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The relationship between physical characteristics and match collision performance among elite international female rugby union players

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ABSTRACT

This study investigated whether anthropometric and physical abilities explained variance in match collision performance among international female rugby union players. Physical performance and anthropometric data for fifty-one international female rugby union players, and collision actions categorised as "effort" or "performance" variables, from 20 international matches, were analysed using partial least squares regression. Among forwards, variance in carries/min was explained ($R^2 = .22$) by a combination of; body mass, skinfolds, acceleration momentum and negative associations with mean aerobic speed and single-leg isometric squat relative force (SLISO/kgBM). Variance in collision dominance among forwards was explained ($R^2 = .21$) by lower skinfolds and higher acceleration momentum, while tackles/min ($R^2 = .19$) were explained by greater jumping power and single-leg isometric squat (SLISO). Among backs, variance in tackles/min ($R^2 = .54$) was explained by greater bench press, SLISO and SLISO/kgBM. Variance in collision dominance among backs was explained ($R^2 = .23$) by negative and positive associations with body mass and SLISO/kgBM, respectively. These findings suggest the development of physical characteristics, such as body mass and composition, strength and power contribute towards successful collision actions among international female rugby union players. The contribution of different physical characteristics towards collision events is dependent on position, and whether the collision event is categorised by "performance" or "effort". It is suggested that physical training programmes should reflect this level of specificity.

KEYWORDS
Women; physical fitness; team sport; collision

Highlights

- Among elite female rugby union forwards, acceleration momentum, body mass and skinfolds are positively associated with winning collisions and carrying the ball into contact more frequently, whilst tackle frequency is positively associated with relative leg strength and power output.
- Among elite female backs, the ability to win collisions is positively associated with relative leg power output, and negatively associated with body mass. Tackle frequency is associated with maximum upper- and lower-body strength in this group.
- Physical characteristics account for some of the variability in collision performance, but interpretation of these findings should consider that factors such as technique during collision events may account for a larger proportion of total variance.
- Sports science practitioners can improve collision performance, to varying degrees, by enhancing specific gross physical characteristics, according to a player's position and the tactical role they are expected to fulfil.

Introduction

In rugby union, the outcome of a match can be partly determined by selected on-field technical and tactical actions, collectively referred to as "performance indicators' (PIs) (Hughes et al., 2017). For example, the effective performance of actions involving collisions have been consistently associated with match outcome, with tackle success rate, metres carried,

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number of defenders beaten, clean breaks and turnovers on opposition ball are also related to successful performance (Bennett et al., 2019; Gaviglio et al., 2014; Hughes et al., 2017; Ortega et al., 2009; Sella et al., 2019). However, it is important to recognise that individual on-field collision actions of rugby players contribute to successful performance in different ways, with some PIs characterised by their high frequency, defined as "effort" variables, whilst others are dependent on successful outcome, defined as "performance" variables (Cunningham et al., 2018). For example, the number of tackles, rucks, or carries performed per unit of playing time, are classed as "effort" variables, whilst "performance" variables are expressed as the ratio of successful or positive actions to the total number across the whole match, such as tackle success rate, collision success rate, and effective ruck rate (Cunningham et al., 2018). Given the differences between these types of variables, effort-based or performance-based actions are likely to be underpinned by different physical abilities.

Successful execution of "effort" and "performance" match collision actions often depends upon the physical abilities of players within the team (Cunningham et al., 2018; Smart et al., 2013; Speranza et al., 2015; Waldron et al., 2014). For example, intermittent aerobic running performance has been reported to represent player's maximal aerobic power and is positively associated with the frequency of "effort" variables, such as rucks, tackles, and possessions (Cunningham et al., 2018). This is presumably because of the ability to cover greater low and high-speed distance during match-play. Similarly, physical characteristics are associated with "performance" variables. For example, counter-movement jumping power outputs, and 10 m sprint acceleration time, are positively associated with the capability to beat defenders in attack (Cunningham et al., 2018; Gabbett et al., 2013; Smart et al., 2013; Waldron et al., 2014), which highlights the importance of lower-limb power when performing a variety of athletic movements required during dynamic match actions. Tackling performance among rugby players is not only associated with performance during lower-limb power and speed assessments, but also with bench press one repetition maximum, and plyometric press performance (Redman et al., 2022; Speranza et al., 2015). Upper- and lower-body strength and power, may therefore, increase the ability to tolerate the high impact forces to the shoulder girdle during tackling (Faria et al., 2017) and underpin the ability to achieve simultaneous leg-drive at the point of collision, whilst maintaining a strong upper-body wrap around the attacker to prevent an offload (Hendricks et al., 2014a). Furthermore, in collision sports, greater 10 m acceleration momentum has been reported as a critical physical characteristic which discriminates elite- and sub-elite players in rugby league (Baker & Newton, 2008). Heavier players with greater momentum also carry the ball into contact more regularly in rugby union (Hendricks et al., 2014a). Unsurprisingly, this momentum is positively related to collision wins and the number of offloads in elite-level male rugby union players (Cunningham et al., 2018). It is therefore well established, that physical characteristics in male rugby are critical to the outcome of contact and collision events (Cunningham et al., 2018; Redman et al., 2022; Smart et al., 2013; Speranza et al., 2015), which may subsequently have a bearing on winning or losing matches (Bennett et al., 2019; Sella et al., 2019). This information highlights that training programs designed for elite rugby players should develop physical characteristics that are associated with effective performance of specific collision actions.

Longitudinal analyses show enhancement in many of these physical characteristics among elite female rugby union players, such as body mass, ten metre acceleration momentum, and bench press performance (Woodhouse et al., 2022). However, there is currently no evidence to suggest these physical characteristics are associated with performance outcomes during collision events among females. Match tactical behaviours are different between males and females (Hughes et al., 2017) and, therefore, it should not be assumed that the relationships between physical characteristics and the performance of collision actions are consistent between sexes. Winning performance in international female matches is characterised by a more expansive running-based game, with less kicking than international male matches (Hughes et al., 2017). Therefore, it is possible that the associations between physical characteristics and the performance of collision actions in female rugby, are different to their male counterparts, which merits further investigation.

Based on the above reasoning, the current study aimed to investigate which combination of anthropometric and physical abilities explained variance in match collision performance, using both effort and performance variables, in international female rugby union matches.

Methods

Participants

To evaluate the relationship between selected match collision performance indicators and physical characteristics, physical performance assessment scores and match-collision variables from the 2017, 2018 and 2019 seasons were sampled from an international team ranked in the top 2 nations across the study period. A total of 53 international female rugby union players agreed to take part in the study, of which, 51 players (age 25 ± 4 years, stature 170.6 ± 7.0 cm, body mass 79.1 ± 10.7 kg) were eligible based on the inclusion criteria of having played five international matches during the sampling period. This inclusion criteria was used to ensure the average match performance accounted for typical match-match variation in rugby union (McLaren et al., 2016). During each season, a full battery of anthropometric and physical performance assessments was carried out three times (228 total observations for the full battery of assessments, mean and SD 4 ± 2 observations per player per season). Due to variation in the squad personnel throughout the study, players were involved in three ($n = 15$), two ($n = 28$) and one ($n = 9$) seasons of data collection. Collision performance was analysed during 20 full international matches (438 individual player performances, mean and SD matches per player; 9 ± 4). The number of matches played, according to each opposing team's World ranking at the time of competition, was; 2nd ($n = 3$), 3rd ($n = 4$), 4th ($n = 4$), 5th ($n = 1$), 6th ($n = 1$), 8th ($n = 2$), 10th ($n = 2$), 12th ($n = 3$). Performances lower than a threshold of 20 min, either because the player sustained an injury, or was a substitute, were excluded from the analysis (Cunningham et al., 2016). For players competing in more than one position during the sampling period, only match performances for the position in which they most frequently played were included in the analysis. Players provided informed consent to allow data to be used for analysis and institutional ethical approval was granted for the study.

General procedures

Assessment days were conducted at three consistent time points each year, corresponding with the "late physical development" stage prior to major competitions (early-September, early-January, late-June). Assessment days were composed of multiple physical tests, delivered by the same practitioners, and conducted at the same standardised training facilities throughout the sampling period. For each specific physical assessment, individual participants' best scores from each of the assessment sessions they attended across all years were combined; and the average was calculated for each test and used within the analysis. Collision metrics from notational analysis of all international matches undertaken during the sampling period as part of standard operating procedures were derived from the Rugby Football Union performance analysis department. All matches were coded by the same performance analyst, who had over five years-experience in elite-standard rugby union, and typically produced intra and inter-coder reliability levels of CV ∼5% across all pooled variables measured in the current study. Definitions of collision variables are provided in Table 1.

Table 1. Definitions of collision variables (adapted from Cunningham et al. (2018)).

Performance variables	Definition
Collision Dominance (%)	Percentage of collisions in which the player made ground into opposition territory after being tackled, or after executing a tackle, by forcing the ball carrier backwards.
Effective Rucks (%)	Percentage of times the player, as one of the first three supporters arriving at the breakdown, actively prevented competition for the ball during attacking rucks or caused the opposition to actively protect the ball during defensive rucks.
Tackle Completion (%)	Percentage of total tackles in which the attacker was held, resulting in an offload, ruck, or stoppage in play
Effort variables	Definition
Tackles/min	Total number of tackles attempted per minute of playing time
1st 3 Ruck Arrivals/min	Total number of rucks (attack and defence) where the player was one of the first three support players arriving at the breakdown per minute of playing time
Carries/min	Total carries into contact per minute of playing time

Physical assessments

Anthropometric and strength and power assessment protocols were undertaken in the morning, followed by a 2.5-h break. Sprint and endurance running assessments were then completed in the afternoon. Specific protocols, their reliability, and rationale for use, have been reported previously for all the following assessments (Woodhouse et al., 2021).

Body mass and skinfolds

Participants' body mass was measured before breakfast, wearing shorts, vests and undergarments only using calibrated electronic scales (Seca, London, UK). The sum of eight skinfolds (bicep, tricep, subscapular, supraspinale, suprailiac, abdomen, mid-thigh, medial calf) was measured using Harpenden callipers (British Indicators, Hertfordshire, United Kingdom) by a level 3 ISAK practitioner.

Single-leg isometric squat

Following a standardised progressive warm-up, participants performed a maximum of 3 trials per leg of the single leg isometric squat with a 5 min rest between trial (Hart et al., 2012). Trials were performed within an integrated isometric rig secured above a force platform installed at floor height (FD4000, Force Decks, Vald Performance, Brisbane, Australia). Absolute peak force (SL ISO) and force relative to body mass (SL ISO/kgBM) were recorded for analysis (Woodhouse et al., 2021).

Single leg drop jump

Single leg drop jump (SL DJ) reactive strength index (RSI) from a 20 cm box was recorded using a jump mat and its associated software package (Kinematic Measurement Systems, Innervations, Australia). Participants hopped onto the jump mat from the box, with hands fixed on their hips, landing and rebounding on the same leg from which they hopped. Participants were instructed to jump "high and fast" with minimal ground contact time. Participants carried out six jumps per leg, alternating between left and right, with the maximum of the final three jumps recorded for analysis. Trials were discarded and repeated if ground contact time was greater than 250 ms. RSI was calculated as; flight (ms) time/contact time (ms).

Countermovement jump

Participants performed a maximum of five countermovement jump (CMJ) trials on a force platform (Vald Performance, Brisbane, Australia) with 1 min rest between trials. Participants self-selected their stance width and jump depth, and hands were kept on the hips throughout each trial. The maximum power output (CMJ PPO) and relative power output (CMJ PPO/BM) were recorded for analysis.

One-repetition maximum bench press

Following a standardised progressive upper body warm-up, participants performed a one-repetition maximum (1-RM) bench-press protocol with the absolute weight lifted in kg (Bench 1-RM) recorded for analysis (Hene et al., 2011).

Acceleration and momentum

Following a standardised warm-up, participants performed three trials of a maximal 10 m sprint on an indoor sprint track with 5 min rest between trials. The 10 m distance was chosen due to previous associations with collision performance (Gabbett, 2011; Waldron et al., 2014). Timing gates were positioned at 0 and 10 m (Brower timing systems, Utah, USA) and participants initiated the sprints from a two-point stance with the front foot placed 0.5 m behind the first gate line. Average acceleration velocity was calculated from the best 0–10 m time (distance/time) and average acceleration momentum was calculated for 0–10 m.

Endurance testing

To determine average aerobic running ability, participants performed a 1,200 m continuous run on a 100 m indoor running track (12×100 m shuttles) from which the mean aerobic speed (MAS) was derived (1,200/time to completion (s)) and reported as m/s.

Statistical analysis

We performed a preliminary statistical analysis to account for the potential influence of position specific collision behaviours, prior to evaluating relationships between physical characteristics and collision actions in rugby (Cunningham et al., 2016; Smart et al., 2013). Principle-Components Analysis (PCA) was initially carried out to establish between-position variance in collision actions. Players were split into six position groups; front row (FR) ($n = 12$) consisting of prop and hooker, locks (L) ($n = 6$), back-row forwards (BR) ($n = 8$) consisting of open- and blind-side flanker and number 8, scrum-halves (SH) ($n = 5$), inside backs (IB) ($n = 9$) consisting of fly half and centre, and outside backs (OB) ($n = 12$) consisting of wing and full-back (Woodhouse et al., 2021). The six collision variables were entered into the PCA with position as a qualitative variable, using RStudio (version 1.4.1106, RStudio package FactoMineR 2.4). The PCA grouped individuals according to their loadings on three principle-components (PCs) which explained 77.5% of the variation in collision behaviour. PC 1 accounted for 40.2% of the total explained variance and was composed of 1st 3 Ruck Arrivals/min ($r = 0.86$), Tackles/min ($r = 0.81$), Carries/min ($r = 0.66$) and Tackle Completion (%) ($r = 0.71$). PC 2 accounted for 19.9% of the total explained variance and was composed of Collision Dominance (%) ($r = 0.86$). PC 3 accounted for 17.5% of the total explained variance and was composed of Breakdown Effectiveness (%) ($r = 0.91$). The Bhattacharyya distance (RStudio package fpc 2.2-9) between position groups was subsequently calculated, demonstrating statistically significant differences in collision behaviours between all forward positions (FR, L, BR) and all back positions (SH, IB, OB) ($p \leq 0.05$), and that all back positions were different to each other ($p \leq 0.05$). Therefore, these initial results demonstrated that typical collision behaviours differ between back positions but are similar between forward positions; and

Table 2. Partial least squares regression models for collision variables among forwards

Model	Carry/min			Tackles/min			Collision dominance		
Components	1			1			1		
RMSEP CV	10.19			9.92			10.0		
R^2	0.22			0.19			0.21		
Predictor Variables	Estimate	*t*	*P*	Estimate	*t*	*P*	Estimate	*t*	*p*
Body mass (kg)	0.08	3.37	**0.01****	−0.07	−1.50	0.16	0.10	2.17	0.06
Skinfolds (mm)	0.09	2.85	**0.02***	−0.07	−2.02	0.07	0.10	2.57	**0.03***
Bench press 1 RM (kg)	−0.09	−1.14	0.29	0.02	0.41	0.69	0.01	0.12	0.91
Countermovement jump peak power (W)	0.04	0.78	0.45	0.04	0.74	0.48	0.06	1.06	0.32
Countermovement jump relative peak power output (W/kgBM)	−0.05	−2.03	0.07	0.10	4.50	**0.00****	−0.02	−0.34	0.74
Single leg drop jump RSI (ft/ct)	−0.08	−1.91	0.09	0.07	1.82	0.10	−0.05	−1.54	0.16
Single leg isometric squat peak force (N)	−0.00	−0.10	0.09	0.05	0.86	0.42	0.03	0.53	0.61
Single leg isometric squat relative force (N/kgBM)	−0.08	−3.13	**0.01***	0.09	2.50	**0.03***	−0.07	−1.24	0.25
0-10 m acceleration velocity (m/s)	−0.01	−0.16	0.87	−0.08	−1.92	0.09	−0.03	−0.49	0.64
0-10 m acceleration momentum (kg/m/s)	0.09	2.38	**0.04***	−0.03	−0.66	0.53	0.11	2.55	**0.03***
MAS (m/s)	−0.10	−2.41	**0.04***	0.02	0.28	0.78	−0.07	−1.49	0.17

*statistical significance (<0.05) **statistical significance (<0.01).

all back positions are different to all forward positions. Subsequently, individual player data for both physical characteristics and collision variables were standardised using Z-scores calculated with the means and standard deviations from these groups (Forwards, and SH, IB, OB). This controlled for the position-specific collision behaviours, prior to the next stage of analysis.

For the main research question, standardised data were split into forwards and backs position groups. To increase the likelihood of identifying meaningful relationships between collision behaviours and physical characteristics, backs were analysed as one group due to a small sample size, despite the between-position differences in collision behaviours. and partial least squares regression (PLSR, RStudio package pls 2.8-0) models were constructed for each group, to explain the common variance between physical characteristics and each of the six collision variables. PLSR finds components that are optimised for both the variability of predictors and the strength of correlation with the response variable; and is robust in instances where a large number of independent variables is combined with a relatively small number of data points (Hair et al., 2019). The root mean squared error of prediction (RMSEP) was calculated for each PLSR component model using k-fold cross validation, to determine the number of model components with the lowest residual error of prediction. This was then taken as the most appropriate model for prediction of each collision variable. The statistical significance of the PLSR coefficients within each model were then calculated by applying the Jack-knife T-test function (RStudio package pls 2.8-0).

Results

The results of the PLSR showed that among forwards, a one-component model accounted for 22% of the variance in carries/min (Table 2). Five predictor variables contributed significantly to the model. Of these, body mass, skinfolds and 0–10 m acceleration momentum, were positively associated with carries/min, whereas SL ISO/kgBM and MAS were negatively associated with carries/min (Table 2). For tackles/min, 18.9% of the variance was accounted for by a one-component model, explained by higher CMJ PPO/BM and SL ISO/kgBM values. For collision dominance, 21.4% of the variance was accounted for by a one-component model, where positive associations with skinfolds and 0–10 m acceleration momentum were found (Table 2).

Among backs, a larger proportion of the variance was explained, where a two-component model accounted for 54% of the variance in tackles/min, within which SL ISO, 1RMBench and SL ISO/kgBM were positively associated (Table 3). For collision dominance, 18% of the variance was accounted for by a one-component model comprising positive and negative associations with SL ISO/kgBM and body mass respectively (Table 3).

Discussion

The current study demonstrates, for the first time among an elite female rugby population, that physical characteristics such as body mass and composition, and strength and power, explain between ∼18% and ∼54% of the variance in collision performance. We also show that performance and effort variables are associated with different physical characteristics. Finally, the contribution of different physical characteristics towards specific collision events is dependent on position, presumably because of the variation in typical collision demands across positions.

Among forward positions, we show that carries/min were positively associated with body mass, skinfolds and 0-10 m acceleration momentum, and inversely

Table 3. Partial least squares regression models for collision variables among backs.

Model	Tackles/min			Collision dominance		
Components	2			1		
RMSEP CV	8.15			9.66		
R^2	0.54			0.23		
Predictor Variables	Estimate	*t*	*P*	Estimate	*t*	*P*
Body mass (kg)	0.18	1.95	0.08	−0.16	−3.16	0.01*
Skinfolds (mm)	0.09	0.81	0.44	−0.01	−0.21	0.84
Bench press 1 RM (kg)	0.32	3.52	0.00*	0.04	0.53	0.61
Countermovement jump peak power (W)	−0.07	−0.70	0.50	−0.03	−0.32	0.75
Countermovement jump relative peak power output (W/kgBM)	−0.19	−2.01	0.07	0.09	1.64	0.13
Single leg drop jump RSI (ft/ct)	−0.05	−0.40	0.69	−0.04	−0.45	0.67
Single leg isometric squat peak force (N)	0.25	2.58	0.03*	0.05	0.62	0.55
Single leg isometric squat relative force (N/kgBM)	0.16	3.13	0.01*	0.13	2.27	0.05*
0-10 m acceleration velocity (m/s)	0.14	1.29	0.23	0.01	0.24	0.82
0-10 m acceleration momentum (kg/m/s)	0.09	0.92	0.38	−0.12	−1.86	0.10
MAS (m/s)	0.16	1.23	0.25	0.12	1.65	0.13

*statistical significance (<0.05) **statistical significance (<0.01).

related to mean aerobic speed and relative leg force. However, combining these characteristics accounted for only ~22% of the variance in carries/min. We also show that acceleration momentum and skinfolds explain ~21% of the variance in collision dominance among these elite forwards. The association between acceleration momentum and both collision dominance and carry frequency is consistent with evidence from male rugby union and league (Baker & Newton, 2008; Hendricks et al., 2014a). Given that player's body mass contributes to their acceleration momentum (i.e. velocity x body mass), and that over-ground velocity alone did not contribute to the regression models reported here, it is likely that increased body mass was largely responsible for the proposed role of momentum in collision dominance and carries/min. Indeed, greater body mass is reported among higher performing forwards (~87-94 kg) compared to lower performers (~78 kg) in female rugby union (Hene et al., 2011; Nyberg & Penpraze, 2016; Posthumus et al., 2020; Woodhouse et al., 2021), and we confirm this characteristic is specifically advantageous, for female forwards who are required to carry the ball into contact and dominate collisions.

It might be expected that "effort" variables, such as carries/min, would be positively associated with aerobic running performance, as reported in elite male rugby (Cunningham et al., 2018). Higher aerobic endurance may facilitate the capacity to maintain higher average speeds of locomotion during match play and recover quickly from high-intensity efforts (Gabbett et al., 2013; Vachon et al., 2021). However, our findings show that lower mean aerobic running performance is associated with more carries/min. This may be explained by the greater body mass and skinfolds observed among forwards who carry frequently, which might negatively affect running capacity because of the greater energy cost of movement among players with higher fat mass (Meir et al., 2001). We also show that mean aerobic speed did not contribute to the regression model for tackles/min. Instead, greater relative leg strength and power positively contributed towards the model, which accounted for ~19% of the variance in tackles/min. These forwards are likely to exhibit a greater force to body mass ratio (A = F/M), which may underpin the ability to repeat bouts of high-intensity actions common in collision sports (Gabbett & Seibold, 2013).

Our findings in regard to running endurance are contradictory to previous reports among elite males (Cunningham et al., 2016). This may be explained by the use of a continuous, shuttle-based aerobic test adopted in this study, compared to the intermittent running tests used in previous reports (Cunningham et al., 2016; Smart et al., 2013). Performance during intermittent and repeated sprint tests is determined not only by aerobic running ability, but by additional physical characteristics, such as maximum speed and acceleration (Pyne et al., 2008). This may reduce the capability of such tests to determine how specific physical characteristics underpin team sport running performance. Continuous measures of running endurance, albeit lacking sport specificity, may represent a narrower range of physical characteristics, and subsequently, hold greater physiological deterministic capability. We maintain therefore, that continuous aerobic running performance is not related to collision performance among this cohort.

Physical characteristics accounted for ~22% of the variance in collision dominance among the backs. But in direct contrast to the forwards, we show that collision dominance was negatively associated with body mass, and positively associated with relative leg force production. The women's game has historically biased ball-in-hand running as the primary attacking means

(Hughes et al., 2017), suggesting that backs may typically attack and defend with more space around them, increasing the likelihood of one-on-one tackles. This is favourable for the attacking team, as one-on-one tackles account for 93% of tackle breaks (Wheeler et al., 2010). Winning collisions among backs, could, therefore, be more strongly related to characteristics that underpin movement speed and agility, than mass and momentum characteristics, which are more strongly associated with winning collisions among forwards. Although we did not show acceleration over 10 m to contribute to collision dominance, as shown in male rugby (Cunningham et al., 2016), it is well established that high levels of relative strength and power are strongly related to acceleration speed and agility in elite male rugby players (Cunningham et al., 2018; Delaney et al., 2015; Hansen et al., 2011). Greater relative strength could, therefore, underpin the ability to achieve high speed prior to the collision in defence (Hendricks et al., 2012) and apply powerful leg-drive at the point of contact when carrying and tackling (Gabbett & Ryan, 2009).

We also show that ∼54% of the variance in tackles/min was accounted for by a combination of bench press 1RM, single-leg peak and relative force among backs. Higher strength levels are associated with a reduced decrement in tackle technique when fatigue levels are high (Davidow et al., 2020), and a greater capacity to maintain running outputs between high-intensity efforts (Gabbett, 2016). Therefore, tackle impacts and grapples may be executed at a lower relative intensity by stronger players compared to weaker players and are subsequently tolerated with less induced fatigue. We carried out a preliminary investigation of position specific collision behaviours using PCA, which was separate to, but served to inform the subsequent PLSR. The PCA confirmed that the collision behaviours of back positions differ from one another. This indicates that relationships between collision performance and physical characteristics, should be analysed within these groups, to avoid erroneous associations. For example, strength might be associated with Tackles/min, but should be questioned because centres are bigger, stronger (Quarrie et al., 1995), and due to their tactical placement, make more frequent tackles than half backs (Schoeman et al., 2015). Whilst we standardised physical characteristics and collision variables within back positions (SH, IB, OB) prior to the PLSR, the small sample size meant they were analysed as one group. Therefore, although our findings suggest that absolute and relative strength and power characteristics should be developed to optimise collision performance among elite female rugby union backs, similar research projects should consider the possible bias of tactical opportunity within their methodology.

This is the first study to show that physical characteristics are associated with the ability to perform a high "density" (high frequency per min) of tackles, and to win collisions among elite female rugby players. However, the extrapolation of our findings to future female rugby playing populations, should be approached with some caution. For example, the physical characteristics of opposing players, with more professionally mature training habits, may be advanced compared to those players from amateur teams (Smart et al., 2013; Woodhouse et al., 2021). We cannot, therefore, discount that collision performance was not influenced by the strength of the opposition as this was not controlled for. The number of nations providing professional contracts to female players is also increasing, which may reduce the typical deficits observed, in the physical capabilities of amateur, compared to professional teams (Smart et al., 2013; Woodhouse et al., 2021). Finally, intra- and inter–coder agreement was ∼5%CV for whole matches using the performance analysis definitions featured in the current study. We did not investigate the consistency of each performance indicator separately. This is a limitation to both the generalizability and consistency of collision variables, and it is recommended that the reliability of each specific variable is reported in future studies. Therefore, interpretation and applications of our findings to future research, should consider factors such as the sampling of a single squad, the standard of opposition, the context of the sampling period, and the consistency of collision definitions. Future research should investigate whether the physical characteristics associated with collision performance have changed over time. Practitioners should also be mindful that physical characteristics accounted for only ∼ 19-54% of the variance in collision performance. This is consistent with previous reports (Speranza et al., 2017) and suggests that factors, such as training volume, and technique during the tackle and carry, might also account for variance in collision performance (Hendricks et al., 2014b; Wheeler et al., 2010). We therefore concur with previous suggestions that the development and maintenance of physical characteristics such as leg strength, should be viewed as an adjunct for optimal collision skill development during training and match play exposures (Speranza et al., 2017).

Our findings are informative for elite female rugby sports performance coaches. We suggest strength and conditioning practitioners can improve collision performance by advancing specific gross physical characteristics, according to a player's position and the tactical role they are expected to fulfil. The R^2 values for each regression model and the coefficients within each model can support objective decision-making for physical development programmes. For example, according to our regression coefficients, a 2.38 kg/m/s increase in acceleration momentum may elicit a 1% increase in collision dominance among forwards. Practitioners should estimate whether this magnitude of change in performance justifies the investment required to achieve such physical changes. With regard to this, the minimum detectable change for our assessments varied between 1.5 and 5% (Hopkins, 2004), which in many cases fell within the typical inter-trial variability (CV 2–10%) (Woodhouse et al., 2021). Determination of meaningful change using these assessments should, therefore, consider the typical variation associated with each assessment.

In summary, our findings indicate that the development of acceleration momentum could benefit the performance of forwards, based on its association with ball carrying frequency and collision dominance. To enhance acceleration momentum, strength and conditioning coaches should consider a combination of strategies designed to balance increases in lean body mass, and the maintenance, or concurrent development of acceleration, such as resistance training (Appleby et al., 2012), and resisted sled training (Harrison & Bourke, 2009) respectively. Relative strength and power characteristics can also contribute positively towards effort variables such as tackles/min among forwards. Among backs, well-developed upper- and lower-body strength is important for increased tackle frequency, and relative lower-body strength may facilitate the ability to dominate attacking and defensive collisions.

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