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SPORTS PERFORMANCE



# An investigation into the relationships between technical collision behaviours and physical characteristics in world-class, international female rugby players

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**ABSTRACT**

This study first investigated how the probability of winning collision events is affected by technical characteristics among world-class, international female rugby union players, and second, whether enhanced performance of these technical characteristics was related to physical attributes. Carry and tackle events from 16 international matches played by a top-two world ranking team were coded according to technical characteristics and performance outcomes. Binary classification tree models revealed that carry performance was successfully predicted ($p < 0.01$) by combinations of the variables: carrier velocity at the line, change of direction and straightening angle, leg drive, body mass and system mass (carrier combined with assistance from team-mate(s)). Tackle performance was predicted by combinations of the variables: initial line-speed, tackle direction, tackle type, collision zone entry, body mass, system mass, arm use and leg drive. Cumulative link mixed effects models subsequently revealed that performance increases of ~2% in single-leg isometric squat, counter-movement jump, bench press, single-leg drop jump, 10 m acceleration momentum and velocity, and skinfolds and body mass; were associated with increasing and decreasing likelihoods of superior technical performance, depending on the investigated variable. These findings may increase the precision of practices, physical training and assessment methods, among elite-standard female rugby union players.

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Women; physical fitness; team sport; collision

## Introduction

The ability to defend or breach the "gain-line" is critical for making territorial gains in rugby union matches and is underpinned by the ability to win attacking and defensive collisions (Bennett et al., 2019; Gaviglio et al., 2014; Hughes et al., 2017; Sella et al., 2019). Indeed, gross collision outcomes, such as tackle breaks, metres made per carry, offloads, defenders beaten and tackle completion, are directly associated with winning performance in male and female rugby (Bennett et al., 2019, Bremner et al., 2013; Callinan et al., 2024; Gaviglio et al., 2013; Nicholls et al., 2023; Scott et al., 2023; Sella et al., 2019; van Rooyen et al., 2014). The technical characteristics of collision events in rugby union are highly variable depending on the tactical context of the event (Dane et al., 2024, Sayers & Washington King, 2005; Sewry et al., 2015), which may explain why these gross collision performance outcomes are associated with a variety of contrasting technical behaviours and are not exclusively associated with a specific technical model (Sayers & Washington King, 2005; Wheeler et al., 2010). For example, the likelihood of a tackle break is increased if ball carriers can create one-on-one scenarios and use footwork and fending in advance of the collision (Hendricks et al., 2013, Sayers & Washington King, 2005; Wheeler et al., 2010). In contrast, straight running lines and receiving the ball at high speed are similarly associated with positive breakdown outcomes and tackle breaks, respectively (Wheeler et al., 2010). In defence, territorial gains are associated with fast line speeds and being square to the attacker (Hendricks et al., 2013) and the likelihood of offloads or tackle breaks is reduced by tackling with the shoulder compared to the arm, and leg driving after contact (Hendricks et al., 2014). These investigations are highly informative for coaches in developing collision performance enhancement strategies because they highlight the specific technical collision behaviours that should be practiced to facilitate collision perform. Such investigations of the direct mechanistic link between technical characteristics of collision events and successful gross collision performance outcomes have, however, been overshadowed more recently by research into their mechanistic links with injury, and specifically concussion (Dane et al., 2024; Hopkinson et al., 2022; Lang et al., 2024; Shill et al., 2024). This is particularly true among elite females, for whom the association between technical collision behaviours and gross collision performance outcomes has not been thoroughly investigated. It is therefore recommended that further research is undertaken in this area to inform collision performance development strategies among rugby coaches who support elite standard female rugby union players.

Superior physical characteristics such as upper- and lower-body strength, power output, lean mass, and sprint momentum underpin gross collision performance "outcomes", such as

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dominant carries and tackle frequency, in both male and female rugby (Cunningham et al., 2016; Gabbett, 2011; Redman et al., 2022; Speranza et al., 2015; Woodhouse et al., 2022). The interaction between physical characteristics and the specific technical "behaviours" within successful collision events has also been explored, although these investigations are sparse in male rugby (Redman et al., 2022; Speranza et al., 2017) and do not exist in female rugby. However, the consideration of tactical context in these investigations is limited to the analysis of forwards and backs position groups. It has subsequently been shown that collision behaviours differ significantly between discrete positions in elite standard female rugby union (Woodhouse et al., 2021) presumably because of the variation in tactical context discussed in the earlier paragraphs. Therefore, a more sophisticated understanding of how specific physical characteristics underpin critical technical collision behaviours, which are governed by tactical context, will enhance the specificity of collision preparation practices among rugby practitioners.

Based on the above reasoning, we conducted a novel two-stage analysis of a world-class, international female rugby union squad's matches, across a three-year period, to understand the technical and physical attributes associated with successful ball-carrying and tackling. First, we used binary classification trees to identify which technical characteristics were associated with successful carry and tackle performance outcomes in the specific tactical context of carry and tackle events. Second, we used cumulative link mixed effects models to identify which physical characteristics were associated with these technical characteristics among international female rugby union players.

## Methods

### *Stage 1: Match analysis of technical collision characteristics*

Following institutional ethical approval (SMEC_2018-19_057), 16 senior international women's matches played by a top 2 world ranked team between 2018 and 2021 were analysed (438 individual player performances, mean and SD matches per player; $9 \pm 4$). To account for the increased physical intensity that has been observed when competing against superior opposition in elite-standard female rugby union (Woodhouse et al., 2021), only matches played against opposition teams with a world ranking of five and above at the time of competition were analysed. The number of matches played against different top 5 teams was mean and SD $4 \pm 1$. All matches were sampled from competitive international female competitions or test match windows within Europe and North America (women's super-series $n = 10$, women's six nations $n = 4$, women's test matches $n = 2$). Prior to the analysis, coding templates for both tackle and carry performance were built within performance analysis software (Longomatch 1.10.26). Carries and tackles were divided into seven specific classifications (modified from Wheeler et al., 2010; Table 1).

The specific technical characteristics of each tackle and carry were selected based on prior published evidence and the opinion of eight elite-standard rugby coaches and performance analysts (Table 2). The coaches and analysts were provided with definitions and visual examples of each carry and tackle category and were requested to list the technical components they believed most strongly underpinned successful and unsuccessful outcomes, the definitions of which were also provided (Table 2). These outcome variables included: collision, post-contact metres, territory and result, which were classified using a binary score of win or loss. The definitions and coding criteria for each variable are shown in Table 2. All tackles and carries were coded from each match by an expert performance analyst (PA) with over five years' experience in elite standard rugby union. This amounted to 1,603 tackles ($n = 102 \pm 27$ per match) and 1,764 carries ($n = 112 \pm 29$ per match). To increase the validity and reliability of coding, the number of matches analysed per day was restricted to a maximum of one, and coding sessions were restricted to a maximum duration of two hours, with a minimum of one hour rest between sessions (Bloomfield et al., 2004; Eaves et al., 2005; Wheeler et al., 2010). Following the analysis of the 16 matches, the first match that was analysed was re-coded to calculate coder reliability using Cohen's kappa statistic, which was classed as excellent (>0.8) (McHugh, 2012) for all coded carry and tackle variables. Spaces and errors were removed from the data in Microsoft Excel, before filtering according to carry type. Second order metrics,

Table 1. Carry and tackle type definition criteria (modified from Wheeler et al., 2010).

| Carry and Tackle Type | Definition |
|---|---|
| Immediate | Origin: breakdown, scrum or lineout<br>Passes from origin: none<br>Defensive line: unbroken |
| Close | Origin: breakdown, scrum or lineout<br>Passes from origin: one<br>Defensive line: unbroken |
| Middle | Origin: breakdown, scrum or lineout<br>Passes from origin: two<br>Defensive line: unbroken |
| Wide | Origin: breakdown, scrum or lineout<br>Passes from origin: more than two<br>Defensive line: unbroken |
| Kick off and counter-attack | Origin: kick receipt/chase or pass from kick receipt<br>Passes from origin: zero to two<br>Defensive line: unbroken |
| Open play | Origin: carry or tackle after clean break or offload<br>Passes from origin: zero and greater<br>Defensive line: broken |

**Table 2.** Definitions of technical collision characteristics.

| | | Source | Tackle Coding Definition | Carry Coding Definition |
|---|---|---|---|---|
| Outcome KPIs | Collision | McKenzie et al. (1989) | **Win/Neutral**: From point of contact, ball carrier travels towards own try line or does not progress in either direction<br>**Loss/Neutral**: From point of contact, ball carrier travels towards tackler try line | **Win**: From point of contact, ball carrier travels towards tackler try line<br>**Loss/Neutral**: From point of contact, ball carrier travels towards own try line or does not progress in either direction |
| | Post-contact metres | Bennett et al. (2019), Watson et al. (2017) | **Win**: Tackler drives carrier back >1 m towards opposition try line from point of initial contact<br>**Loss/Neutral**: Carrier advances > 1m towards tackler try line from point of contact | **Win**: Carrier advances >1 m towards tackler try line from point of contact<br>**Loss/Neutral**: Tackler drives carrier back >1 m towards opposition try line from point of initial contact |
| | Territory | Hendricks et al. (2013) | **Win**: Tackle is completed in front of the gain-line<br>**Loss/Neutral**: Tackle is completed behind or on the gain-line | **Win**: Carrier is tackled behind the gain-line<br>**Loss/Neutral**: Carrier is tackled in front or on the gain-line |
| | Result | Bennett et al. (2019), Hollander et al. (2016), Wheeler et al. (2010), Sella et al. (2019) | **Incomplete**: Carrier breaks the line or offloads in the tackle<br>**Complete**: Tackle results in a breakdown | **Incomplete**: Carrier breaks the line or offloads in the tackle<br>**Complete**: Tackle results in a breakdown |
| Technical Variables | Initial defensive line-speed | Hollander et al. (2016) | **Fast**: Tackler accelerates maximally when ball leaves ruck<br>**Medium**: Tackler jogs when the ball leaves the ruck<br>**Slow**: Tackler is stationary or walks when ball leaves ruck | **Fast**: Tackler accelerates maximally when ball leaves ruck<br>**Medium**: Tackler jogs when the ball leaves the ruck<br>**Slow**: Tackler is stationary or walks when ball leaves ruck |
| | Carry reception velocity | Hollander et al. (2016), Wheeler et al. (2010) | **N/A** | **Fast**: Ball carrier running, sprinting or accelerating maximally at ball reception<br>**Medium**: Ball carrier jogging or cruising at ball reception<br>**Slow**: Ball carrier stationary or walking at ball reception |
| | Carry velocity at line | Hollander et al. (2016), Wheeler et al. (2010) | **N/A** | **Fast**: Ball carrier running, sprinting or accelerating maximally at point of meeting defensive line<br>**Medium**: Ball carrier jogging or cruising at point of meeting defensive line<br>**Slow**: Ball carrier stationary or walking at point of meeting defensive line |
| | Velocity at line vs. line-speed | Hendricks et al. (2014) | **N/A** | **Carrier**: Carrier velocity at line > defensive line-speed<br>**Neutral**: Carrier velocity at line is equal to defensive line-speed<br>**Tackler**: Carrier velocity at line < defensive line-speed |
| | Reception velocity vs. Line-speed | | **N/A** | **Carrier**: Carrier velocity at ball reception > defensive line-speed<br>**Tackler**: Carrier velocity at ball reception < defensive line-speed<br>**Neutral**: Carrier velocity at ball reception is equal to defensive line-speed |
| | Distance from carrier/ defence at reception | Hollander et al. (2016), Wheeler et al. (2010) | **Close**: Tackler <1 body length of carrier at ball reception<br>**Near**: Tackler 1–2 body lengths away from carrier at ball reception<br>**Far**: Tackler > 2 body lengths away from carrier at ball reception | **Close**: Carrier <1 body length of tackler at ball reception<br>**Near**: Carrier 1 to 2 body lengths away from tackler at ball reception<br>**Far**: Carrier >2 body lengths away from tackler at ball reception |
| | Pre-contact agility | Sewry et al. (2015), Wheeler et al. (2010) | **N/A** | **Side-step**: Ball carrier changes direction on outside leg to breakdown<br>**Cross-over**: Ball carrier changes direction on inside leg to breakdown<br>**Straight**: Ball carrier runs straight at the defensive line |
| | Change of direction angle | Wheeler et al. (2010) | **N/A** | **Great**: Change of direction angle is <20°<br>**Moderate**: Change of direction angle is between 20 and 60°<br>**Slight**: Change of direction angle is >60° |
| | Straightening angle | Wheeler et al. (2010) | **N/A** | **Great**: Straightening angle after direction change is <20°<br>**Moderate**: Straightening angle after direction change is between 20 and 60°<br>**Slight**: Straightening angle after direction change is >60° |

(*Continued*)

Table 2. (Continued).

| | Source | Tackle Coding Definition | Carry Coding Definition |
|---|---|---|---|
| Collision zone entry | Gabbett (2011), Hendricks et al. (2010), Hendricks et al. (2014) | **Accelerate Optimal**: Pre-impact, tackler is moving forward, with COM in front of BOS, hitting with shoulder<br>**Accelerate Upright**: Pre-impact, tackler is moving forward, in upright position, hitting with chest or arms<br>**Static Optimal**: Pre-impact, tackler is static, with COM in front of BOS, hitting with shoulder<br>**Passive Absorb**: Pre-impact, tackler is static, with COM over or behind BOS, and concedes metres passively in the tackle | **N/A** |
| Tackle direction | Gabbett (2011), Hendricks et al. (2018) | **Front**: Tackler enters collision zone front on to carrier<br>**Oblique**: Tackler enters collision zone at an angle<br>**Side/Behind**: Tackler enters collision zone from the side or behind | **N/A** |
| Body height | Wheeler and Sayers (2009) | **Upright**: Tackler is upright with knees and hips extended<br>**Medium**: Knees and hips are slightly flexed; chest higher than hips<br>**Low**: Knees and hips are flexed; chest is level or lower than hips | **Upright**: Carrier is upright with knees and hips extended<br>**Medium**: Knees and hips are slightly flexed; chest higher than hips<br>**Low**: Knees and hips are flexed; chest is level or lower than hips |
| Fend | Hendricks et al. (2014), Hendricks et al. (2018), Wheeler and Sayers (2009) | **N/A** | **Strong**: Carrier demonstrates an active, strong fend<br>**Weak**: Carrier demonstrates a weak, passive fend<br>**Absent**: Carrier demonstrates no fend |
| Tackle type | Gabbett (2011), Hendricks et al. (2014), Sewry et al. (2015) Wheeler et al (2009). | **Shoulder**: Tackler uses shoulder to make initial contact with carrier<br>**Smother**: Tackler uses chest to make initial contact with carrier<br>**Collision**: Tackler does not use arms in the tackle<br>**Arm/Jersey**: Tackler uses arms to make initial contact, or grabs the jersey of the carrier | **N/A** |
| Hit point | Gabbett (2011), Hendricks et al. (2014), Wheeler and Sayers (2009) | **Legs**: Tackler makes contact between carrier's hips and ankles<br>**Mid Torso**: Tackler makes contact between carrier's hip<br>**Shoulder/Arm**: Tackler makes contact with the carrier's shoulder or arm<br>**Head/Neck**: Tackler makes contact with the carrier's head or neck | **N/A** |
| Arm use | Sewry et al. (2015), Hendricks et al. (2014) | **Strong Wrap and Pull**: Tackler wraps arms and does not release grip or slide lower down tackler's body than initial wrap height<br>**Weak Wrap and Pull**: Tackler wraps arms but releases grip and/or slides lower down tackler's body than initial wrap height<br>**No Wrap and Pull**: Tackler does not wrap arms | **N/A** |
| Mass | Hendricks et al. (2014) | **Advantage**: Primary tackler is visibly larger than primary carrier<br>**Neutral**: Primary tackler and carrier are of similar size<br>**Disadvantage**: Primary carrier is visibly larger than primary tackler | **Advantage**: Primary carrier is visibly larger than primary tackler<br>**Neutral**: Primary tackler and carrier are of similar size<br>**Disadvantage**: Primary tackler is visibly larger than primary carrier |
| Assistance | | **Many**: Two or more additional tacklers assist the primary tackler immediately following the initial collision with the carrier<br>**Double**: One additional tackler hits the carrier immediately following the initial collision with the primary tackler<br>**Single**: The primary tackler is not assisted in stopping the carrier | **Many**: The carrier is assisted by two or more team mates immediately following the initial collision with the primary tackler<br>**Double**: The carrier is assisted by one team mate immediately following the initial collision with the primary tackler<br>**Single**: The carrier is not assisted in carrying past the tackler |
| System mass | | **Advantage**: Tackler + assistance > carrier + assistance<br>**Neutral**: Tackler + assistance is equal to carrier + assistance<br>**Disadvantage**: Tackler + assistance < carrier + assistance | **Advantage**: Carrier + assistance > tackler + assistance<br>**Neutral**: Carrier + assistance is equal to tackler + assistance<br>**Disadvantage**: Carrier + assistance < tackler + assistance |
| Leg drive | Sewry et al. (2015), Hendricks et al. (2014) | **Strong**: Tackler takes > 2 driving steps following the collision<br>**Moderate**: Tackler takes 1–2 driving steps following the collision<br>**Absent**: Tackler takes no driving steps following the collision | **Strong**: Carrier takes >2 driving steps following the collision<br>**Moderate**: Carrier takes 1–2 driving steps following the collision<br>**Absent**: Carrier takes no driving steps following the collision |

Abbreviations: COM = centre of mass, BOS = base of support, ≥ greater than, ≤ less than.

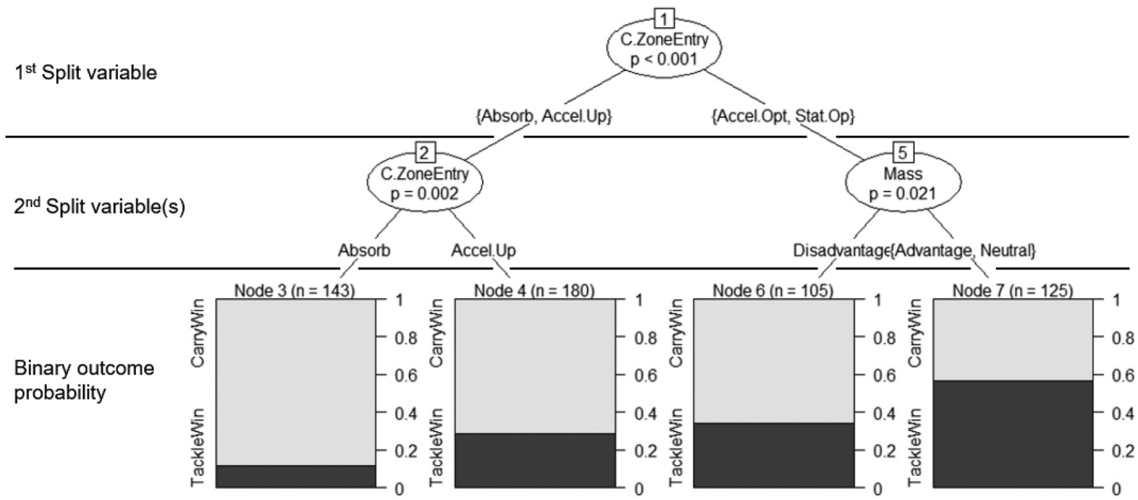


Figure 1. An example of a binary classification tree structure for the prediction of post-contact metres during close tackle events. Abbreviations: C.Zone Entry = Collision zone entry, Accel Up = Accelerate upright, Accel Opt = Accelerate optimal, Stat Op = Static optimal.

which were derived from a comparison between two other variables (such as velocity at the line vs. line-speed), were also calculated at this stage.

### *Stage 1: Statistical analysis*

To determine which technical variables increased the probability of successful outcomes in carry and tackle events, binary classification analysis was undertaken using statistical analysis software (RStudio, version 1.4.1106, package party). Raw categorical data for all variables were converted into factors and partitioned into training (70%) and testing (30%) data sets, and bar-plots were used to visualise the distribution of the outcome classes.

Binary classification trees were built using the training data set, with outcome and technical variables entered as dependent and independent variables, respectively. To reduce the risk of type 1 error and to increase the interpretability of the outcomes through reduced tree complexity, an alpha level of 0.01 was integrated into each model. Models were created to investigate the fixed effects of pre- and post-collision variables on collision and post-contact metres outcomes and to investigate the fixed effects of all variables on territory and result outcomes. Individual was entered as a random factor within the models to account for repeated measures. Sensitivity of the target binary class (e.g., tackle or carry win) and overall model accuracy were calculated using confusion matrix and receiver operating characteristic (ROC) curves, with an acceptance threshold set at 70% (Hosmer & Lemishow, 2000). The binary outcome classes for carry and tackles are typically imbalanced in rugby union (Wheeler & Sayers, 2009). Therefore, to optimise the accuracy of the analysis and avoid degradation of the sample, training data sets producing predictive models with a sensitivity less than 70% (Hosmer & Lemishow, 2000) (see below) were balanced using classification analysis (*R package Rose*). The balanced data sets were then re-entered into the predictive model. An example of a binary classification tree for the visualisation of model structure is depicted in Figure 1.

## Stage 1: Results

For stage 1 of the analysis, 17 and 13 technical characteristics contributed significantly to the carry and tackle classification models, respectively. The carry models included different combinations of the following technical variables: carrier velocity at the line, individual body mass and system mass, velocity at line vs. line-speed, body height, leg drive, collision, post-contact metres, change of direction angle, straightening angle, reception velocity vs. line-speed, running line, tackler assistance, pre-contact agility, defensive line-speed and fending. The tackle models included different combinations of the following technical variables: collision zone entry, mass, tackle direction, distance from carrier, body height, leg drive, hit point, collision, post-contact metres, system mass, tackle type, initial line-speed and arm use. Tables 3 and 4 present summaries of the carry and tackle classification model structures, according to the probability of achieving a positive outcome. Figure 1 also provides visual context to support the interpretation of the data presented in Tables 3 and 4. This example shows that when pre-contact technical behaviours are examined during close tackles, the greatest probability of the tackler winning post-contact metres (57%) is attained by the tackler entering the collision zone in either a static optimal posture, or accelerating in an optimal position, with comparable body mass or a mass advantage over the ball carrier. For each classification model, only the "root" with the greatest probability of a successful outcome is reported in Tables 3 and 4.

### *Stage 2: The relationship between technical and physical characteristics*

For the stage 2 of the analysis, the technical variables which significantly contributed to the classification models in stage 1 were retained. However, the following variables which incorporated the relative actions of opposition players in their scoring levels and subsequently did not solely represent the physical

Table 3. Binary classification tree outcomes by carry type.

| Model | Carry type | 1st Split variable | 2nd Split variable(s) | 3rd Split variable(s) | Probability |
|---|---|---|---|---|---|
| Pre-contact variables Collision outcome | Immediate | | Model did not reach accuracy threshold | | |
| | Close | Carrier velocity at line – Moderate/Fast | Carrier velocity at line – Fast | | 85% |
| | Middle | Carrier velocity at line – Moderate/Fast | Velocity at line vs. line-speed – Attack win | | 82% |
| | Wide | Carrier velocity at line – Fast | Body height – Upright<br>COD angle – Moderate/Great | | 99%<br>77% |
| | KO & CA | Carrier velocity at line – Slow/Moderate | COD angle – Moderate/Great | | 98% |
| | OP | | Model did not reach accuracy threshold | | |
| Pre-contact variables Post-contact metres outcome | Immediate | Reception velocity vs. line-speed – Attack win/Equal | | | 77% |
| | Close | | Model did not reach accuracy threshold | | |
| | Middle | | Model did not reach accuracy threshold | | |
| | Wide | | Model did not reach accuracy threshold | | |
| | KO & CA | Carrier velocity at line – Slow/Moderate | Straightening angle – Moderate/ Great | | 90% |
| | OP | Carrier velocity at line – Fast | Velocity at line vs. line-speed – Attack win | Running line – Straight | 93% |
| Post-contact variables Collision outcome | Immediate | | Model did not reach accuracy threshold | | |
| | Close | Leg drive – Moderate/Strong | Leg drive – Strong | | 78% |
| | Middle | Leg drive – Moderate/Strong | Tackler assistance – Single | | 82% |
| | Wide | Leg drive – Moderate/Strong<br>Leg drive – Absent | Mass – Advantage | | 89%<br>61% |
| | KO & CA | Leg drive – Moderate/Strong | | | 64% |
| | OP | | Model did not reach accuracy threshold | | |
| Post-contact variables Post-contact metres outcome | Immediate | Collision – Carrier win | Leg drive – Moderate/Strong | | 92% |
| | Close | Collision – Carrier win | Leg drive – Moderate/Strong | System mass – Attack | 90% |
| | Middle | Leg drive – Moderate/Strong | Collision – Carrier win<br>Collision – Tackler win | | 90%<br>52% |
| | Wide | Collision – Carrier win | Leg drive – Moderate/Strong | Mass – Advantage<br>Mass – Disadvantage | 99%<br>61% |
| | KO & CA | Collision – Carrier win | Leg drive – Moderate/Strong | | 95% |
| | OP | Collision – Carrier win | Leg drive – Moderate/Strong | | 81% |
| All variables Territory outcome | Immediate | Post-contact metres – Carrier Win<br>Post-contact metres – Tackler win | Collision – Carry win | | 98%<br>50% |
| | Close | Post-contact metres – Carrier win<br>Post-contact metres – Tackler win | Velocity at line vs. line-speed – Attack win<br>Defensive line-speed – Moderate/Slow | Reception velocity vs. line-speed - Attack win | 90%<br>55%<br>73% |
| | Middle | Collision – Carrier win | Carrier velocity at line – Carry win | | 87% |
| | Wide | | Model did not reach accuracy threshold | | |
| | KO & CA | | Model did not reach accuracy threshold | | |
| | OP | Post-contact metres – Carry win<br>Post-contact metres – Tackle win | COD angle – Moderate<br>Carrier velocity at line – Fast | | 99%<br>50% |
| All variable Result outcome | Immediate | Fend | | | 62% |
| | Close | Straightening angle – Moderate/Great | Fend – Strong | | 55% |
| | Middle | Leg drive – Strong<br>Leg drive – Strong | Pre-contact agility – Side-step<br>Pre-contact agility – Cross-over /Straight | | 88%<br>52% |
| | Wide | Leg drive – Strong | | | 60% |
| | KO & CA | Leg drive – Strong<br>Leg drive – Absent/Moderate | Straightening angle – Moderate/ Great<br>Straightening angle – None/ Slight | COD angle – Moderate/Great<br>COD angle – Slight<br>System mass – Defence<br>System mass – Attack/Equal | 90%<br>92%<br>62%<br>55%<br>92% |
| | OP | | Model did not reach accuracy threshold | | |

Abbreviations: KO = kick off, CA = counterattack, OP = open play, COD = change of direction.

actions of the carrier or tackler were discarded: reception velocity vs line-speed, carrier velocity at the line vs line-speed, tackler assistance, system mass, defensive line-speed (for carries).

The relationship between physical characteristics and the retained technical variables from stage one of the study was evaluated. Under the same ethical approval (SMEC_2018-19_057), physical performance assessment scores were

Table 4. Binary classification tree outcomes by tackle type.

| Model | Tackle type | 1st Split variable | 2nd Split variable(s) | 3rd Split variable(s) | Probability |
|---|---|---|---|---|---|
| Pre-contact variables Collision outcome | Immediate | | Model did not reach accuracy threshold | | |
| | Close | Collision zone entry – SO/AU/AO | Mass – Advantage/Neutral | Tackle Direction – Front | 80% |
| | Middle | Tackle direction – Front | Collision zone entry – AU/AO | | 50% |
| | Wide | Tackle direction – Oblique/Front | Distance from carrier – Near/Close | | 96% |
| | KO & CA | Model did not reach accuracy threshold | | | |
| | OP | Collision zone entry – SO/AU | | | 62% |
| Pre-contact variables Post-contact metres outcome | Immediate | Collision zone entry – AO | | | 63% |
| | Close | Collision zone entry – SO/AO | Mass – Advantage/Neutral | | 57% |
| | Middle | | Model did not reach accuracy threshold | | |
| | Wide | | Model did not reach accuracy threshold | | |
| | KO & CA | | Model did not reach accuracy threshold | | |
| | OP | Body height – Low | Distance from carrier – Near | | 55% |
| Post-contact variables Collision outcome | Immediate | Model did not reach accuracy threshold | | | |
| | Close | Leg drive – Strong<br>Leg drive – Absent | Mass – Advantage | Hit point – Shoulder/Neck/ Legs | 75%<br>55% |
| | Middle | | Model did not reach accuracy threshold | | |
| | Wide | | Model did not reach accuracy threshold | | |
| | KO & CA | | Model did not reach accuracy threshold | | |
| | OP | | Model did not reach accuracy threshold | | |
| Post-contact variables Post-contact metres outcome | Immediate | Collision – Tackler win | | | 78% |
| | Close | Collision – Tackler win<br>Collision – Carrier win | System mass – Advantage | Arm use – Strong/No wrap | 72%<br>88% |
| | Middle | Collision – Tackler win | | | 73% |
| | Wide | Collision – Tackler win | Arm use – Strong wrap | | 86% |
| | KO & CA | Collision – Carrier win<br>Collision – Tackler win | Arm use – Strong wrap | | 88%<br>59% |
| | OP | Tackle type – Shoulder<br>Tackle type – Arm/Jersey/Collision/ Smother | Collision – Tackler win | | 73%<br>50% |
| All variables Territory outcome | Immediate | Collision – Tackler win | System mass – Advantage/ Disadvantage<br>System mass – Equal | | 81%<br>97% |
| | Close | Post-contact metres – Tackler win<br>Post-contact metres – Carrier win | Initial line-speed – Moderate/Fast | Collision -Tackler win | 83%<br>70% |
| | Middle | Initial line-speed – Moderate/Fast | Collision – Tackler win<br>Collision – Carry win | | 89%<br>50% |
| | Wide | | Model did not reach accuracy threshold | | |
| | KO & CA | | Model did not reach accuracy threshold | | |
| | OP | Post-contact metres – Tackler win | | | 72% |
| All variable Result outcome | Immediate | Tackle direction – Front/Behind<br>Tackle direction – Oblique/Side | Collision zone entry – AB/AU/AO<br>Collision zone entry – AO | Tackle type – Shoulder/ Smother<br>Tackle type – Arm/ Collision | 98%<br>71%<br>73% |
| | Close | Arm use – Strong/Weak wrap<br>Arm use – No wrap | Tackler assistance – Double | | 92%<br>96% |
| | Middle | | Model did not reach accuracy threshold | | |
| | Wide | Arm use – Strong/Weak wrap<br>Arm use – No wrap | Tackle type – Arm/Shoulder | | 78%<br>70% |
| | KO & CA | Arm use – Strong wrap<br>Arm use – Weak/No wrap | System mass – Tackler<br>System mass – Carrier/Equal | Collision – Tackler win | 90%<br>99%<br>83% |
| | OP | Arm use – Strong/Weak wrap | Arm use – Strong wrap<br>Arm use – Weak wrap | | 91%<br>67% |

Abbreviations: KO = kick off, CA = counterattack, OP = open play, SO = static optimal, AU = accelerate upright, AO = accelerate optimal, AB = absorb.

determined for 67 players between January 2018 and December 2021 (age 24 ± 4 years, stature 171.1 ± 7.6 cm, body mass 80.5 ± 10.5 kg), who provided written informed consent to participate and were members of this elite squad during the three-season sampling period (181 total observations for the full battery of assessments, mean and SD 3 ± 1 observations per player). Variation in the individuals selected in the squad throughout the study meant that players were involved in either three ($n = 23$), two ($n = 27$) or one ($n = 17$) season/s of data collection. Each player was tested between two and three times per year, depending on injuries, on physical performance tests (see Woodhouse et al., 2022). The assessments comprised: body mass and sum of 8 skinfolds, single-leg isometric squat, single leg drop jump, counter-movement jump, one-repetition maximum bench press, and 10 m sprint, from which mean velocity (distance/time) and acceleration momentum (body mass × mean velocity) were calculated (see Woodhouse et al., 2021).

### *Stage 2: Statistical analysis*

Physical performance data were checked for multicollinearity using a correlation matrix. No correlation coefficients exceeded 0.7; therefore, no multicollinearity was assumed (Shrestha, 2020). To maximise the validity of each player's annual physical fitness, mean individual annual performance for each physical assessment was then calculated. To prepare the data for analysis, individual physical assessment scores were standardised as *Z*-scores within forward and backs groups for each season and matched to individual collision actions in games played in the same season, using a custom-built database (Microsoft Excel 2021). To ensure the sample size recommendations of minimum ten events per prediction variable (Riley et al., 2020), carry and tackle types were combined based on the similarity of their characteristics (see Table 1): Close, Middle and Set-piece, and Wide, Open play and Kick-off counterattack. The immediate carry and tackle category was analysed independently because it was deemed unique to all other classifications. For model compatibility, all technical variables were converted to factors and their levels were given an ordinal structure according to the findings of stage one. Cumulative link mixed effects models were then built for each technical variable (Rstudio, version 1.4.1106, *package ordinal, function clmm*) to analyse the fixed effects of physical characteristics on technical collision variables during each of the three carry and tackle groups described above. Individual was entered into each model as a random factor to account for repeated measures. Brant tests for parallel lines were conducted for each model to assess the assumption of proportional odds, which held for all models. Regression estimates were then exponentiated to produce odds ratios.

## Stage 2 results

For stage 2 of the analysis, Tables 5 and 6 summarise the mixed effects ordinal regression models that analysed the relationship between technical collision characteristics and physical characteristics for each of the three carry and tackle categories, respectively. With the exception of straightening angle, each of the other seven technical carry variables was significantly associated with physical characteristics among forwards. Among backs, except for body height and change of direction angle, six of the eight technical carry variables were significantly associated with physical characteristics. For the tackle, each of the eight technical variables was significantly associated with physical characteristics among forwards. Among the backs, five of the eight technical variables were significantly associated with physical characteristics. The variables that did not reach significance were initial line-speed, body position and tackle type. Mixed effects ordinal regression models for each of the tackle and carry categories showed that a one *Z*-score change increased the likelihood of moving into a higher or lower class for technical tackle and carry variables by: 10–40% for 0–10 m MOM, 5–31% for body mass, 6 and 14% for 10 m SPR, 5–11% for skinfolds, 4–10% for Bench AB, 4–10% for CMJRELPPO, 4–7% for RELIS and 4–6% for SLDJRSI, depending on the technical tackle and carry variable under analysis.

## Discussion

For the first time among world-class, international female rugby union players, our primary findings reveal similar positive associations between technical characteristics and collision outcomes during the carry, to those previously shown in male rugby (Hendricks et al., 2010; 2013; 2014, Sayers & Washington King, 2005; Wheeler et al., 2010). During the carry, these technical characteristics included: carrier velocity at the line, individual body mass and system mass, leg drive, evasive footwork with less acute straightening angles, and fending. Similarly, during the tackle, technical characteristics that were positively associated with collision outcomes included: line-speed, tackle direction, body position and acceleration immediately before contact, leg drive and arm use. Various levels of association were found between these technical behaviours and physical characteristics, which included: body mass, peak relative leg strength and power, body fat levels, acceleration velocity and momentum, and upper-body strength.

Greater body mass has been associated with dominant collisions among backs in both elite male and female rugby union (Cunningham et al., 2018; Hendricks et al., 2014; Woodhouse et al., 2022). Consistent with this evidence, our current classification findings demonstrated that a body mass advantage contributed to the post-contact variables, collision wins and post-contact metres, but only in wide carries, which were mainly observed among backs. This may be explained by the greater range in body mass among backs compared to forwards (Cunningham et al., 2018; Woodhouse et al., 2022). In the subsequent ordinal regression analysis, however, it was found that neither body mass nor any other physical characteristics were related to gaining a body mass advantage during carries among backs. Because a body mass advantage was only advantageous during wide carries, we suggest that our methods, in which carry categories were combined, may have masked this relationship. Furthermore, because a mass advantage was a lower-order variable in the classification analysis, typically secondary to leg drive, we suggest coaches should consider the negative effects of gaining body mass (Silva et al., 2022) on other physical characteristics that underpin higher-order variables, such as leg drive. Greater relative countermovement jump power enabled forwards to gain a mass advantage during W, CA and OP carries. Relative leg power is associated with speed of movement in male rugby players (Cronin & Hansen, 2005). Presumably, this characteristic was advantageous for the evasion of heavier tacklers and gaining one vs one scenarios with smaller defenders, among our elite-standard female cohort. While heavier forwards carry the ball more often than lighter forwards (Cunningham et al., 2018; Woodhouse et al., 2022), the majority of these carries may be opposed by players of similar mass. For this reason, assistance from fellow players is critical in providing the additional mass

**Table 5.** Mixed effects ordinal regression model outcomes to describe the relationships between technical and physical characteristics for different carry categories, by position.

| | Model 1: Close, Middle, Set Piece | | | | | | Model 2: Wide, Kick off & Counterattack, Open Play | | | | | | Model 3: Immediate | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Characteristic | | Est | SE | *p* | 95% CI | OR | | Est | SE | p | 95%CI | OR | | Est | SE | p | 95%CI | OR |
| **Forwards Carry Models** | | | | | | | | | | | | | | | | | | |
| Body mass advantage | | | NS | | | | CMJ RELPPO | 0.12 | 0.04 | 0.03 | 1.0–1.3 | 1.04 | Body Mass | 0.40 | 0.16 | 0.03 | 1.0–2.0 | 1.3 |
| Body height | SLDJ RSI | 0.05 | 0.02 | 0.02 | 1.0–1.2 | 1.06 | | | NS | | | | | | NS | | | |
| Carrier velocity at line | Bench AB | −0.05 | 0.02 | 0.00 | 0.9–1.1 | 0.95 | | | | | | | | | | | | |
| Fend | Bench AB | 0.05 | 0.02 | 0.05 | 0.8–1.1 | 1.05 | 10 m SPR | 0.10 | 0.03 | 0.02 | 0.7–1.1 | 1.12 | | | | | | |
| | | | | | | | Bench AB | 0.10 | 0.04 | 0.05 | 0.8–1.1 | 1.10 | | | | | | |
| | | | | | | | 10 m MOM | −0.30 | 0.04 | 0.11 | 0.9–2.1 | 0.70 | | | | | | |
| Leg drive | Body mass | −0.2 | 0.04 | 0.00 | 0.4–0.9 | 0.86 | Body mass | −0.10 | 0.03 | 0.16 | 0.5–0.9 | 0.80 | | | | | | |
| | Bench AB | 0.04 | 0.01 | 0.00 | 0.9–1.3 | 1.04 | 10 m MOM | 0.40 | 0.02 | 0.16 | 1.0–2.0 | 1.40 | | | | | | |
| | 10 m MOM | 0.13 | 0.04 | 0.00 | 1.1–2.0 | 1.14 | | | | | | | | | | | | |
| Pre-contact agility | | | NS | | | | Body mass | 0.30 | 0.02 | 0.11 | 0.8–1.5 | 1.31 | | | | | | |
| | | | | | | | Skinfolds | −0.10 | 0.02 | 0.07 | 1.0–1.2 | 0.93 | | | | | | |
| | | | | | | | 10 m MOM | −0.31 | 0.03 | 0.16 | 0.6–1.1 | 0.76 | | | | | | |
| COD angle | RELIS | −0.04 | 0.02 | 0.02 | 0.9–1.1 | 0.96 | | | NS | | | | | | | | | |
| Straightening angle | | | NS | | | | | | | | | | | | | | | |
| **Backs Carry Models** | | | | | | | | | | | | | | | | | | |
| Body mass advantage | Body mass | −0.22 | 0.10 | 0.01 | 0.6–1.0 | 0.8 | | | NS | | | | | | NS | | | |
| Body height | | | NS | | | | | | | | | | | | | | | |
| Carrier velocity at line | Body mass | −0.21 | 0.08 | 0.01 | 0.7–1.0 | 0.85 | Body mass | −0.30 | 0.03 | 0.04 | 0.8–1.1 | 0.95 | | | | | | |
| | Skinfolds | 0.05 | 0.02 | 0.03 | 1.0–1.1 | 1.05 | Bench AB | 0.09 | 0.02 | 0.02 | 0.9–1.1 | 1.09 | | | | | | |
| | RELIS | −0.05 | 0.02 | 0.03 | 0.9–1.0 | 0.95 | 10 m SPR | −0.15 | 0.03 | 0.03 | 0.9–1.1 | 0.86 | | | | | | |
| | Bench AB | 0.05 | 0.02 | 0.03 | 1.0–1.1 | 1.05 | 10 m MOM | 0.04 | 0.05 | 0.01 | 0.8–1.1 | 1.31 | | | | | | |
| | 10 m MOM | 0.26 | 0.08 | 0.02 | 0.9–1.3 | 1.15 | RELIS | −0.06 | 0.02 | 0.00 | 0.9–1.0 | 0.94 | | | | | | |
| Fend | Skinfolds | −0.06 | 0.03 | 0.03 | 0.9–1.0 | 0.94 | Body mass | −0.21 | 0.09 | 0.01 | 0.7–1.0 | 0.92 | | | | | | |
| | | | | | | | Bench AB | 0.05 | 0.02 | 0.02 | 1.0–1.1 | 1.06 | | | | | | |
| | | | | | | | 10 m MOM | 0.20 | 0.08 | 0.00 | 1.1–1.4 | 1.10 | | | | | | |
| Leg drive | | | NS | | | | Skinfolds | −0.04 | 0.02 | 0.01 | 0.9–1.0 | 0.89 | | | | | | |
| | | | | | | | RELIS | 0.06 | 0.02 | 0.03 | 0.9–1.0 | 1.06 | | | | | | |
| Pre-contact agility | | | | | | | Body mass | 0.13 | 0.06 | 0.01 | 1.0–1.3 | 1.14 | | | | | | |
| COD angle | | | | | | | | | NS | | | | | | | | | |
| Straightening angle | | | | | | | Body mass | 0.30 | 0.10 | 0.00 | 1.1–1.6 | 1.31 | | | | | | |
| | | | | | | | CMJ RELPPO | 0.09 | 0.04 | 0.02 | 1.0–1.2 | 1.10 | | | | | | |
| | | | | | | | 10 m MOM | −0.27 | 0.10 | 0.00 | 0.6–0.9 | 0.78 | | | | | | |

Abbreviations and measurement units: Est = ordinal regression estimate, SE = standard error, *p* = *p* value, 95% CI = 95% confidence intervals, OR = odds ratio, NS = no significant relationships between technical and physical characteristics, SLDJ RSI (flight time (sec)/contact time (sec))= single leg drop jump reactive strength index, CMJ RELPPO (Watts/kg) = counter movement jump relative power output, RELIS (Newtons/kg) = single leg relative isometric squat, 10 m MOM (kg/m/sec) = 10-metre momentum, 10 m SPR (sec) = 10-metre sprint, Bench AB (kg) = absolute bench press.

Table 6. Mixed effects ordinal regression model outcomes to describe the relationships between technical and physical characteristics for different tackle categories, by position.

| | Model 1: Close, Middle, Set Piece | | | | | | Model 2: Wide, Kick off & Counterattack, Open Play | | | | | | Model 3: Immediate | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Characteristic | | Est | SE | *p* | 95% CI | OR | | Est | SE | p | 95%CI | OR | | Est | SE | p | 95%CI | OR |
| **Forwards Tackle Models** | | | | | | | | | | | | | | | | | | |
| Body mass advantage | | | NS | | | | SLDJ RSI | −0.06 | 0.02 | 0.00 | 0.9–1.0 | 0.94 | | | NS | | | |
| | | | | | | | RELIS | 0.07 | 0.03 | 0.02 | 1.0–1.1 | 1.07 | | | | | | |
| Initial line-speed | | | | | | | Skinfolds | 0.07 | 0.03 | 0.02 | 1.0–1.1 | 1.08 | | | | | | |
| Collision zone entry | SLDJ RSI | 0.03 | 0.03 | 0.02 | 0.9–1.1 | 1.04 | Body mass | 0.07 | 0.07 | 0.01 | 1.0–1.3 | 0.14 | | | | | | |
| | | | | | | | Skinfolds | −0.10 | 0.03 | 0.02 | 0.8–1.0 | 0.91 | | | | | | |
| Tackle direction | CMJ RELPPO | 0.04 | 0.01 | 0.02 | 0.8–1.1 | 1.05 | RELIS | 0.06 | 0.04 | 0.03 | 0.9–1.0 | 1.05 | | | | | | |
| Body position | SLDJ RSI | 0.07 | 0.02 | 0.00 | 1.0–1.1 | 1.06 | Body mass | 0.23 | 0.08 | 0.00 | 1.1–1.5 | 1.25 | 10 m SPR | −0.12 | 0.04 | 0.00 | 0.8–1.0 | 0.90 |
| | 10 m SPR | −0.10 | 0.04 | 0.02 | 0.8–1.0 | 0.91 | Skinfolds | −0.1 | 0.03 | 0.00 | 0.8–1.0 | 0.89 | RELIS | 0.06 | 0.03 | 0.02 | 1.0–1.1 | 1.05 |
| Tackle type | SLDJ RSI | 0.05 | 0.12 | 0.00 | 1.0–1.1 | 1.04 | | | NS | | | | | | NS | | | |
| | Bench AB | −0.03 | 0.13 | 0.01 | 0.9–1.0 | 0.97 | | | | | | | | | | | | |
| Arm use | Bench AB | −0.04 | 0.01 | 0.02 | 0.9–1.0 | 0.96 | | | | | | | | | | | | |
| Leg drive | Bench AB | −0.04 | 0.02 | 0.03 | 0.9–1.0 | 0.96 | | | | | | | | | | | | |
| | 10 m SPR | 0.07 | 0.03 | 0.00 | 1.0–1.1 | 1.06 | | | | | | | | | | | | |
| | RELIS | 0.04 | 0.02 | 0.01 | 1.0–1.1 | 1.05 | | | | | | | | | | | | |
| **Backs Tackle Models** | | | | | | | | | | | | | | | | | | |
| Body mass advantage | | | NS | | | | CMJ RELPPO | 0.07 | 0.02 | 0.03 | 1.0–1.1 | 1.08 | | | NS | | | |
| Initial line-speed | | | | | | | | | NS | | | | | | | | | |
| Collision zone entry | Skinfolds | −0.06 | 0.06 | 0.00 | 0.9–1.0 | 0.94 | | | | | | | | | | | | |
| Tackle direction | Skinfolds | −0.04 | 0.02 | 0.01 | 0.9–1.0 | 0.96 | | | | | | | | | | | | |
| Body position | | | NS | | | | | | | | | | | | | | | |
| Tackle type | | | | | | | | | | | | | | | | | | |
| Arm use | | | | | | | RELIS | −0.06 | 0.02 | 0.00 | 0.9–1.1 | 0.94 | | | | | | |
| Leg drive | Skinfolds | −0.08 | 0.02 | 0.00 | 0.9–1.0 | 0.92 | | | NS | | | | | | | | | |
| | 10 m MOM | 0.10 | 0.05 | 0.04 | 1.0–1.2 | 1.11 | | | | | | | | | | | | |

Abbreviations and measurement units: Est = ordinal regression estimate, SE = standard error, *p* = *p* value, 95% CI = 95% confidence intervals, OR = odds ratio, NS = no significant relationship between technical and physical characteristics, SLDJ RSI (flight time (sec)/contact time (sec))= single leg drop jump reactive strength index, CMJ RELPPO (Watts/kg) = counter movement jump relative power output, RELIS (Newtons/kg) = single leg relative isometric squat, 10 m MOM (kg/m/sec) = 10-metre momentum, 10 m SPR (sec) = 10-metre sprint, Bench AB (kg) = absolute bench press.

advantage to produce a successful collision outcome during carries at close proximity to the breakdown (Table 2).

Our classification analysis showed that moderate and strong leg drive was associated with ~30% greater probability of achieving collision wins compared to no leg drive. Subsequently, leg drive underpinned territorial gains and positive carry outcomes, such as line-breaks and off-loads. We also found that strong leg drive was associated with a 55% probability of winning post-contact metres even if the initial collision was lost. There have been reports that peak relative leg force is associated with carries over the gain-line (Cunningham et al., 2016). Our findings build on this evidence by more specifically identifying that relative single leg isometric squat performance among backs underpins the ability to leg drive after the collision during W, CA and OP carries. Among forwards, leg drive was positively related to acceleration momentum during all carry types but negatively related to body mass, except during immediate carries. Therefore, in the absence of relative explosive leg capabilities, high body mass may be detrimental to leg drive, except during immediate carries. Furthermore, only a positive trend was observed between leg drive and relative counter-movement jump power, suggesting acceleration momentum is a higher order indicator of leg drive compared to "one-off" propulsive efforts. This may relate to the importance of a combination of cyclical thigh velocity (Clark et al., 2020) and ankle power (Bezodis et al., 2015) in the skilful application of force to the ground to optimise forward propulsion (Loturco et al., 2018). Given that heavier forwards were more likely to be at a mass disadvantage, our findings could also suggest that forwards are unable to achieve strong leg drive because they are targeted by tacklers of comparable mass with low tackles.

The positive relationship between bench press performance and leg drive among forwards during C, M and SP carries could be interpreted to infer that systemically stronger players have an advantage during physical contacts, rather than the bench press strength relating directly to (i.e., causing) leg-drive performance. However, bench press performance was also positively related to fending among both forwards and backs across most carry classes (Table 1). Strong fending may, therefore, facilitate leg drive after the initial contact, by maintaining space between the tackler and the carrier's legs. Maximum upper-body pushing strength may indirectly increase the likelihood of exhibiting this capability, which would explain why pushing power is also positively associated with metres after contact (Redman et al., 2022). This concept of maintaining space between carrier and defender has been described previously (Dos'Santos et al., 2018), and we suggest it is enhanced by a combination of footwork and fending. For example, during close carries, the combination of fending with large straightening angles after the initial change of direction was associated with clean breaks and offloads. Fending was also positively related to acceleration velocity among forwards during wide carries but negatively related to acceleration momentum, suggesting faster forwards are more likely to exhibit strong fending and evade tacklers, while players who are fast and heavy may bias direct carries. Similarly, when strong leg drive was present, the likelihood of clean breaks and offloads during middle carries was enhanced by sidestepping before contact, compared to running straight or using a cross over-step (88% and 53%, respectively). Backs with higher relative counter-movement jump power and lower acceleration momentum were more likely to produce great straightening angles and forwards with higher acceleration momentum were less likely to demonstrate pre-contact footwork. This suggests that these physical characteristics underpin evasive and direct carry preferences, respectively. In support of this suggestion, forwards with superior single leg drop-jump and relative counter-movement jump performance were more likely to carry in medium or upright positions in which greater speed can be attained. In conflict with these findings, however, pre-contact agility among forwards and backs, and straightening angle among backs, were positively related to body mass in W, CA and OP carries. Greater lean mass has been observed among rugby players with enhanced change of direction ability (Silva et al., 2022), which might explain our finding because players with enhanced muscle mass in the large hip muscles that underpin speed and change of direction ability (Falch et al., 2020; Miller et al., 2021) may also have greater absolute mass. However, it should also be considered that other factors, such as collision experience, may be more strongly related to physical skills in rugby (Gabbett, 2011), although we cannot confirm this assertion within this sample.

Higher body mass also reduced the likelihood of attacking the line at moderate and fast velocities, compared to slow, by ~20% for all carry type among backs. Heavier backs may not need to achieve maximal relative sprint intensity to generate sufficient momentum to achieve positive collision outcomes compared to smaller backs. However, faster backs also attacked the line at slower relative speeds during W, CA and OP carries. To account for this finding, our classification analysis showed that a combination of moderate or slow velocities at the line, and moderate or great direction change, is associated with ~90% probabilities of collision wins and post-contact metres during CA and KO carries. Faster players carrying in wider spaces may, therefore, implement the strategy of slowing down before contact or taking a moderate approach speed to facilitate change of direction according to the angle-velocity trade-off (Dos'Santos et al., 2018), whereby the velocity of approach is compromised as the magnitude of direction change increases. Increased acceleration momentum among backs raised the likelihood of carrying at moderate and fast velocities at the line by 15–30% for both carry types. This evidence agrees with existing findings among males (Cunningham et al., 2018) but goes further in demonstrating that the technical mechanism by which high momentum carriers gain positive collision outcomes is by attaining high velocities at the line and achieving leg drive after the collision.

The ability to demonstrate greater relative velocity before contact and strong leg drive after the collision is critical for players who typically carry directly through the collision zone. These players should practice catching the ball at high velocities before the defensive line and producing strong leg drive after the initial collision. The development of these technical skills may be further complimented by the enhancement of acceleration momentum by increasing relative explosive leg capabilities, which are proportional to any increases in body mass. The ability to utilise a combination of large change of direction angles, fending and leg drive is an important skill among players who carry in wider spaces. We suggest such players should develop relative leg force, maximum upper-limb pushing force and relative propulsive and reactive power and should be optimised by reducing body fat. In practice, an increase in single leg isometric squat, counter-movement jump power, or a reduction in skinfolds, by one Z-score among backs, which equates to approximately 3 kg, 0.5 W/kg and 1.6 mm in this cohort, respectively, would increase the likelihood of moving into a higher performance classification by 6%, 10% and 11% respectively. Rugby practitioners should, therefore, consider the magnitude of change in specific physical characteristics that is attainable based on the athlete's training status, with consideration for the error of the test, and whether the likelihood of enhancing performance by the modification of such characteristics, is sufficient to ensure performance transfer.

In agreement with findings from male rugby, we show that fast defensive line-speeds are positively related to territorial gains (Hendricks et al., 2013), and post-contact metres, and collision wins among forwards were more likely when the tackler accelerated into the collision zone, preferably, leaning forwards with a front-on or oblique body position relative to the carrier (Hendricks et al., 2018; van Rooyen et al., 2014). The attainment of fast initial line-speeds prior to simultaneously decelerating, reorientating to a square body position in response to the carrier's movement and maintaining sufficient velocity to match or exceed the carrier's momentum immediately before the collision is a highly complex and dynamic task (Hendricks et al., 2012, 2013, 2014; Hopkinson et al., 2022; Sewry et al., 2015). The successful performance of this sequence of events is underpinned by high levels of relative strength and both propulsive and reactive power, based on the previous knowledge that the same characteristics are positively related to acceleration, deceleration, change of direction ability and fatigue resistance when repeating high intensity efforts in rugby (Cronin & Hansen, 2005; Delaney et al., 2016; Harper et al., 2022; Speranza et al., 2017). Indeed, relative strength and power characteristics were positively related to optimal performance in the pre-contact area among forwards. For example, during C, M and SP tackles, greater single leg drop jump performance was related to accelerating square and low into the carrier, with forward body lean and hitting with the chest or shoulder. Higher relative counter-movement jump power and single leg relative isometric squat performance were also related to square tackle entry positions, and faster initial line-speeds during all tackle types except immediate. Among backs, only skinfolds were related to pre-contact performance variables, with lower body fat benefitting collision zone entry and tackle direction during C, M and SP tackles. The same pattern was observed for forwards, but only for W, CA and OP tackles. Our evidence shows that those specific physical characteristics associated with performance during conventional assessments in speed and agility performance also underpin the ability to attain optimal body positions prior to the tackle, which is subsequently related to positive tackle outcomes. These characteristics include relative leg force, propulsive and reactive power, and lower body fat.

Heavier forwards were also more likely to enter the collision zone in optimal positions during W, CA and OP tackles, perhaps because of an enhanced ability to tolerate the large peak impact forces experienced during tackling (Faria et al., 2017) compared to smaller players. Our findings, in agreement with others (Speranza et al., 2017), show that stronger players are more likely to adopt square body positions prior to the tackle, which was subsequently related to collision wins. This may explain our slightly counterintuitive finding that stronger forwards and backs with greater bench press performance and single leg relative isometric squat performance, respectively, were less likely to use their arms effectively in the tackle. Stronger players who achieve square body positions may not need to wrap the arms strongly to complete the tackle. This is in contrast to weaker players who are more likely to execute side-on tackles during which forces are lower (Seminati et al., 2016) but require more arm use to complete the tackle. Therefore, while our findings substantiate previous evidence that a strong wrap and pull are critical for preventing clean breaks, half breaks, offloads (Hendricks et al., 2014) and gaining post-contact metres, whether a player wraps effectively or not, may be more strongly driven by contextual and technical factors compared to physical characteristics. Furthermore, we suggest other technical tackling skills may be more valuable than arm use in the pursuit of dominant tackles.

Leg drive during the tackle is associated with tackle completion and preventing offloads (Hendricks et al., 2017; Hendricks et al., 2014; Sewry et al., 2015). While our findings did not confirm this evidence exactly, we show for the first time in a rugby union study that strong leg drive is associated with collision wins among elite female forwards and is underpinned by enhanced single leg relative isometric squat performance and acceleration ability. Peak relative leg force facilitates optimal pre-contact body positions and increases the ability to maximise power output when high external resistances must be overcome (Suchomel et al., 2016), such as tackling. Acceleration ability most strongly matches the kinematic profile of leg driving in the tackle compared to other assessments, again suggesting that like carry performance, the ability to produce "reactive power" in a cyclical fashion (Clark et al., 2020; Mann & Murphy, 2018) is more important than "one off" propulsive jump efforts. Among backs, lower body fat was the only physical characteristic related to stronger leg drive during C, M and SP tackles, which mirrored our findings with regard to pre-contact factors. This limited impact of physical characteristics on pre- and post-contact variables suggests that other factors such as match experience (Gabbett, 2011) are more important to the defensive performance of backs. However, body fat should be reduced to optimise pre- and post-contact performance among backs, presumably because of an indirect enhancement of relative strength and power, which we show to be directly related to carry and tackle performance.

This investigation is not, however, without limitations. The methodological decision to exclusively analyse top 5 ranked teams means the generalisability of the findings may not stretch to lower standards of competition. Furthermore, the complexity of splitting collision type according to tactical context meant that sample size was compromised for some models. Similar carry types were subsequently combined in stage two of the analysis to increase sample size. While this may not have altered the fundamental outcomes, future investigations should sample more matches to avoid such compromise.

In conclusion, we highlight the individual and combined technical characteristics that increase the probability of successful performance outcomes during specific carry and tackle types, among elite female rugby union players. From a practical standpoint, this evidence enables rugby coaches and strength and conditioning professionals to precisely collaborate in the construction of practices, drills and physical training methods that are specifically aligned to individual player's essential technical skills.

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