (1.0)**	**0%**	**0%**	**100%**
The tackler's head being struck during contact increases the risk of injury to the tackler.	**5 (1.0)**	**0%**	**2%**	**98%**
The ball carrier's head being struck first during contact increases the risk of injury to the ball carrier.	**5 (0.0)**	**0%**	**4%**	**96%**
The tackler shortening their steps, having their head up and forward, keeping their back straight and watching the ball carrier onto their shoulder reduces the risk of injury during a tackle.	**5 (1.0)**	**4%**	**6%**	**90%**
The ball carrier raising their knees and elbows before initial contact increases the risk of injury during a tackle.	**4 (0.3)**	**6%**	**13%**	**81%**
The tackler placing their head in front of the ball carrier increases the risk of injury during a tackle.	**4 (1.0)**	**7%**	**15%**	**78%**
A tackle with high force upon impact increases the risk of injury to the ball carrier and tackler.	**4 (0.5)**	**7%**	**19%**	**74%**
The ball carrier being tackled in the air increases the risk of injury to the ball carrier and tackler.	4 (1.0)	15%	33%	52%
The tackler making contact near the ball carrier's knee increases the risk of injury during a tackle.	3 (2.0)	38%	12%	50%
The ball carrier being tipped in the tackle increases the risk of injury.	3 (1.0)	22%	30%	48%
The tackler making initial contact to the mid or lower trunk/abdomen of the ball carrier reduces the risk of injury during a tackle.	3 (2.0)	37%	19%	44%
Two tacklers' joining at the same time increases the risk of an injury during a tackle event.	3 (1.0)	19%	44%	38%
The ball carrier and tackler's body position being relatively similar increases the risk of injury during a tackle event.	3 (1.3)	25%	38%	38%
The tackler making contact near the ball carrier's hip increases the risk of concussion, head injury assessment or a head acceleration event during a tackle.	3 (1.3)	25%	38%	38%
The ball carrier being tackled from the front increases the risk of injury during a tackle.	3 (2.0)	33%	33%	33%
The tackler making initial contact to the upper leg of the ball carrier reduces the risk of injury to the ball carrier and tackler.	3 (1.5)	37%	37%	26%
More than one tackle joining the tackle event increases the risk of injury during a tackle.	2 (1.0)	63%	25%	13%
The tackler making initial contact to the upper trunk of the ball carrier increases the risk of injury to the ball carrier and tackler.	1 (1.5)	44%	44%	11%

Injury Mechanism - Post-contact				
The ball carrier and tackler sharing head space during the tackle increases the risk of injury	**4 (0.5)**	**15%**	**7%**	**78%**
The tackler's head hitting the ground during the tackle increases the risk of injury to the tackler.	**4 (1.0)**	**8%**	**22%**	**70%**
The tackler stopping pulling/wrapping the ball carrier and losing control of the tackle increases the risk of injury to the tackler.	3 (1.5)	44%	30%	26%

Bold = reached consensus (≥70%); IQR = Interquartile range

Table 8. Ratings of importance for each risk factor or mechanism associated with concussion, HIA, HIE following round two of the Delphi poll.

	Median importance (IQR)	Low	Medium	High
Injury Risk Factors				
A physical deficit sustained during the match increases the risk of injury during a tackle.	**4 (0.0)**	**7%**	**8%**	**85%**
Poor pitch conditions increase the risk of injury to a player during a tackle.	**4 (0.7)**	**6%**	**13%**	**81%**
A tackler or ball carrier with concussion or neck injury symptoms increases the risk of injury during a tackle.	**4 (1.5)**	**8%**	**22%**	**70%**
The tackler or ball carrier being involved in significantly more tackles compared to normal increases risk of injury during a tackle event.	3 (0.9)	37%	48%	15%
A turfed pitch increases the risk of injury during a tackle event.	2 (1.3)	75%	19%	6%
A tackle occurring in the fourth quarter compared to the first increases the risk to the tackler.	2 (0.8)	81%	11%	8%
Injury Mechanism - Pre-contact				
The ball carrier being aware of the incoming contact reduced the risk of injury to the ball carrier.	**4 (1.1)**	**15%**	**11%**	**74%**
The ball carrier or tackler travelling at high speed increases the risk of injury during a tackle.	4 (1.0)	14%	30%	56%
The tackler did not have sufficient time to face forward at the offside line increases the risk of injury during a tackle.	3 (1.1)	33%	44%	23%
The ball carrier protecting the ball during contact reduces the risk of injury during a tackle.	2 (1.1)	70%	22%	8%
Injury Mechanism - Contact				
The tackler twisting the ball carrier's legs when bringing the tackler to ground increases the risk of injury to the ball carrier during a tackle.	**4 (1.0)**	**4%**	**15%**	**81%**
The tackler not using their arms after initial contact increases the risk of injury during a tackle.	**4 (1.0)**	**19%**	**11%**	**70%**
The tackler shortening their steps, having their head up and forward, keeping their back straight and watching the ball carrier onto their shoulder reduces the risk of injury during a tackle.	**4 (2.0)**	**16%**	**14%**	**70%**
A tackler extending their arm and abducting/raising increases the risk of injury during a tackle.	**4 (1.0)**	**15%**	**15%**	**70%**
The tackler placing their head on the incorrect side of the ball carrier increases the risk of injury during a tackle.	4 (1.0)	6%	31%	63%
The tackler tackling the ball carrier with high impact force increases the risk of injury during a tackle.	4 (0.9)	15%	26%	59%
The tackler using their own body weight to bring the ball carrier to ground increases the risk of injury to the ball carrier during a tackle.	4 (0.9)	4%	44%	52%
A tackler tackling near the ball carrier knee increases the risk of injury during a tackle.	3 (2.0)	44%	25%	31%
The tackler moving from an upright to low position before contacting the ball carrier reduces the risk of injury during a tackle.	3 (1.1)	29%	41%	30%

The tackler making initial contact with their shoulder or arm reduces the risk of injury to the tackler during a tackle.	2 (0.8)	70%	22%	8%
Injury Mechanism - Post-contact				
A player landing with an abducted/horizontally abducted and externally rotated arm increases the risk of injury to that player during the tackle.	**4 (1.0)**	**0%**	**22%**	**78%**
The tackler loading their weight on the ball carrier at shoulder level	**4 (0.3)**	**13%**	**13%**	**75%**
The second, third or fourth tackler joining the tackle via the ball carrier legs or spine increases the risk of injury to the ball carrier.	4 (1.0)	19%	19%	63%
The tackler's head hitting the ground during the tackle increases the risk of injury to the tackler.	2 (1.0)	56%	26%	18%
The tackler extending the arms, wrapping, and then pulling the ball carrier reduces the risk of injury during a tackle.	3 (1.0)	33%	48%	19%
The ball carrier performing a fend reduces the risk of injury to the ball carrier during a tackle.	2 (1.2)	70%	15%	15%
Two tacklers' joining the tackle at the same time increases the risk of an injury during a tackle event.	2 (0.3)	81%	13%	6%
More than one tackler joining the tackle event increases the risk of injury during a tackle.	2 (1.0)	63%	31%	6%
The tackler looking down when contacting the ball carrier increases the risk of injury during a tackle event.	3 (1.0)	38%	56%	6%
A player landing on their back increases the risk of injury during a tackle.	2 (1.0)	94%	6%	0%

Bold = reached consensus (≥70%); IQR = Interquartile range

Consensus on the feasibility of managing tackle injury risk factors and mechanisms.

The results for feasibility ratings of whether the risk factor or mechanism could be managed by law change, coach or player education and training are provided in figure 3 and figure 4. Of the 26 risk factors or mechanisms presented to the panel, eight were found to be highly feasible for change by law change (2), coach and player education (3) or training (3). Five were specific to concussion, HIA or HIE and three for musculoskeletal injuries. Of the risk factors and mechanisms deemed highly feasible, 75% were from the literature and 25% from expert recommendation. For the highly important and feasible injury risk factors and mechanisms, ten recommendations were described by the experts, and can be found in table 9.

INSERT FIGURE 3 HERE

Figure 3. Importance and feasibility ratings for each musculoskeletal injury risk factor and mechanism found to be important during round two. Likert scale was interpreted as: *Low = 1-2*; *Medium = 3*; or *High = 4 or 5*. *= reached consensus (≥70%).

**INSERT FIGURE 4 HERE*

Figure 4. Importance and feasibility ratings for concussion/HIA/HIE injury risk factors and mechanisms found to be important during round two. Likert scale rating was interpreted as: *Low = 1-2*; *Medium = 3*; or *High = 4 or 5*. *= reached consensus (≥70%)

Table 9. Highly feasible interventions recommended by expert group during round three for injury risk factors and mechanisms deemed important for injury.

Risk factor/mechanism	Intervention	Expert Recommendation
Musculoskeletal - Risk Factor		
A tackler or ball carrier with concussion or neck injury symptoms increases the risk of injury during a tackle	Coach and player education	• Compulsory and continual education on identifying these injuries for players, coaches, referees, and medical team at all levels.
Musculoskeletal – Contact Phase		
The tackler not using their arms after initial contact increases the risk of injury during a tackle.	Coach and player education	• Compulsory and continued coach and player education on tackle technique in the form of 'tackle school'.
Musculoskeletal and Concussion/HIA/HIE – Contact Phase		
The tackler shortening their steps, having their head up and forward, keeping their back straight and watching the ball carrier onto their shoulder reduces the risk of injury during a tackle.	Training	• Tackle school for players. • Specific conditioning for tackling.
Concussion/HIA/HIE – Contact Phase		
The tackler placing their head in front of the ball carrier increases the risk of injury during a tackle.	Training	• Tackle school for players.
The ball carrier's head being struck first during contact increases the risk of injury to the ball carrier.	Law Change	• Law not allowing the ball carrier to drop their head below their hips when entering the tackle.
The ball carrier raising their knees and elbows before initial contact increases the risk of injury during a tackle.	Law Change	• Sanctions for the ball carrier for knee lifting into a tackle. • Sanctions for the ball carrier for going into the tackle with a low body position.
The tackler placing their head on the incorrect side of the ball carrier increases the risk of injury during a tackle	Coach and player education	• Educational tools for coaches and players, online resources, infographics, and new training manuals.
	Training	• Tackle technique school for players.

DISCUSSION

Based on our systematic review, a range of risk factors and mechanisms were associated with an injurious tackle event, head impact, head injury assessment or head acceleration. The range of risk factors and mechanisms highlights the complexity of the rugby tackle and the challenges with modifying behaviours to prevent injury. From the risk factors and mechanisms identified, less than 20% were deemed of 'high importance' by the expert panel. Of those, a consensus on feasible interventions was achieved for eight, resulting in nine feasible intervention strategies. Seven mechanisms were from the contact phase, suggesting that technique related variables are the most feasible to modify. The results of this study can guide injury prevention initiatives in rugby by targeting the risk factors identified by the expert panel – particularly the highly feasible ones. Current coach and player educational resources focusing on technique (e.g., Tackle Ready) should be evaluated to see whether they incorporate the risk factors highlighted. Further, how effective these interventions are at modifying risk factors and mechanisms should be empirically assessed. Also, only two studies were within women's rugby, highlighting a clear need for further research in this area.

Tackle injury events occur frequently [1,8,11], and a large number of risk factors and mechanisms are associated with these events. The greatest number of injury risk factors and mechanisms were found to be specific to concussion, HIA, HIE or HAE. This is unsurprising given the drive to reduce head injury risk [88,89]. The validation and use of instrumented mouthguards to quantify head acceleration will further drive this research area [90,91]. Of the 138 injury risk factors or mechanisms found in the literature, 51% were in the contact phase of the tackle. This could indicate that preventive interventions should be focussed in this area. However, given 49% of the risk factors and mechanisms were from outside the contact phase provides insight into the diverse risks associated with the tackle event [60,73]. The tackle is a complex event and failure to execute certain techniques preceding contact likely increases injury risk [60]. Therefore, training the tackle can occur without having to make physical contact, and this should be considered when developing training programmes [92].

During part two, head placement of the tackler and other key technical aspects for making a tackle (shortening steps, head up and forward, back straight and watching the ball carriers onto their shoulder, wrapping arms after contact) were rated as an important mechanism for concussion, HIA or HIE and musculoskeletal injury, with 'training' along with 'coach and player education' being highly feasible interventions. Optimising tackler head placement is an

important tackling technique to reduce concussion risk [38,72,93] and experts recommended that players should take part in ‘tackle schools’ to improve and/or maintain tackle skill. World Rugby’s Tackle Ready programme [94] attempts to address a number of important mechanisms which are found within the study. “Tracking”, “preparation”, “connection”, “acceleration”, and “finish” are key stages within the programme, with additional neck strengthening and ‘head reaction’ exercises also recommended. While the programme provides example drills to train tackling, [92] coaches should be cognisant of the dynamic and complex nature of the tackle [30,38], and the importance skills transferring to matches [92].

A coaching intervention programme has been implemented by World Rugby since 2021, with the aim to reduce the number of tackles with head contact. Players who have been penalised for dangerous high tackles are invited to the programme and, at the time of writing, 120 rugby players have been through the programme. For those that have completed the programme, 94% have not been penalised again [95]. This suggests it is important that ‘tackle schools’ are available for all coaches and players within rugby [96]. Currently, this is only available for through the referral process on the programme; given its efficacy, making a coaching intervention of this nature more widely available for community level players and coaches may be highly beneficial. Additionally, the experts suggest that the use of educational tools, new training materials and tackle conditioning programmes would be valuable. Coaches in men’s and women’s rugby acknowledge the risk of injury in the tackle, however they only typically spend a small amount time developing the skill or do not provide effective drills which reflect match tackle conditions [97–99]. A coach’s training behaviour is related to how competent they believe they are in delivering certain skill sessions in training [97,100]. Currently, the BokSmart [101], RugbySmart [102] and Tackle Ready [94] programmes provide free, online injury prevention resources for men’s rugby coaches to build a degree of competence in training the tackle. Recent studies in women's and men’s’ rugby union revealed modest adoption of Tackle Ready and Rugby Smart recommended tackle techniques, with average adoption of 47% and 58% during match-play, respectively [99,103]. Also, current programmes are only underpinned by men’s rugby research [104,105], therefore an immediate focus for governing bodies should be to develop an evidence-base to inform tackle programmes in women’s rugby. Research should also continue to develop an understanding of the barriers influencing end-user uptake of available tackle training resources.

Law change was a highly feasible intervention to reduce the risk of injury to both the tackler and ball carrier. The experts recommended that sanctioning the ball carrier for lifting their knees into a tackle would be effective to reduce injury risk. Furthermore, sanctioning the ball carrier for dropping their body into a low position prior to contact was suggested as a potentially effective intervention. This would naturally encourage ball carriers to enter the tackle in a more upright position, resulting in a more exposed 'target' area for tacklers such as upper and lower trunk [65]. Plausibly, a tackler is less likely to make direct head on knee contact when the ball carrier is in an upright position. Contrary to the expert recommendation, studies have found HIA propensity is greater when both tackler and ball carrier are upright before entering the tackle, and propensity was at its lowest when the tackler and ball carrier were bent at the waist [67,83]. While promoting bent at the waist body positions of the tackler and ball carrier is possible [67], 'extreme' bent at the waist positions (i.e., head dropping below their hips) of the ball carrier may make it challenging for tacklers to target the safer body regions. As a consequence, tacklers could then compromise important technical aspects such as head position [73].

The only risk factor that was recognised as important for musculoskeletal injury, which also had a highly feasible intervention was 'a player with concussion or neck injury symptoms continuing to play'. The expert group rated coach and player education as a highly feasible intervention strategy to reduce the occurrence of this risk factor. The experts recommended that all appropriate stakeholders should attend compulsory and continual education on identifying these injuries during matches at all levels, such as HEADCASE [106]. At the elite level, a comprehensive HIA process is undertaken for any players showing clear signs of concussion using video review and concussion assessment via a qualified medical professional [62]. As this support is unlikely available at the amateur level, it is critical that coaches, referees, players, any medical support staff, and spectators assume some level of responsibility for concussion identification, such as the Blue Card Protocol [108]. It is recommended that all those involved in amateur rugby should access educational resources such as concussion recognition tools [110] and concussion guidelines for non-medical professionals. Governing bodies should continue to promote and provide various educational resources, including attendance-based workshop to identify and manage concussion in community and youth settings.

Whilst evidence from the systematic review showed risk factors and mechanisms presented to experts were significantly associated with either an increase or decrease in injury risk, experts did not perceive all of them as being 'important'. Indeed, 33% of all the injury risk factors and mechanisms presented were agreed to have 'low' importance for tackle injury risk, with 45% of those being risk factors and 55% being mechanisms. In addition, some risk factors and mechanisms that did not reach consensus of 'high' importance are often incorporated into governing body tackle safety guidelines such as Tackle Ready [94]. An example of one such mechanism is '*the tackler moving from an upright to low position before contacting the ball carrier reduces the risk of injury during a tackle',* which only 30% of the experts believed to be 'highly important'. World Rugby guidelines suggests tacklers that drop their height early may be in a less effective position to make a tackle [94], and have a higher likelihood to place their head in the wrong position [70]. Tackle Ready also highlights the importance of timing when a player moves into a lower position to make the tackle, which has been found as an important mechanism of concussion injury in rugby league [70]. Therefore, a possible explanation for why the 'upright to low' mechanism was not found to be of 'high' importance may be related to timing.

Limitations

The Delphi part of the study was informed by the initial findings of the review, and not the updated search, and this can be considered a limitation. The review also focused on injury factors and mechanisms assessed within a match. As such, physical and training-related risk factors (e.g., muscular strength, player fatigue) that may be associated with injury have been excluded. The expert opinion group consisted of 50 participants, with a response rate of 28%.

Research and Policy Implications

Overall, this review consolidates the current match-related risk factors and mechanisms associated with tackle-related injuries. Whilst the contact phase can be considered the most important part of the tackle, there was an almost even split of risk factors and mechanisms from within and outside the contact phase of the tackle. The results of the Delphi present potential targets for intervention based on expert consensus. Of the 26 risk factors or mechanisms that achieved consensus for being important, only nine interventions achieved consensuses on how the risk factor or mechanism could be modified. Seven of these were during the contact phase,

all of which were related to tackle technique and training, and coach education was rated as the most common method to modify risk [30,111]. The results of this study can be combined with socioecological and implementation frameworks to design and optimise tackle training interventions.

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Data sharing statement

All data relevant to the study are included in the article or uploaded as supplementary information.

Competing interests

BJ is employed in a consultancy capacity by the Rugby Football League and Premiership Rugby. SH is an associated editor of the British Journal of Sports Medicine. JP is an editor of the British Journal of Sports Medicine, a member of the World Rugby Concussion Advisory Group, the NFL head, neck and spine committee and the UEFA concussion advisory committee. JP is also an independent concussion consultant for World Rugby, a medical consultant to South African Rugby, co-chair of the scientific committee for the 6th international conference on concussion in sport, a board member of the concussion in sport group and received sponsorship support for schools' concussion programme from NeuroFlex® and Your Brain Health. GT has previously received funding and consultancy work for World Rugby. AG has a clinical practice in neuropsychology involving individuals who have sustained sport-related concussion. He has been a contracted concussion consultant to Rugby Australia. He is a member of the World Rugby Concussion Working Group, and a member of the Australian Football League Concussion Scientific Advisory Committee. He has received travel funding or been reimbursed by professional sporting bodies, and commercial organisations for discussing or presenting sport-related concussion research at meetings, scientific conferences, workshops, and symposiums. Previous grant funding includes 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 is currently supported by a National Health and

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Guarantor

Mike Hopkinson

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Supplemental material

The data extracted during the systematic review, along with the importance rating have been provided within the supplementary material.

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