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Physical abilities and morphological variables of International female rugby union players and relationships with match performance variables across five seasons

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Abstract

Purpose: The aim of this study was to examine the relationships between combinations of physical abilities and morphological variables with KPIs and running loads during matches in International rugby union players. **Methods**: A total of 831 match performances from seventy-six female players, across five competitive seasons, were analysed between 2015 and 2019 using global positioning systems and performance analysis. A total of 309 physical assessments over 33 testing dates were also used for analysis. The relationships between match running and performance analysis variables, and closed testing variables were assessed using linear mixed modelling, with control for positional and season variation. **Results**: Several relationships were found between match and testing data. Maximal aerobic speed (MAS) had a positive relationship with the number of sprints, total distance, total distance < 3 $m \cdot s^{-1}$, total distance 3 to 5.5 $m \cdot s^{-1}$, and total distance > 5.5 $m \cdot s^{-1}$ performed in games (η^2 = 0.31, 0.22, 0.02, 0.14, 0.18, respectively). Countermovement jump (CMJ) was positively associated with all kinematic variables, including: accelerations (η^2 = 0.12), decelerations (η^2 = 0.09), sprints (η^2 = 0.28), total distance (η^2 = 0.21), and total distance greater than 5.5 $m \cdot s^{-1}$ (η^2 = 0.26). Skinfolds showed a positive relationship with total distance (η^2 = 0.40) and sprints (η^2 = 0.34). Sprints also had a negative relationship with 10 m split time (η^2 = -0.22). **Conclusion**: The positive relationship of MAS and CMJ with various on-field work-rate metrics highlight the importance of conditioning both endurance capacity and explosive power to achieve international standards in female rugby union. Skinfold results were unexpected but were attributed to positional variance within the current squad and possible 'protective' effects of higher fat mass. The current results suggest that practitioners can potentially improve match-running performance by improving certain physical abilities; namely, CMJ and MAS, irrespective of positional influence, in female rugby union.

Declarations

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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GPS – Global Positioning System

TD – Total Distance

KPI – Key Performance Indicators

CMJ – Countermovement Jump

1RM – One Repetition Maximum

F-V – Force-Velocity

F_0 – Theoretical Maximal Force

V_0 – Theoretical Maximal Velocity

P_{max} – Theoretical Maximal Power

$\dot{V}O_2$ max – Maximal Oxygen Uptake

TMA – Time-Motion Analysis

HSR – High-Speed Running

WCS – Worst Case Scenarios

MAS – Maximal Aerobic Speed

P-V – Power-Velocity

FR – Front Row

BR – Locks and Back Row

SH – Scrum-Halves

IB – Inside Backs

OB – Outside Backs

PA – Performance Analyst

ISAK - International Society for the Advancement of Kinanthropometry

η^2 - Effect Size Correlation

CI – Confidence Interval

df – Degrees of Freedom

Mom10 – Momentum over 10 m

Mom20 – Momentum over 20 m

Mom30 – Momentum over 30 m

SSC – Stretch-Shortening Cycle

Chapter 1.0 – Introduction

Rugby union is a technical and tactical sport, requiring high levels of physical exertion, at various speeds and intensities (Duthie et al., 2003; Cahill et al., 2013; Eaton & George, 2006; Nicholas, 1997). The physical demands of men's rugby union are well-documented, using both time-motion analysis (Roberts et al., 2006; Deutsch et al., 2007), and global positioning systems (GPS; Cunningham et al., 2016a; Cahill et al., 2013; Reardon et al., 2015; Cunniffe et al., 2009; Coughlan et al., 2011). The use of GPS-based microtechnology is considered a reliable method for the analysis of physical loads in team sports (Cunniffe et al., 2009; Petersen et al., 2010; Wisbey et al., 2010; Carling, 2013; Buchheit et al., 2014). Using this method, match and training load is often described by kinematic measures, such as running distance, speed, accelerations, decelerations, impacts and contacts (Cunningham et al., 2016a; Cahill et al., 2013). The ability to understand the physical demands of rugby union is especially important in order to develop effective training programmes and maximise on-field performance (Quarrie et al., 2013).

In rugby union, different field positions tend to perform different physical loads during matches. For example, elite-level forwards cover between 4,000 and 7,000 m Total Distance (TD), and backs between 5,000 and 8,000 m (Quarrie et al., 2017; Roberts et al., 2008; Swaby et al., 2016). Forwards have more collisions than backs across a match (26 ± 9 *vs.* 14 ± 6; Roe et al., 2016), whereas backs cover greater high-speed running distance than forwards (Cunningham et al., 2016a; Roberts et al., 2008; Swaby et al., 2016). Moreover, approximately 25% of backs' TD is covered at sprinting speeds, in comparison to 4% for forwards (Duthie et al., 2006b; Duthie et al., 2005). Further analysis has shown that there is also variance in physical loads between forwards and amongst backs. For example, Cahill et al. (2013) reported that Scrum Halves cover the most TD amongst backs (7098 ± 778 m), whereas Cunningham et al. (2016a) reported that Centres cover the most TD amongst backs (6510 ± 710 m). Furthermore, Cunningham et al. (2016a) also report that the Front Row cover the least TD, 4970 ± 750 m, which is supported by the findings of Cahill et al. (2013), despite having the greatest impact load among forwards (MacLeod et al., 2018). In addition, Cunningham et al. (2016a) also suggest that Full-Backs and Wingers cover the greatest distances at high-speeds (728 ± 150.2 m). In summary, backs tend to have greater sprinting and distance loads than forwards, while forwards tend to have greater contact loads.

There is very little data relating to the match demands or the physical and performance characteristics of elite female players. Indeed, only two studies have reported on international female players (Suarez-Arrones et al., 2014b; Sheppy et al., 2019), with TD covered (between 5,308 and 6,332 m), similar to that of male players (between 4,015 and 7,117 m; Roberts et al., 2008; Swaby et al., 2016). Backs cover significantly more TD than forwards (6,356 ± 144 m *vs.* 5,498 ± 412 m; Suarez-Arrones et al., 2014b), like the men's game (Suarez-Arrones et al., 2014a; Cunningham et al., 2016a; Roberts et al., 2008; Swaby et al., 2016). This suggests that female rugby players have similar distance loads as their male counterparts (Cunningham et al., 2016a; Virr et al., 2014). Conversely, Sheppy et al. (2019) reported no significant difference in TD loads between forwards and backs (5784 ± 569 m), which contradicts the findings of Suarez-Arrones et al. (2014b) and well-documented findings from the men's game (Quarrie et al., 2017; Cunningham et al., 2016a; Cahill et al., 2013). Despite this finding, Sheppy et al. (2019) reported that during the most intensive periods of a match, backs cover higher distances than forwards; which, is consistent with the men's game (Cunningham et al., 2018). Furthermore, Sheppy et al. (2019) suggest that the difference in distance covered amongst forwards and backs can be accounted for by the time spent at close proximities to other players, and the number of contacts and collisions. In summary, these findings suggest that female rugby union players can cover similar distances to the male rugby union players, and that differences in tactical roles in rugby union matches can account for some of the variation in distance covered and running thresholds (Sheppy et al., 2019; Quarrie et al., 2013; Suarez-Arrones et al., 2014b; Virr et al., 2014).

Extensive research highlights the importance of strength, power, aerobic and anaerobic fitness on the movement capabilities of rugby union players (Cunningham et al., 2016b; Swaby et al., 2016; Sheppard & Young, 2006). Thus, closed physical testing can be used to partially inform the likelihood of success in sport and whether an athlete is physically prepared for performance. In rugby union, successful teams outperform their opposition in key performance indicators (KPI), such as successful mauls, line breaks, tackles, clean breaks and turnovers (Cunningham et al., 2018;

Watson et al., 2017; Vaz et al., 2010; Den Hollander et al., 2016; Ortega et al., 2009), which often require high-intensity efforts at crucial moments of the game. For example, acceleration, sprinting and high-speed running is related to the success rate of KPIs, such as clean breaks and tackles (Gabbett & Kelly, 2007; Hendricks et al., 2014b). Cunningham et al. (2016b) reported that a rugby player's acceleration capacity is significantly related to relative strength, relative power, and jump height. Similarly, Cronin and Hansen (2005) suggest that countermovement jump (CMJ) height and squat jump relative power outputs are significantly greater in faster players over short distances. This suggests that acceleration and sprinting performance is related to jump height. Furthermore, McMaster et al. (2017) report that jump height and jump distances were the best predictors of 10 m sprint acceleration ability in female, elite rugby sevens players. This suggests that explosive movements, such as a CMJ, are good predictors of a rugby players' acceleration capabilities and, thus, a good predictor of the likelihood of success in KPI such as clean breaks and tackles.

High sprinting speed, achieved during longer distances, is also an important ability in rugby union, which might be most useful to support match actions, such as line breaks and recovery runs. Typically, rugby union athletes achieve their maximum velocities between 20 and 30 m (Cross et al., 2015), with backs reaching higher maximum velocities compared to forwards in the men's game (9.28 ± 0.37 *vs.* 8.65 ± 0.59 $m \cdot s^{-1}$) and in the women's (6.78 ± 0.22 *vs.* 6.11 ± 0.97 $m \cdot s^{-1}$) (Cross et al., 2015; Suarez-Arrones et al., 2014b). Female backs also perform higher sprint frequencies, maximal sprint distances, and greater average sprint distances than their forward counterparts (Suarez-Arrones et al., 2014b). This suggests that backs get closer to maximal velocities more frequently, and for longer, during matches than forwards. However, the findings of Suarez-Arrones et al. (2014b) may be limited and not representative of elite female players given the small sample size (n = 8) and the sub-elite status of the teams used. Furthermore, Cunningham et al. (2016b) suggest that, in comparison to acceleration, maximum velocity sprinting is related to relative power, reactive strength index and leg spring stiffness. These findings suggests that maximum velocity and acceleration rely on different underlying qualities.

Cunningham et al. (2016b) found that absolute strength was not related to 10 m speed in professional rugby union players; whereas, relative strength was. This suggests that a suitable balance between strength or force production capability and body mass will determine powerful whole-body actions, such as sprinting and accelerating. The difference in body mass between players could be explained by the different tactical roles and physical demands of matches for forwards and backs. Duthie et al. (2006a) reported that body mass, skinfold thickness, and lean mass index were all higher for forwards than backs. Similar findings were also reported in the women's game, with forwards reporting higher body mass results (57.5 ± 7.50 *vs.* 49.5 ± 4.93 kg) and greater skinfold thickness (51.8 ± 10.51 *vs*. 39.4 ± 11.39 mm) than backs (Sarkar & Dey, 2019). It was suggested that a higher skinfold thickness for forwards could have provided a 'protective layer', to absorb some of the impact from collisions (Sarkar & Dey, 2019). In summary, heavier athletes (i.e. forwards) produce higher levels of absolute force and initial sprint momentum (< 10 m) to assist with collisions (Cross et al., 2015; Barr et al., 2014), which presumably assist with crucial elements of the game, such as tackles, carries, rucks, mauls and scrums (Hendricks et al., 2014a). Conversely, backs tend to be lighter and produce more vertical force, horizontal force, and power, relative to body mass, during initial acceleration phases, up to 15 m (Brown et al., 2016). Thus, according to Newton's second law of motion, backs tend to have better acceleration capabilities, which might assist with reaching the frequent high-speed requirements, and permitting higher force ($F = m \cdot a$) and momentum ($p = m \cdot V$) (Barr et al., 2014), outputs compared to forwards. Moreover, body mass and skinfold thickness, without an increase in muscular force, negatively correlate with sprint and acceleration performance (Perez-Gomez et al., 2008; Duthie, 2006); although, this is probably more beneficial in collisions and tackles by providing a protective layer to dissipate energy of collisions forces, and by increasing a player's momentum heading into the tackle (Sarkar & Dey, 2019; Hendricks et al., 2014a).

Strength and power are also important attributes in rugby union, given the high number of contacts in games. Forwards, especially the front row, tend to have greater upper-body strength and power than backs, as demonstrated in exercises such as bench press at 1 repetition maximum (1RM; Smart et al., 2013). Furthermore, forwards have greater absolute lean mass index (61.3 ± 1.9 *vs.* 53.3 ± 1.7 $kg \cdot mm^{-1}$) than backs; as well as greater lean mass in the arms (12.7 ± 0.5 *vs.* 10.5 ± 0.5 kg) and in the trunk (42.7 ± 1.3 *vs.* 36.8 ± 1.3; Zemski et al., 2015). This could be explained by the physical demands of each playing position, whereby forwards are involved in more force- and power-dominant activities involving upper body strength, such as collisions. Therefore, a greater body mass and greater propulsive mass would increase the likelihood of success in these scenarios.

Crucial moments of the games and KPI predominantly occur in high-intensity environments, such as sprinting, tackling, carries, collisions, clean breaks and involvement in rucks, mauls and scrums (Cahill et al., 2013; Barr et al., 2014). Force-velocity (F-V) profiling allows practitioners to estimate mechanical capabilities of the neuromuscular system for gross and complex tasks (Cross et al., 2015), which could inform the likelihood of success in crucial moments. Furthermore, F-V profiling can be used to predict an athlete's theoretical maximum force (F_0), maximal velocity (V_0) and maximal power (P_{max}); both horizontally and vertically (Cross et al., 2015; Cross et al., 2017). For example, Escobar Álvarez et al. (2020) show that, in amateur female rugby union, backs demonstrated faster split times at 5 and 20 m, and demonstrate higher horizontal F_0, V_0 and P_{max} than forwards. This suggests that F_0, V_0 and P_{max} correlate with sprint and acceleration performance. However, these findings also imply that backs would perform better than forwards in activities thought to require higher amount of absolute force, such as rucks, carries, collisions and mauls. This contradicts findings in the men's game, suggesting that forwards possess a more force-orientated profile; whereby, forwards produce larger absolute force and power than backs (Cross et al., 2015). Thus, it is possible that female athletes may not share the same positional traits as male athletes; however, this is not yet known in well-trained athletes.

The findings by Escobar Álvarez et al. (2020) also report that backs had higher body masses than forwards, contradicting well-documented findings from the men's game (Nicholas, 1997; Duthie et al., 2003). Thus, considering the effect of momentum ($p = m \cdot V$; Barr et al., 2014), these findings suggest that backs would be more successful in tackles and collisions. Rather, momentum is an essential determinant of success in force-related and contact activities in rugby such as tackling, collisions, rucks and mauls (Hendricks et al., 2014a; Barr et al., 2014). Conversely, the findings by Escobar Álvarez et al. (2014) could also be explained by the difference between elite and amateur level. This highlights the need for further research of F-V profiling in elite women's rugby union.

High-intensity activities only contribute 15% of total game time; with 85% consisting of sub-maximal activities such as standing, walking and jogging (Duthie et al., 2003; Swaby et al., 2016). In order to sustain performance during the sub-maximal periods of the game, and to assist recovery between high-intensity activities, high levels of aerobic fitness are essential for rugby union performance. Furthermore, backs perform greater high-intensity runs, 59 ± 28, than forwards, 41 ± 16 (Roberts et al., 2008), and cover greater distance at sprinting speeds (Cunningham et al., 2016a). Roberts et al. (2008) also suggest that elite-level backs cover significantly greater distances at high running speeds (448 ± 149 m) compared to forwards (298 ± 107 m), as well as non-significantly greater distances at sprinting speeds (207 ± 185 m) than forwards (164 ± 189 m). Conversely, forwards perform high-intensity static exertion for longer periods, 7:56 ± 1:56 min, than backs, 1:18 ± 0.30 (Roberts et al., 2008; Swaby et al., 2016). Therefore, both forwards and backs require aerobic fitness for recovery from different high-intensity activities (Duthie, 2006). However, forwards are typically heavier than backs with higher muscle and fat mas; therefore, backs typically produce higher relative maximal aerobic capacity ($\dot{V}O_2$ max) values than forwards (Scott et al., 2003). This suggests that backs tend to be more aerobically fit than their forward counterparts, which is likely to support their in-match activity profiles (Swaby et al., 2016) but this is yet to be determined in female players.

Whilst the overall physical demands of male rugby union are well-documented, those of female players are not and it is unclear if an elite female player's physical size and abilities influence the number of KPI and running loads completed during matches. Therefore, the purpose of the current study was, for the first time, to examine the relationships between combinations of physical abilities and morphological variables with KPIs and running loads during matches in International female rugby union players, across five consecutive seasons, with statistical control for season and positional variations.

Chapter 2.0 – Review of Literature

2.1 Literature search methodology

A literature search was conducted to evaluate the present findings surrounding the match demands of elite female rugby union and the physical profiling of players. From this literature search, the present research question was formulated based on gaps and inconsistencies in other research findings (Grewal, Kataria, & Dhawan, 2016).

The literature search had to be systematic and well-organised to identify the breadth of research and to ensure the quality of research on elite female rugby union (Rau, 2004). Several search engines, electronic databases and sport journals were used for the literature search, including google scholar, PubMed and EBSCOhost. To maximise the retrieval of relevant research and findings, questions were translated to keywords and synonyms were considered for all keywords. Spelling was also considered, such as the difference between US English and UK English. Research and findings that have been published in peer-reviewed journals were considered as primary sources of literature for the literature review (Cronin, Ryan, & Coughlan, 2008). Where gaps and inconsistencies became apparent in the literature, secondary and tertiary sources of literature, such as systematic reviews, meta-analyses and reference books, were considered and used where appropriate (Cronin et al., 2008).
The research topic derived from both the primary literature search and the existing theories and findings outside of female rugby union, surrounding the relationships between physical abilities and morphological variables, as well as match running and performance. A literature review was conducted to document the findings from the literature search. The literature search first examined the match demands of rugby union. It became clear that the majority of literature concerned men's rugby union, therefore the search was then specialised into female rugby union. From this search, it became apparent that players' match running demands and contact loads differed between positions (Cahill et al., 2013; Cunningham et al., 2016a; Quarrie et al., 2013). Therefore, the anthropometric characteristics of elite female players were reviewed, as well as their physical capabilities, by position. Based on findings into the physical characteristics of rugby union players, and a framework provided by Duthie (2006),

the physical capabilities of elite female rugby union players were assessed as maximal oxygen uptake, anaerobic performance, force-velocity relationship, upper-body strength and power, and speed. Where relationships between variables, such as the linked between physical capabilities and match performance, became apparent in existing literature, phrases, Boolean operators and filters were used to expand and specialise the literature search - into elite female rugby union where appropriate (Grewal et al., 2016).

To mitigate bias within the literature review, pre-, mid- and post-trial bias were considered for all primary sources of literature, as identified by Pannucci and Wilkins (2010). For example, in a study by Suarez-Arrones et al. (2014b), possible pre-trial bias was identified as the elite classification of players and sample size suggest potential selection and channelling bias. Furthermore, to mitigate personal bias, all literature from the literature search was carefully examined for design bias, selection bias, data collection bias, analysis bias and publication bias (Smith & Noble, 2014); in order to create a clear and unbiased representation of the current findings and research into elite female rugby union.

2.2 Physical match demands of Rugby Union

2.2.1 Analysis of physical match demands in elite rugby union

Rugby union is a complex and tactical contact sport that requires high levels of physical exertion throughout an 80 min match (Duthie et al., 2003; Cahill et al., 2013; Eaton & George, 2006; Nicholas, 1997). Moreover, there are fifteen playing positions, generically sub-grouped into ‘forwards’ or ‘backs’, that require different physical attributes and skill sets (Cahill et al., 2013). Thus, the physical demands of rugby union are dependent on field position, and can be quantified through various physical metrics, such as distance, speed and contact loads (Quarrie et al., 2017; Cahill et al., 2013; Roe et al., 2016; Cunningham et al., 2016a).

The ability to quantify the physical demands of rugby union allows practitioners to monitor overall physical loads, which is especially important in injury prevention, rehabilitation, developing effective training programmes and maximising performance (MacLeod et al., 2009; Quarrie et al., 2013). Several studies have attempted to quantify the physical demands of rugby union, based on both manual time-motion analysis (TMA) and, more recently, information gathered from global positioning system (GPS). TMA is a non-invasive method of identifying the physical demands of field-based sports by quantifying the movement patterns of players (Roberts et al., 2006). However, the validity of TMA has been questioned as some studies have shown that it underestimates GPS and semi-automated systems (Randers et al., 2010; Dobson & Keogh, 2007; Cahill et al., 2013; Coughlan et al., 2011; Cunniffe et al., 2009). In comparison, although the validity and reliability of GPS devices has also been questioned (Gray et al., 2010; Scott et al., 2016); the validity and reliability of the technology has improved (Hoppe et al., 2018). Therefore, player monitoring using GPS devices remains common practice in most field-based sports (Cunniffe et al. 2009; Petersen et al., 2010; Wisbey et al., 2010; Carling, 2013; Buchheit et al., 2014).

Total distance (TD) covered by an elite rugby union player during matches can range anywhere between 4,000 and 7000 m for forwards, and between 5000 and 8000 m for backs (Quarrie et al., 2017; Roberts et al., 2008; Swaby et al., 2016). For example, Cunningham et al. (2016a) report that backs cover greater TD, 6230 ± 800 m *vs.* 5370 ± 830 m, and greater high speed running (HSR) distance, 656.9 ± 182.7 *vs.* 284.2 ± 134.9 m than forwards. Furthermore, approximately 4% of TD for forwards is covered at sprinting speeds, whereas backs cover approximately 25% of TD at sprinting speeds (Duthie et al., 2006b; Duthie et al., 2003). Moreover, backs also have higher maximum velocities, 9.01 ± 0.34 *vs.* 8.45 ± 0.54 $m \cdot s^{-1}$ for forwards (Cross et al., 2015), and perform a greater number of sprints during a match; 26.44 ± 7.47 *vs.* 11.15 ± 5.06 for forwards (Cunningham et al., 2016a). However, forwards have a greater number of collisions than backs, 26 ± 9 for forwards *vs.* 14 ± 6 for backs (Roe et al., 2016). In summary, current assessments of the physical demands in elite male rugby union suggest that backs cover greater overall and high speed running distances; whereas, forwards have greater contact loads.

Although the differences in physical performance between forwards and backs are consistent across most studies, there are discrepancies regarding the positional differences in the physical performance within said units for men's rugby union. For example, some studies report that Half-Backs, the Scrum Half and Fly Half, cover the most TD amongst backs (Cahill et al., 2013; Quarrie et al., 2013); whereas, Cunningham et al. (2016a) report that Centres cover the most TD. Furthermore, Cahill et al. (2013) report that the Back Row cover greater distances at ‘sprinting’ speeds. This contradicts other findings suggesting that the greatest HSR distances are covered by Full Backs and Wingers (Cunningham et al., 2016a; Quarrie et al., 2013). Sprints or high-speed intensity movements are important in determining success or related to superior teams in rugby league (Gabbett, 2005; Gabbett et al., 2008) and union (Tee et al., 2017). Thus, this highlights the importance of sprint, HSR and contact load monitoring in rugby union. However, one consistent finding is that the Front Row cover the least TD (Cahill et al., 2013; Cunningham et al., 2016a). Furthermore, the Front Row have the greatest impact load amongst the forwards despite there being no difference total number of collisions between the forwards (MacLeod et al., 2018). Therefore, while the Front Row do not cover as much TD as other forwards, they contribute to the overall team success through low velocity, high force actions to gain and retain possession; such as carries, rucks and mauls (Nicholas, 1997; Rigg & Reilly, 1988; Duthie et al., 2003). The same could be said for the difference in distance loads between forwards and backs.

2.2.2 Analysis of physical match demands in elite female rugby union

To the best of the current authors’ knowledge, only two studies have examined the physical demands of match play in elite female rugby union. Suarez-Arrones et al. (2014b) reported that mean total distance (TD) covered by elite female player in a single match was 5,820 ± 512 m, with backs covering significantly more distance than forwards (6,356 ± 144 m *vs.* 5,498 ± 412 m respectively). These figures suggest that female rugby players can cover similar absolute TD than their male counterparts (Cunningham et al., 2016a; Virr et al., 2014). Moreover, Sheppy et al. (2019) found that whilst TD was comparable to that of elite male rugby players, TD and high-speed running (HSR) during the most intense periods was higher in the men’s game. Rather, average TD covered by international female players in these ‘worst-case scenarios’ (WCS), ~143-161 m min^{-1}, falls below that of reported figures for international men,

~154-184 m min^{-1} (Cunningham et al., 2018; Delaney et al., 2017). This suggests that male rugby union is more demanding during the most intensive periods of the game than the female game; however, it is also arguably less demanding during the least intensive periods given the similar outputs in TD covered between men and women.

In contrast to the findings of Suarez-Arones et al. (2014b), Sheppy et al. (2019) reported no differences in TD covered between backs and forwards in international female player, despite reporting similar outputs for overall TD (5784 ± 569 m). Despite no difference in TD, Sheppy et al. (2019) reported that WCS TD in the women's game is higher for backs than forwards. This has also been reported in the men's game (Cunningham et al., 2018). It is hypothesised that differences in tactical roles within gameplay, between forwards and backs, can account for some of the differences in WCS TD (Sheppy et al., 2019; Quarrie et al., 2013; Suarez-Arrones et al., 2014b; Virr et al., 2014). Rather, the running demands for forwards is largely influenced by the high number of contacts and the amount of time spent in close proximity to other players (Sheppy et al., 2019). Furthermore, backs tend to have larger amounts of space to work in than forwards, which theoretically facilitates greater HSR than forwards. However, Sheppy et al. (2019) highlight a key limitation of comparing HSR outputs, for example between positions and gender, as the disparity in the thresholds used to indicate HSR. Nonetheless, previous research into the men's and women's game suggests that forwards tend to cover less TD and HSR than backs throughout a whole game (Quarrie et al., 2013; Suarez-Arrones et al., 2014b).

The Front Row in the elite women's game have been shown to produce lower TD and WCS TD than most other positions. Rather, Sheppy et al. (2019) reported that the Front Row covered less total TD in the first half of games than all positions other than the Second Row, as well as less TD in the second half of games than all positions other than Half-Backs. Sheppy et al. (2019) also reported that the Front Row covered less WCS TD than Half-Backs and Back Three at all epochs of the WCS, as well as less WCS TD than all other positions for more than one epoch. Furthermore, all positions performed more HSR at all epoch durations of the WCS. This suggests that the Front Row return the lowest locomotor demands during matches; with the Half-Backs and Back Three returning the highest. However, as previously suggested, forwards, including the Front Row, tend to operate in smaller spaces and have greater number of contacts than backs. Thus, Front Row players are likely to perform more high-intensity activity through static exertions, such as rucks, mauls and scrums (Roberts et al., 2008). This highlights the need for future research to examine other physical performance metrics other than locomotor activities, such as collision loads and acceleration metrics, to better quantify the positional physical demands of elite female rugby union.

2.3 Physical characteristics of Rugby Union players

2.3.1 Anthropometric characteristics of elite female rugby union players

Few studies have examined the anthropometrical and physical characteristics of elite female rugby union players, or examined the difference between different positions. One study compared differences between forwards and backs amongst 25 national Indian rugby union players (Sarkar & Dey, 2019). It was reported that forwards were heavier (57.5 ± 7.50 *vs.* 49.5 ± 4.93 kg) and had greater skinfold thickness (51.8 ± 10.51 *vs.* 39.4 ± 11.39 mm) than backs. In contrast, backs showed higher relative muscle mass (0.42 ± 0.02 *vs.* 0.40 ± 0.02 kg·kg body mass^{-1}). Sarkar and Dey (2019) suggested that the higher skinfold thickness seen in forwards was conducive to absorbing some of the impact from collisions; thus, providing a form of protective layer. As highlighted previously, forwards tend to operate in areas close to other players, and have more collision based high-intensity efforts than backs (Cahill et al., 2013; Roe et al., 2016; Cunningham et al., 2016a; Sheppy et al., 2019). Therefore, it is logical that higher skinfolds and body masses are beneficial to a forward's game related efforts; likewise, a lower fat mass is beneficial to a back's game related efforts as they tend to cover more TD, HSR distance, sprinting distance and general locomotor activity (Cahill et al., 2013; Roe et al., 2016; Cunningham et al., 2016a; Sheppy et al., 2019). However, as of 1st May 2020, India ranked 41st in the world for women's rugby union (World Rugby, 2020); thus, using national Indian women rugby union players is not a good representative of elite, international female rugby union players. Furthermore, international female players tend to be taller, heavier and produce better fitness results than national female players (Newton, 2011).

Posthumus et al. (2020b) assessed the anthropometric and body composition characteristics of elite female rugby union players from New Zealand. It was reported that forwards were taller (175.6 ± 6.3 *vs.* 167.0 ± 6.6 cm), heavier (93.7 ± 10.9 *vs.* 73.3 ± 7.5 kg), had greater body fat percentages (26.5 ± 3.1 *vs.* 20.8 ± 3.0 %) and greater lean mass (66.2 ± 6.3 *vs.* 55.6 ± 5.3) than backs; which support findings from previous studies (Kirby & Reilly, 1993; Hene et al., 2011; Hene & Bassett, 2013). However, the figures and findings from Posthumus et al. (2020b) are more representative of current elite female rugby union players, with the majority of English international athletes only being offered professional contracts in 2019 (De Menezes, 2019).

Body mass is a key determinant of performance in locomotor activities in rugby union. For example, a larger body mass and size have been shown to correlate with force produced in the scrum, and competitive success (Quarrie & Wilson, 2000; Olds, 2001). This is logical given that force is a product of mass and acceleration ($F = m \cdot a$; Barr et al., 2014). Similarly, it is suggested that adequate amounts of body mass, including fat mass, is essential for athletes to withstand the effects of collisions (Zemski et al., 2015). However, excess fat mass reduces power-to-weight ratio, increases energy expenditure and reduces horizontal and vertical acceleration (Duthie et al., 2003; Duthie, 2006; Withers et al., 1986). Thus, athletes with leaner body mass and lower body fat increases both mobility and power (Duthie et al., 2003; Olds, 2001; Dacres-Manning, 1998), which is again logical given power is a product of force and velocity (Knuttgen & Kraemer, 1987). Therefore, body mass, fat mass and lean mass directly impact an athlete's ability to generate force, velocity and power. This is essential when determining the ideal somatotype of rugby union athletes, given the impact on performance in sprints, accelerations and collisions (Smart et al., 2014; Zemski et al., 2015; Duthie et al., 2003). To the best of this authors knowledge, it is yet to be confirmed if the effects of body, fat and lean mass on performance are replicated in female rugby union.

2.4 Physical capabilities of rugby union players

2.4.1 Maximal oxygen uptake

Aerobic fitness is an essential component of rugby union given that approximately 85% of the game is played at submaximal intensities; for example, standing, walking and jogging (Duthie et al., 2003; Swaby et al., 2016). High levels of aerobic fitness also facilitate the repetition and recovery of high-intensity efforts (Reid & Williams, 1974) Thus, aerobic fitness could determine the performance during crucial high-intensity efforts, such as tackles, carries, rucks, mauls and scrums, across the course of the game (Duthie et al., 2006b; Roberts et al., 2008). Maximal oxygen uptake ($\dot{V}O2_{max}$) can be used as an indicator of aerobic fitness in rugby union players (McMahon & Wenger, 1998), and is positively related to the total distance covered, number of sprints performed and number of involvements by players in team sports (Stone & Kilding, 2009; Helgerud et al., 2001; Bishop & Spencer, 2004). Moreover, Swaby et al. (2016) suggest that improvements in aerobic fitness can increase total distance covered by rugby union in games; however, research is limited and less conclusive than that of soccer.

Male rugby union players report mean $\dot{V}O2_{max}$ values between 43.2 and 52.7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (Kramer et al., 2019; Williams et al., 1973; Deutsch et al., 1998; Warrington et al., 2001), with international players yielding higher $\dot{V}O2_{max}$ scores of 54.1 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (O'Gorman et al., 2000). Furthermore, backs yield higher $\dot{V}O2_{max}$ scores than forwards, 57.5 ± 2.7 *vs.* 53.8 ± 3.5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, which is logical given the greater locomotor demands (Deutsch et al., 2007; Roberts et al., 2008; Swaby et al., 2016; Quarrie et al., 2017; Cunningham et al., 2016a). In contrast, research examining the aerobic fitness of female rugby union players is very limited, with only one study reporting $\dot{V}O2_{max}$ values for international Indian players (35.8 ± 4.65 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ for forwards *vs.* 40.2 ± 4.66 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ for backs; Sarkar & Dey, 2019). This conforms to the finding that backs yield higher $\dot{V}O2_{max}$ values than forwards, as reported in the men's game (Deutsch et al., 2007; Roberts et al., 2008; Swaby et al., 2016; Quarrie et al., 2017; Cunningham et al., 2016a). Furthermore, it is logical that female athletes would yield lower $\dot{V}O2_{max}$ scores than their male counterparts; however, the results of Sarkar and Dey (2019) is not a good representative of elite, international female rugby union players. This highlights the need for further research examining the aerobic capacity of elite female athletes.

Using $\dot{V}O2_{max}$ testing to predict aerobic fitness in team sports can be impractical and time-consuming (Clarke et al., 2014). Moreover, maximal aerobic speed (MAS) has been found to be a practical and reliable method for determining an athlete's aerobic capacity in team sports (Baker, 2011). For example, in rugby union, Swaby et al. (2016) suggest that elite level backs record higher MAS scores than forwards (4.9 ± 0.13 $m{\cdot}s^{-1}$ *vs.* 4.2 ± 0.43 $m{\cdot}s^{-1}$). Furthermore, Swaby et al. (2016) suggest that MAS scores correlate with total distance covered in games; however, research into MAS scores in rugby union is limited and its relationship with other performance variables is unknown. To the best of this authors knowledge, there is no research of MAS scores and its relationship with performance in the female game.

2.4.2 Anaerobic performance

Primary work periods in intermittent team sports occur at high intensities; thus, energy contributions during critical work periods are primarily anaerobic in nature (Duthie et al., 2003). For example, a player's ability to produce power is essential in tackling, explosive accelerations, scrummaging, rucking and mauling (Cheetham et al., 1988), and can dictate the likelihood of success in collisions (Mayes & Nuttall, 1995). Early assessments of power in rugby union suggest that forwards produce higher absolute and peak power than backs (Rigg & Reilly, 1988; Maud & Shultz, 1984; Cheetham et al., 1988; Dotan & Bar-Or, 1983); however, more recent literature suggests that the difference between positions is less clear. Some studies report that differences predominantly occur between heavier (forwards) and lighter (backs) players (Crewther et al., 2009b; Crewther et al., 2009a); whereas, Crewther et al. (2012) report no positional difference in peak force and peak power.

Power is a function of both force and velocity ($P = F \cdot V$; Knuttgen & Kraemer, 1987); thus, the ability to use strength quickly. Strength is especially required during contact situations, such as rucks, mauls and scrums (Reilly, 1997; Lander & Webb, 1983). Furthermore, static exertions equate to ~70 % of work performed by forwards and ~25 % of the work performed by backs (Duthie, 2006). Therefore, given the higher contact loads and greater involvement in low-speed strength exertions for forwards (Gamble, 2004; Austin et al., 2011), it is unsurprising that forwards produce greater force at low isokinetic speeds than backs (Miller et al., 1996). Conversely, given backs have higher involvements with high-speed tackling and contact evasion (Gamble, 2004; Austin et al., 2011), it is logical that backs produce greater horizontal force than forwards at higher speeds (Miller et al., 1996). Strength is the maximal force produced by the muscles at a given speed (Knuttgen & Kraemer, 1987). Furthermore, force (strength) is a product of mass and acceleration ($F = m \cdot a$; Barr et al., 2014); hence, a parallel relationship exists between body mass, force and power. This could explain findings suggesting that heavier athletes produce greater power (Brown et al., 2014; Crewther et al., 2009b; Crewther et al., 2009a).

To the best of this authors knowledge, there is no research examining the power and strength capabilities of female rugby union athletes. Jones et al. (2016) examined the physical qualities of international female rugby league players; reporting that differences in countermovement jump (CMJ) peak power (2,827 ± 363 *vs.* 2,986 ± 573 W), jump squat peak power (2,027 ± 270 *vs.* 2,304 ± 487 W), and jump squat relative peak power (30.74 ± 2.69 *vs.* 28.60 ± 3.24 W·kg^{-1}) were statistically insignificant between backs and forwards, respectively. Although, CMJ height (0.29 ± 0.05 *vs.* 0.24 ± 0.05 m), CMJ relative peak power (43.03 ± 5.18 *vs.* 37.12 ± 3.61 W·kg^{-1}), and jump squat height (0.17 ± 0.04 *vs.* 0.13 ± 0.03 m) were significantly higher for backs in comparison to forwards. This finding suggests that lower-body power production is indifferent between rugby league backs and forwards; however, backs have higher jump heights and relative peak power in a CMJ than forwards. In comparison to rugby league, rugby union male forwards compete in more force-dominant, low-kinetic actions such as scrums, rucks and mauls; which require high levels of strength and power (Brown et al., 2014). As such, rugby union forwards are typically heavier and stronger than rugby league athletes (Cross et al., 2015; McMaster et al., 2016). Therefore, a comparison between rugby league and union may be misleading. Moreover, in the study by Jones et al. (2016), forwards also had significantly larger body masses (80.7 ± 14.3 *vs.* 66.0 ± 7.3 kg), legs fat masses (10,053 ± 2,857 *vs*. 7,258 ± 1,794 g), and legs lean masses (17,506 ± 2,916 *vs.* 15,184 ± 1,834 g); although, lower effect sizes were found for legs lean mass than body mass and legs fat mass (0.98 *vs.* 1.34 *vs.* 1.20, respectively). It suggested that both an increase in lean muscle mass and decrease in fat mass would improve lower-body power outputs (Jones et al., 2016). In addition, backs are also likely to have better acceleration and velocity capacities, thus increasing both force and power is explosive locomotive tasks (Jones et al., 2016; Cross et al., 2015). The lack of coverage regarding the power and strength capabilities of female rugby union athletes highlights the need to examine the physical capabilities of players in elite female rugby union.

2.4.3 Force-velocity relationship

The force-velocity (F-V) relationship explains an athlete's ability to produce and maximise power output (Cross et al., 2017), which is a key determinant of athletic performance (Baker & Nance, 1999; Comfort et al., 2011; Comfort et al., 2012; Cormie et al., 2007; Cronin et al., 2001; Garhammer & Gregor, 1992). Thus, F-V and power relationships provide a greater understanding of a motor task and highlight the mechanical determinants of performance (Cross et al., 2017). Furthermore, F-V profiling allows practitioners to predict and track the mechanical capabilities of an athlete's neuromuscular system for gross and complex tasks (Cross et al., 2015). Through various calculations, quantified work (effort) done at various time-points of a multi-joint task, can be used to predict an athlete's theoretical maximal force (F_0), maximal velocity (V_0) and maximal power (P_{max}) (Cross et al., 2015; Cross et al., 2017). Hence, these metrics can be used to build a theoretical maximal output profile for an athlete. Profiles can also be used to establish optimal force and optimal velocity outputs for maximising training and performance gains (Simpson et al., 2020). Key moments, rather high intensity movements such as sprints or collisions, during rugby union matches are often those that occur at high metabolic loads, high velocities (sprinting and high speed running), or at high forces, such as collisions and tackles (Cahill et al., 2013; Roberts et al., 2008). Thus, the ability to predict an athlete's V_0, F_0 and P_{max} could inform the likelihood of success in these crucial moments – although this has not been described thoroughly in the current literature.

Graphically, these metrics are commonly presented via a linear F-V and parabolic power-velocity (P-V) plot; whereby, F_0 and V_0 are portrayed as the x- and yintercepts respectively, and P_{max} as the apex of the parabolic P-V curve. The ability to plot F-V and P-V profiles against each other can be a useful tool to draw comparisons between athletes or positions. For example, Figure 1 (Cross et al., 2015), shows a horizontal F-V and P-V profile comparison between rugby league and rugby union athletes for a 30 m sprint. Figure 1 shows that the rugby union athlete has a higher horizontal F_0 and higher P_{max}, however the rugby league athlete has a higher V_0 and their P_{max} occurs at a higher velocity than the rugby union athlete. From this, it is hypothesised that the rugby union athlete would perform better in the initial acceleration phases of the sprint than the rugby league athlete, and would most likely produce a quicker 30 m sprint time as neither athlete would have hit maximal velocity (Cross et al., 2015). Furthermore, it is hypothesised that over a longer distance, where both athletes are able hit maximal velocities, rugby league athletes would produce a faster sprint time.

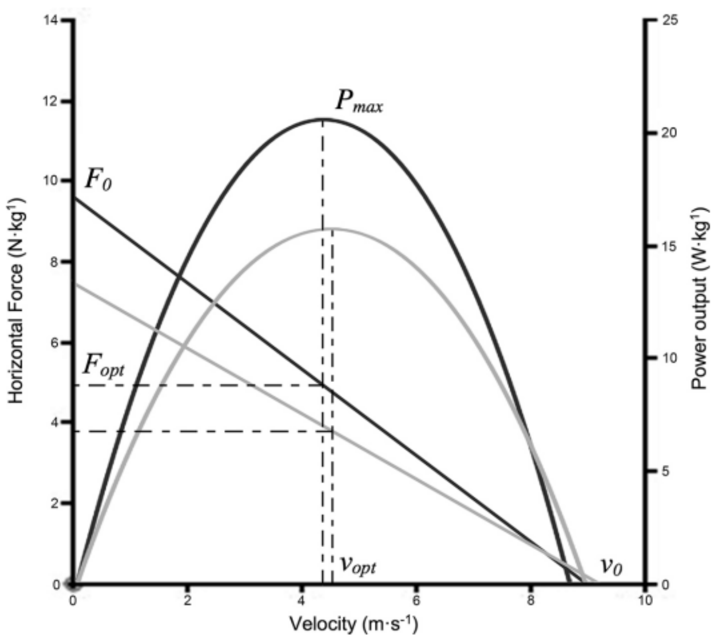

Figure 1 — A graphical representation of the force-velocity-power profiles (and associated optimal force and velocity levels for power production) for 2 athletes from each code (light gray [rugby league player] vs dark gray [rugby union player]) over a 30-m maximal overground sprint. Abbreviations: P_{max}, maximum power; F_0, theoretical maximum force; F_{opt}, optimum force.

Figure 1. Linear F-V and parabolic P-V plot, taken from Cross et al. (2015).

In acceleration and sprinting tasks, up to 30 m, elite rugby union backs produce greater V_0 (9.28 ± 0.37 *vs.* 8.65 ± 0.59 m·s^{-1}), relative F_0 (8.76 ± 0.41 *vs.* 8.48 ± 1.27 N·kg^{-1}) and P_{max} (20.3 ± 1.0 *vs.* 18.3 ± 3.0 N·kg^{-1}) than forwards, as well as faster split times over 2, 5, 10 and 20 m (Cross et al., 2015). This suggests that backs produce greater relative horizontal force, velocity and power during high-intensity locomotor, as well as possessing better acceleration and sprinting capacities than forwards. This may improve performance by improving a back's ability to evade defenders and in high-speed collisions (Gamble, 2004; Austin et al., 2011). However, forwards are typically taller (1.90 ± 0.1 *vs.* 1.82 ± 0.1 m), heavier (114.55 ± 6.3 *vs.* 92.64 ±4.9) and produce larger absolute force than backs. This could improve a forward's performance in collisions, considering the effect of momentum ($p = m \cdot V$), whereby momentum is a product of mass and velocity (Barr et al., 2014). Given that momentum is a determinant of success in tackles and collisions (Hendricks et al., 2014a), an increase in momentum would increase the likelihood of success in tackles and collisions such as rucks, mauls and scrums. However, no direct links have been established between force, velocity, power and successful rugby performance. Similarly, there is no research on the F-V and power profiles of elite female rugby union athletes.

2.4.4 Upper-body strength and power

Upper-body strength and power is especially important in rugby union for forwards, who engage in high numbers of contacts and collisions (McMaster et al., 2016; Roe et al., 2016). The development of strength and power in the upper-body is essential for maximum force production and impact absorption in collisions (McMaster et al., 2016). A valid and reliable method for examining upper-body strength in rugby union athletes is a one repetition maximum (1RM) bench press (Argus et al., 2009; Crewther et al., 2009b; McMaster et al., 2016). In male athletes, forwards possess greater upper-body strength (133.9 ± 9.6 *vs.* 110.9 ± 23.9 kg) and maximum force capabilities, which is likely due to the difference in physical demands between positions (McMaster et al., 2016).

Research in the strength of female rugby athletes is scarce. Agar-Newman et al. (2017) examined the anthropometric and physical qualities of international female rugby sevens athletes, reporting that forwards had greater absolute bench press 1RM outputs than backs (68.79 ± 7.13 *vs.* 61.85 ± 7.15 kg). Although, relative to body mass, bench press 1RM outputs were indifferent (0.94 ± 0.12 *vs.* 0.94 ± 0.11, respectively). However, international male sevens athletes tend to be lighter (between 6 and 17 kg) and smaller (between 1 and 5 cm) than their union counterparts (Higham et al., 2013). Similarly, match demands are different between rugby sevens and rugby union. For example, rugby sevens athletes have greater number of overall collisions per min than union athletes (Suarez-Arrones et al., 2014a; Coughlan et al., 2011), but rugby sevens matches are shorter in duration (14 *vs.* 80 min). Therefore, the total contact and collision loads are likely to be larger for union athletes, with less recovery time. Hence, a sevens and union athletes may yield different results, and may not provide a concrete comparison. Furthermore, to the best of the authors' knowledge, only two studies have examined upper-body strength, and positional differences, in female rugby union athletes with contrasting results (Hene et al., 2011; Yao et al., 2020). This highlights the need for strength profiling in elite female rugby union.

2.4.5 Speed

Possessing good speed and acceleration are essential qualities in rugby union players in order to get to a certain field position ahead of an opponent (Duthie et al., 2003). Speed and acceleration are also important for success in collisions, such as carries and tackles (Gabbett & Kelly, 2007; Hendricks et al., 2014b), given the relationships with force ($F = m \cdot a$; Barr et al., 2014), power ($P = F \cdot V$; Knuttgen & Kraemer, 1987), and momentum ($p = m \cdot V$; Barr et al., 2014). Backs tend to have faster sprint times up to 35 m than forwards (Quarrie et al., 1996; Quarrie et al., 1995) with outside backs producing the fastest split times over 10, 20 and 30 m (Smart et al., 2013). Elite level backs in general are also faster over 2 m (0.69 ± 0.05 *vs.* 0.73 ± 0.07 s), 5 m (1.23 ± 0.05 *vs.* 1.29 ± 0.08 s), 10 m (1.95 ± 0.04 *vs.* 2.04 ± 0.12 s) and 20 m (3.19 ± 0.06 *vs.* 3.33 ± 0.15 s) than forwards (Cross et al., 2015). Furthermore, a strong relationship has been found between speed, acceleration and jump height in rugby union athlete's (Cronin & Hansen, 2005; Cunningham et al., 2016b), suggesting that jump height is a good predictor of sprint and acceleration performance.

The speed and acceleration qualities of elite female rugby union athletes are not yet documented. Jones et al. (2016) found that like men's rugby union, elite female rugby league backs were quicker over 5, 10, 20 and 30 m, and had greater CMJ height, jump squat height and drop jump height than forwards. Thus, this confirms the finding from men's rugby union that a relationship exists between jump height and sprint times (Cronin & Hansen, 2005; Cunningham et al., 2016b); although, this is yet to be confirmed in female rugby union athletes. Furthermore, Lockie et al. (2016) reported 5 m (1.20 ± 0.06 s), 10 m (2.05 ± 0.10 s) and 20 m (3.53 ± 0.23 s) split times for female rugby union athletes. However, by using a small sample (*n* = 8) of collegiate athletes, these results may not be representative for elite or international players. This again highlights the need for physical profiling in elite women's rugby union.

Chapter 3.0 – Methodology

3.1 Participants and sample

A longitudinal analysis was conducted across five competitive seasons, between 2015 and 2019; consisting of match-running data, key performance indicators from matches, and regular physical and anthropometric testing data. Seventy-six international female rugby union players, with a minimum of five international caps as per the pre-determined inclusion criteria, were included in the sample (age 25 ± 4 years, stature 170.6 ± 6.0 cm, body mass 78.24 ± 9.19 kg) across the five seasons (2015, *n* = 39, 2016, *n* = 31, 2017, *n* = 37, 2018, *n* = 33, 2019, *n* = 38). A total of 831 match performances were observed: 2015 (*n* = 137), 2016 (*n* = 107), 2017 (*n* = 268), 2018 (*n* = 165), 2019 (*n* =154). Players were grouped into five positional roles (adapted from Cahill et al., 2013): front row (FR; *n* = 16), locks and back row (BR; *n* = 20), scrum-halves (SH; *n* = 7), inside backs (IB; *n* = 9) and outside backs and full-backs (OB; *n* = 24). Institutional ethical approval was granted for the current study.

3.2 Procedures

All matches were played between 12:30 pm and 10:00 pm across three continents (Europe, America and Australasia), with different environmental conditions. Players had a portable Global Positioning System (GPS) device placed between the scapulae, in the pocket of the playing shirt. A Viper device (STATSports Viper; STATSports, Newry, Northern Ireland) was used from the start of the study until August 2017, when it was then changed to an Apex unit (STATSports Apex; STATSports, Newry, Northern Ireland) until the end of the data collection. Each of these devices is integrated with an accelerometer, configured at 100 Hz, to measure raw and live acceleration and deceleration; as well as a gyroscope and magnetometer, configured at 100 and 10 Hz, respectively, for measuring angular velocity and direction. These devices typically have measurement errors of < 5 % (Beato et al., 2018; Bennett et al., 2019). All devices were activated 15 min before the match and were deactivated after the final whistle.

831 GPS files, from 47 matches, were included in the data analysis. The files were downloaded from the devices using the manufacturer's software (STATSPORTS Apex; STATSports, Newry, Northern Ireland). *Post-hoc* analysis removed inactive periods, including warm-up, half-time and travelling to and from the pitch. Total playing time and match data was inclusive of stoppages due to injuries or general pauses in play.

A total of eight kinematic variables were selected for analysis, including: accelerations (over 4 $m \cdot s^{-2}$), decelerations (over 4 $m \cdot s^{-2}$), total distance covered (m), as well as distance covered at low speeds (< 3 $m \cdot s^{-1}$), moderate speeds (3 to 5.5 $m \cdot s^{-1}$) and high speeds (> 5.5 $m \cdot s^{-1}$). Similar thresholds were used by Suarez-Arrones et al. (2012), whereby standing, walking and jogging matched the present low speed threshold (< 3 $m \cdot s^{-1}$) and sprinting matched the present high speed threshold (> 5 $m \cdot s^{-1}$). The number of entries into the high-speed running zone, sprints, was also recorded. All variables were expressed relative to playing time (per min). Collision metrics were also included for analysis, given the high frequency of contacts in games and the effect they have on successful rugby performance (Gabbett & Kelly, 2007). As such, the number of carries, tackles, clean breaks, and collisions (see Table 1.; Cunningham et al., 2018) were coded by an expert performance analyst (PA), and were expressed relative to playing time (per min). Across each of the collision variables, the reliability of the analyst was < 5% CV.

Table 1. Adapted from a table provided by Cunningham et al. (2018) defining carries, tackles, clean breaks, collisions and other key performance indicators.

KPI Variable- Performance	**Definition**
Clean Break	Count of time a player in possession of the ball breaks the defensive line
Dominant Collisions	Count of collisions (both in attack and defence) where the player makes ground after the collision
KPI Variable- Effort	**Definition**
Carries	Count of times a player carried the ball into contact
Tackles	Count of tackles made by the player

Assessments of player's morphology and physical capabilities were conducted inside pre-arranged training camps, during normal training hours. Assessments occurred at three stages of the season: early-September, early-January and late-June. A total of 309 assessments over 33 testing dates were used for analysis. Assessments across the five seasons were conducted at standardised, world-class facilities, by the same practitioners.

Body mass was measured to the nearest 0.1 kg using electronic scales (Seca, London, UK). Participants were weighed in shorts, vests and undergarments only. Skinfold thickness was assessed using Harpenden callipers (Harpenden, Burgess Hill, UK) on the right side of the body. A sum of eight sites (triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, thigh and calf) was used in accordance with the International Society for the Advancement of Kinanthropometry (ISAK). Measurements were taken from a level 3 ISAK practitioner, with a technical error of measurement of <2%.

Upper-body strength was assessed using a one repetition maximum (1RM) bench press and pull-up. Prior to maximal efforts, participants completed a progressive warm-up, consisting of 10 repetitions at 60% maximum, 5 repetitions at 70%, 3 repetitions at 80% and 1 repetition at 90%, with a 3-min rest period between warm-up sets. For the bench press, participants were asked to keep their feet in contact with the floor, with buttocks and lower back with the bench throughout the lift. The bar was then lowered to the chest, with an approximate 90° angle at the elbow, and then returned to the start position, with full extension at the elbow. Participants chose their own hand position, standardised between a minimum of 150 and maximum of 200% bi-acromial breadth; which has shown to yield the best performances in trained lifters (Wagner et al., 1992) and is used in training for the group. Participants were encouraged not to bounce the bar off the chest, nor to lock their elbows at full extension.

Lower-body power output was assessed using a countermovement jump (CMJ). Participants were asked to stand with their feet a shoulders-width apart on a force platform (Fitness Technology, Adelaide, Australia between 2015 and 2017, and Vald Performance, Brisbane, Australia, between 2017 and 2019), with their hands on their hips. Participants then performed a minimum of three and maximum of five CMJs, with the highest jump height recorded from the force plate software. Participants were asked to jump to full extension of the legs at the knees, to be maintained during the flight stage, with a self-selected squat depth and stance upon take off. Each trial was separated by 1-min rest.

Speed and acceleration was assessed using 10, 20, 30 and 40 m sprint split times, using timing gates (Brower timing systems, Utah, USA). Participants performed three 40 m sprint trials, each separated by a minimum of 5-min rest. Tests took place at an indoor running track, with participants wearing hard surface running footwear. Timing gates were placed 2 m apart, at approximately hip height, at 0, 10, 20, 30 and 40 m. Participants started 50 cm behind the first gate, 0 m, in a stationary and upright position. Participants were then asked to perform a 40 m sprint, so as to cross all gates. Split times were recorded immediately after the sprint. The fastest 40 m sprint was used for recording split times. Prior to sprint trials, participants completed a standardised warm up consisting of general dynamic movements, jogging and progressive intensity running.

Maximal aerobic speed (MAS) was determined via a 1200 m shuttle run, whereby participants completed 12 lots of 100 m shuttles in the fastest time possible. 1200 m time trial is a valid and reliable test for measuring MAS (Swaby et al., 2016). The run took place on an indoor 100 m running tack, with participants wearing hard surface running footwear. Upon completion, times were recorded immediately. To calculate MAS score, distance (1200 m) was divided by time (s); $d = V \cdot t$.

3.3 Data analysis

The closest testing date to the match date (33.34 ± 17.68 days) was chosen to pair each GPS data entry with the corresponding morphological and physical ability predictor variables. F_0, V_0, and P_{max} were all calculated from split times, using the spreadsheet provided by Morin and Samozino (2019) for F-V profiling using split times. F_0, V_0, and P_{max} values were recorded yearly, and were paired with each GPS data entry within that year. Momentum over 10, 20, 30 and 40 m were also calculated from sprint split times, by multiplying velocity and body mass; $P = m \cdot V$ (Barr et al., 2014). Velocity was calculated using the same formula for MAS; $d = V \cdot t$.

3.4 Statistical analysis

Linear mixed modelling was used to determine the independent effects of morphologic and physical capabilities on each dependent variable. Data was assessed for normality through visual impaction of normal plots of residuals (Q-Q plot). To control for seasonal and positional changes and variation, all morphologic and physical variables were group mean centred for position group and season. Furthermore, to account for the dependent observation within participants and playing position, individuals were included as random factors, nested within position group. A step-up model was used, starting with an unconditional null-model containing only random factors before fixed factors were introduced. Fixed factors were retained if they significantly ($P < 0.05$) altered the model according to the maximal likelihood test and χ^2 statistic. The order in which fixed factors, morphologic and physical variables, were introduced into the model based on reported relationships with dependent variables. The intercept, representing a modelled value that corresponds to the convergence of all slopes after fixed factors were included in the model (Dobbin et al., 2019), was derived for each individual's slope after group mean centering. The *t*-statistic was converted to effect size correlations (η^2) with corresponding 90 % confidence intervals (90 % CI) (Rosnow et al., 2000). Effect size correlations were interpreted as trivial (< 0.1), small (0.1-0.3), moderate (0.3-0.5), large (0.5-0.7), very large (0.7-0.9), almost perfect (0.90-0.99) and perfect (1.0) (Hopkins et al., 2009). All statistical analysis was performed using IBM SPSS Statistics (Version 24) and a predesigned spreadsheet for deriving confidence intervals (Hopkins, 2007).

Linear mixed modelling was chosen as the statistical test for this study it can account for incomplete data sets and random effects, such as positional and temporal differences in this study – something that classical ANOVA tests ignore (Bolker et al., 2009). To control for random effects, players were assigned to one of five playing positions and data entries accounted for playing season. Position and season were then entered as random factors into the mixed linear model.

One limitation of the model used in this study is the practical application of the findings for practitioners and players. Whilst the findings suggest several relationships between independent and dependent variables, the practical applications of the findings do not specialise for playing position. Moreover, differences have been identified for match running loads, match involvements, physical capabilities and morphological variables between positions – most notably between forwards and backs (Quarrie et al., 2017; Roberts et al., 2008; Swaby et al., 2016; Suarez-Arrones et al., 2014b; Posthumus et al., 2020a; Posthumus et al., 2020b). Therefore, it is likely that the relationships between independent and dependent variables would vary between positions – this is something that future analysis should look to explore. Furthermore, another limitation of the data and statistical analysis of this study is the positional grouping of players; notably the grouping of locks and back row. The decision to group the locks and back row could account for some of the large variance in the results, given the difference in match running outputs (Cahill et al., 2013; Cunningham et al., 2016a). Future analysis should also consider splitting this position group like previous studies have done (Cahill et al., 2013; Cunningham et al., 2016a; Cunningham et al., 2018).

Chapter 4.0 – Results

4.1 Accelerations and decelerations

CMJ was positively associated with accelerations (η^2 = 0.12) and decelerations (η^2 = 0.09) (Tables 1 & 2). Body mass was also negatively associated with accelerations (η^2 = -0.06) and decelerations (η^2 = -0.26).

Table 2. Effect of fixed factors on accelerations over 4 $m \cdot s^{-2}$ (90% CI).

Accelerations over 4 $m \cdot s^{-2}$	**Coefficient**	**90% CI**	**df**	***t*-value**	***η^2***
Intercept ($m \cdot s^{-2}$)	0.245	0.81, 0.91	89.499	16.715	
CMJ (cm)	0.003	-0.20, 0.41	41.508	0.747	0.12
Body mass (kg)	-0.001	-0.47, 0.33	24.388	-0.305	-0.06

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; CMJ = countermovement jump.

Table 3. Effect of fixed factors on decelerations over 4 $m \cdot s^{-2}$ (90% CI).

Decelerations over 4 $m \cdot s^{-2}$	**Coefficient**	**90% CI**	**df**	***t*-value**	***η^2***
Intercept ($m \cdot s^{-2}$)	0.327	0.92, 0.97	70.974	25.302	
CMJ (cm)	0.002	-0.24, 0.40	37.561	0.571	0.09
Body Mass (kg)	-0.003	-0.74, 0.11	19.639	-1.170	-0.26

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; CMJ = countermovement jump.

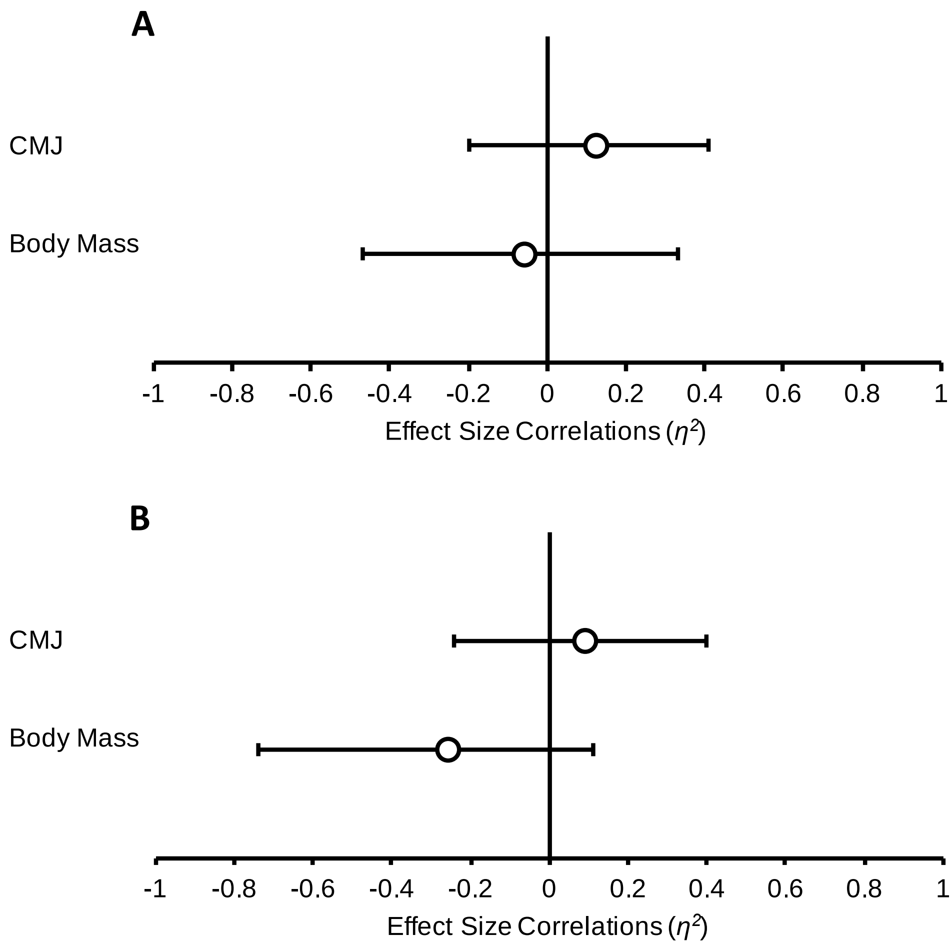

Figure 2. Effect size correlations for accelerations over 4 $m \cdot s^{-2}$ (A), and decelerations over 4 $m \cdot s^{-2}$ (B) (90% CI).

4.2 Sprints

Sprints was negatively associated with 10 m split (η^2 = -0.22) and Mom10 (η^2 = -0.25). 30 m split, and pull-up were also negatively associated with sprints (η^2 = -0.10, -0.09, respectively), while CMJ, V_0, skinfolds, 20 m split, 40 m split, Mom20, MAS and bench 1RM were all positively associated (η^2 = 0.28, 0.01, 0.34, 0.26, 0.03, 0.26, 0.31, 0.09, respectively).

Table 4. Effect of fixed factors on sprints (90% CI).

Sprints	**Coefficient**	**90% CI**	**df**	***t*-value**	η^2
Intercept	0.130	0.73, 0.88	77.502	12.537	
CMJ (cm)	0.009	0.09, 0.44	106.789	2.992	0.28
V_0 (m·s^{-1})	0.004	-0.13, 0.16	182.144	0.200	0.01
Skinfolds (mm)	0.003	0.04, 0.58	42.470	2.364	0.34
10 m Split (s)	-1.876	-0.40, -0.05	110.355	-2.416	-0.22
20 m Split (s)	1.322	0.08, 0.43	110.183	2.864	0.26
30 m Split (s)	-0.263	-0.28, 0.07	123.039	-1.093	-0.10
40 m Split (s)	0.042	-0.17, 0.22	103.753	0.257	0.03
Mom10 (kg m·s^{-1})	-0.010	-0.43, -0.08	111.288	-2.730	-0.25
Mom20 (kg m·s^{-1})	0.009	0.07, 0.43	104.089	2.734	0.26
MAS (m·s^{-1})	0.194	0.11, 0.49	88.454	3.078	0.31
Bench 1RM (kg)	0.001	-0.17, 0.34	57.825	0.695	0.09
Pull-up (kg)	-0.001	-0.32, 0.14	72.286	-0.780	-0.09

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; CMJ = countermovement jump; V_0 = theoretical maximum velocity; Mom10 = momentum over 10 m; Mom20 = momentum over 20 m; MAS = maximal aerobic speed; Bench 1RM = one repetition maximum bench press.

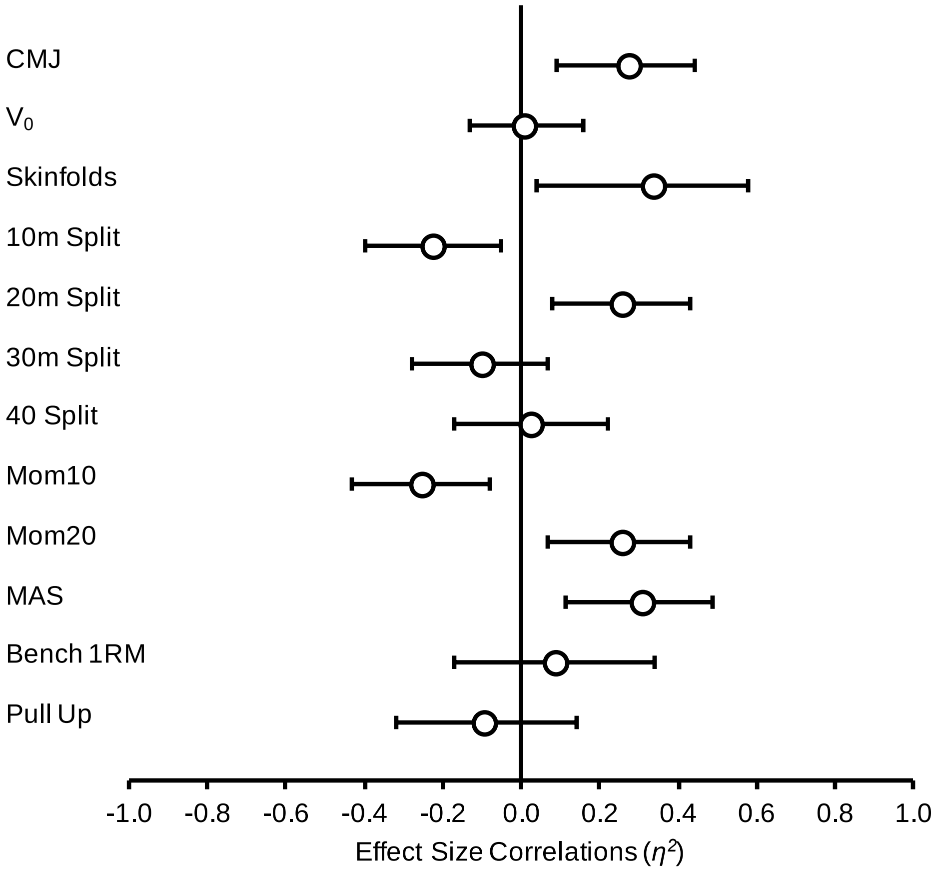

Figure 3. Effect size correlations for sprints (90% CI).

4.3 Distance

MAS, skinfolds and CMJ were all positively associated with TD (η^2 = 0.22, 0.40, 0.21, respectively), TD < 3 m·s^{-2} (η^2 = 0.02, 0.13, 0.01, respectively), TD 3 to 5.5 m·s^{-2} (η^2 = 0.14, 0.23, 0.23, respectively) and TD > 5.5 m·s^{-2} (η^2 = 0.18, 0.17, 0.26, respectively). Bench 1RM and 30 m split were positively associated with TD (η^2 = 0.21, 0.03, respectively), TD < 3 m·s^{-2} (η^2 = 0.12, 0.15, respectively) and TD > 5.5 m·s^{-2} (η^2 = 0.07, 0.10, respectively), but negatively associated with TD 3 to 5.5 m·s^{-2} (η^2 = -0.02, -0.10, respectively). Pull-up and 10 m split was negatively associated with TD (η^2 = -0.23, -0.05, respectively), TD < 3 m·s^{-2} (η^2 = -0.02, -0.01, respectively), TD 3 to 5.5 m·s^{-2} (η^2 = -0.07, -0.07, respectively) and TD > 5.5 m·s^{-2} (η^2 = -0.03, -0.06, respectively). 20 m split was positively associated with TD (η^2 = 0.04) and TD 3 to 5.5

m·s^{-2} (η^2 = 0.15) but negatively associative with TD < 3 m·s^{-2} (η^2 = -0.13) and TD > 5.5 m·s^{-2} (η^2 = -0.03). 40 m split was negatively associated with TD (η^2 = -0.06), TD < 3 m·s^{-2} (η^2 = -0.07) and TD > 5.5 m·s^{-2} (η^2 = -0.13), but positively associated with TD 3 to 5.5 m·s^{-2} (η^2 = 0.05). V_0 was negatively associated with TD (η^2 = -0.03) and TD > 5.5 m·s^{-2} (η^2 = -0.08), but positively associated with TD < 3 m·s^{-2} (η^2 = 0.06) and TD 3 to 5.5 m·s^{-2} (η^2 = 0.00). Body mass was also positively associated with TD < 3 m·s^{-2} (η^2 = 0.02), while F_0 was negatively associated with TD > 5.5 m·s^{-2} (η^2 = -0.14).

Table 5. Effect of fixed factors on total distance m (90% CI).

Total distance m	**Coefficient**	**90% CI**	**df**	***t*-value**	η^2
Intercept (m)	67.446	0.99, 1.00	70.745	74.875	
MAS (m·s^{-1})	13.152	0.04, 0.40	107.648	2.394	0.22
Skinfolds (mm)	0.231	0.04, 0.67	28.827	2.329	0.40
10 m Split (s)	-9.804	-0.20, 0.09	187.975	-0.632	-0.05
20 m Split (s)	9.653	-0.12, 0.19	157.226	0.487	0.04
30 m Split (s)	7.153	-0.14, 0.19	139.601	0.303	0.03
40 m Split (s)	-11.270	-0.22, 0.10	147.073	-0.738	-0.06
V_0 (m·s^{-1})	-0.699	-0.18, 0.11	176.689	-0.364	-0.03
CMJ (cm)	0.613	0.02, 0.39	104.949	2.247	0.21
Bench 1RM (kg)	0.186	-0.12, 0.50	36.598	1.327	0.21
Pull-up (kg)	-0.283	-0.50, 0.01	53.217	-1.738	-0.23

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; MAS = maximal aerobic speed; V_0 = theoretical maximum velocity; CMJ = countermovement jump; Bench 1RM = one repetition maximum bench press.

Table 6. Effect of fixed factors on total distance (m) below 3 m·s^{-2} (90% CI).

Total distance m, below 3 m·s^{-2}	**Coefficient**	**90% CI**	**df**	***t*-value**	η^2
Intercept (m)	43.410	0.97, 0.99	160	63.299	
MAS (m·s^{-1})	0.874	-0.14, 0.17	160	0.201	0.02
Body Mass (kg)	-0.044	-0.18, 0.13	160	-0.244	-0.02
Skinfolds (mm)	0.111	-0.02, 0.28	160	1.716	0.13
10 m Split (s)	-1.076	-0.17, 0.14	160	-0.076	-0.01
20 m Split (s)	-28.805	-0.28, 0.02	160	-1.668	-0.13
30 m Split (s)	34.621	-0.01, 0.29	160	1.855	0.15
40 m Split (s)	-11.557	-0.22, 0.09	160	-0.921	-0.07
V_0 (m·s^{-1})	1.409	-0.09, 0.22	160	0.808	0.06
CMJ (cm)	0.030	-0.14, 0.17	160	0.136	0.01
Bench 1RM (kg)	0.144	-0.04, 0.27	160	1.515	0.12
Pull-up (kg)	-0.035	-0.17, 0.14	160	-0.292	-0.02

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; MAS = maximal aerobic speed; V_0 = theoretical maximum velocity; CMJ = countermovement jump; Bench 1RM = one repetition maximum bench press.

Table 7. Effect of fixed factors on total distance m, from 3 to 5.5 m·s^{-2} (90% CI).

Total distance m, from 3 to 5.5 m·s^{-2}	**Coefficient**	**90% CI**	**df**	***t*-value**	η^2
Intercept (m)	18.092	0.92, 0.96	160	34.986	
MAS (m·s^{-1})	6.050	-0.01, 0.29	160	1.815	0.14
Skinfolds (mm)	0.132	0.08, 0.37	160	2.958	0.23
10 m Split (s)	-8.983	-0.23, 0.08	160	-0.828	-0.07
20 m Split (s)	25.041	-0.01, 0.30	160	1.903	0.15
30 m Split (s)	-19.114	-0.25, 0.06	160	-1.334	-0.10
40 m Split (s)	6.635	-0.10, 0.21	160	0.694	0.05
V_0 (m·s^{-1})	0.023	-0.15, 0.16	160	0.017	0.00
CMJ (cm)	0.505	0.08, 0.38	160	3.048	0.23
Bench 1RM (kg)	-0.015	-0.18, 0.13	160	-0.215	-0.02
Pull-up (kg)	-0.080	-0.22, 0.09	160	-0.951	-0.07

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; MAS = maximal aerobic speed; V_0 = theoretical maximum velocity; CMJ = countermovement jump; Bench 1RM = one repetition maximum bench press.

Table 8. Effect of fixed factors on total distance m, over 5.5 m·s^{-2} (90% CI).

Total distance m, over 5.5 m·s^{-2}	**Coefficient**	**90% CI**	**df**	***t*-value**	η^2
Intercept (m)	1.859	0.61, 0.83	66.806	9.003	
CMJ (cm)	0.141	0.05, 0.45	85.473	2.488	0.26
V_0 (m·s^{-1})	-0.470	-0.22, 0.06	186.421	-1.121	-0.08
F_0 (m·s^{-1})	-0.925	-0.29, 0.00	181.094	-1.851	-0.14
Skinfolds (mm)	0.029	-0.18, 0.48	33.320	0.991	0.17
10 m Split (s)	-2.100	-0.20, 0.08	186.312	-0.836	-0.06
20 m Split (s)	-1.578	-0.18, 0.13	155.155	-0.424	-0.03
30 m Split (s)	5.494	-0.05, 0.24	174.656	1.282	0.10
40 m Split (s)	-4.918	-0.28, 0.02	173.998	-1.775	-0.13
MAS (m·s^{-1})	2.140	-0.01, 0.35	109.633	1.905	0.18
Bench 1RM (kg)	0.017	-0.24, 0.36	42.677	0.450	0.07
Pull-up (kg)	-0.008	-0.32, 0.25	48.915	-0.188	-0.03

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; CMJ = countermovement jump; V_0 = theoretical maximum velocity; F_0 = theoretical maximum force; MAS = maximal aerobic speed; Bench 1RM = one repetition maximum bench press.

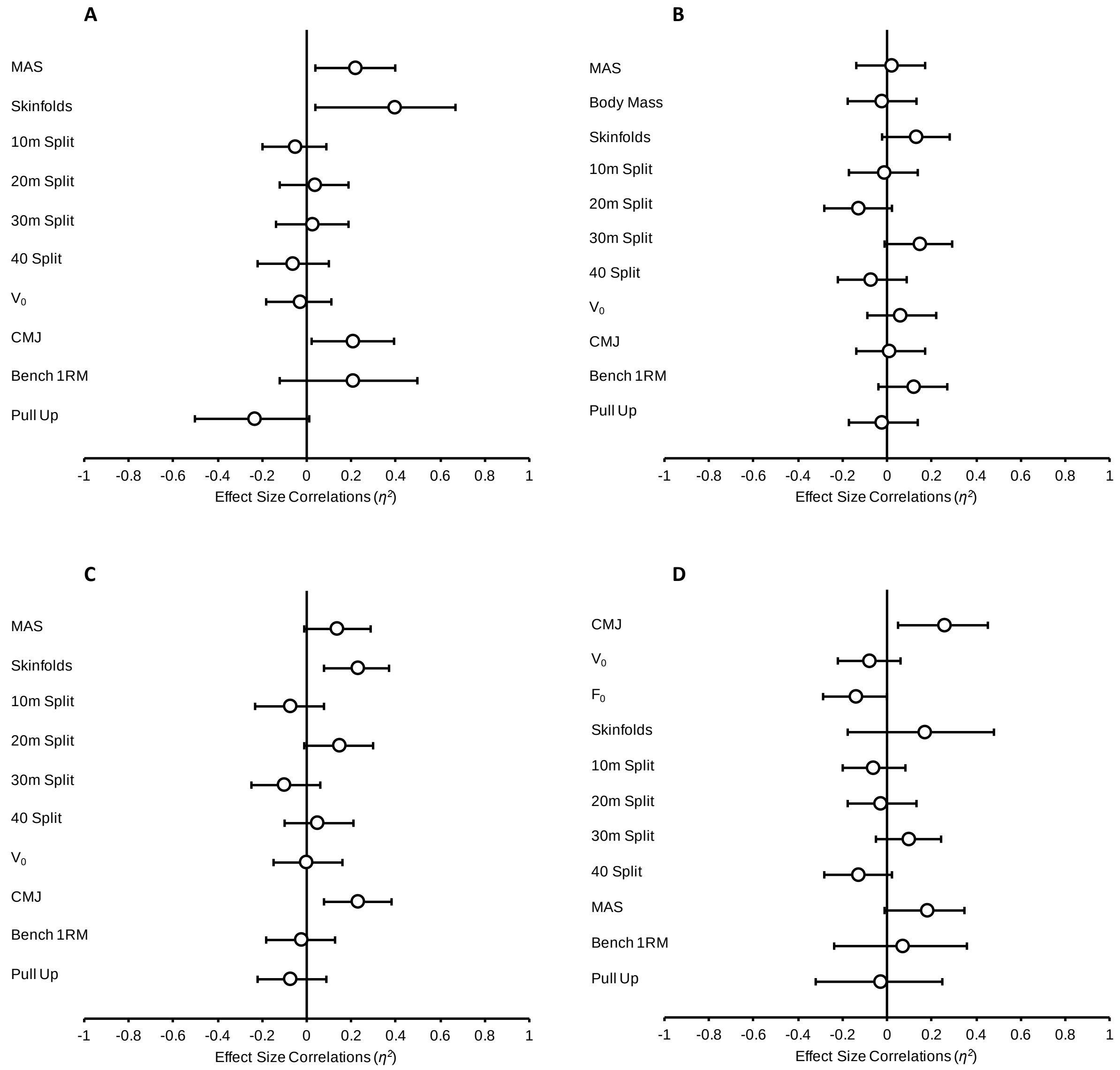

Figure 4. Effect size correlations for total distance m (A); total distance m, below 3 m·s^{-2} (B); total distance m, from 3 to 5.5 m·s^{-2} (C); and total distance m, over 5.5 m·s^{-2} (D) (90% CI).

4.4 Clean breaks, carries, total tackles and collisions

Skinfolds, CMJ and 10 m split were negatively associated with clean breaks (η^2 = -0.37, -0.15, -0.05, respectively), carries (η^2 = -0.19, -0.11, -0.13, respectively) and tackles (η^2 = -0.12, -0.06, -0.12, respectively). 20 m split, 40 m split and MAS were positively associated with clean breaks (η^2 = 0.04, 0.14, 0.02, respectively), while V_0, bench 1RM and pull-up were all negatively associated (η^2 = -0.03, -0.04, -0.19, respectively). 30 m split was positively associated with carries and tackles (η^2 = 0.15, 0.07, respectively), while MAS was negatively associated (η^2 = -0.14, -0.05). Mom10 was also negatively associated with carries (η^2 = -0.02).

Table 9. Effect of fixed factors on clean breaks (90% CI).

Clean breaks	**Coefficient**	**90% CI**	**df**	***t*-value**	***η^2***
Intercept	0.003	0.21, 0.70	39.062	3.549	
CMJ (cm)	0.000	-0.41, 0.08	62.440	-1.174	-0.15
V_0 (m·s^{-1})	-0.001	-0.18, 0.13	152.612	-0.431	-0.03
Skinfolds (mm)	0.000	-0.92, 0.01	14.680	-1.531	-0.37
10 m Split (s)	-0.011	-0.18, 0.08	167.257	-0.681	-0.05
20 m Split (s)	0.009	-0.15, 0.23	111.047	0.447	0.04
30 m Split (s)	-0.024	-0.42, 0.11	52.447	-1.124	-0.15
40 m Split (s)	0.015	-0.13, 0.39	56.021	1.050	0.14
MAS (m·s^{-1})	0.001	-0.25, 0.29	54.171	0.151	0.02
Bench 1RM (kg)	0.000	-0.51, 0.41	18.178	-0.159	-0.04
Pull-up (kg)	0.000	-0.62, 0.17	23.730	-0.930	-0.19

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; CMJ = countermovement jump; V_0 = theoretical maximum velocity; MAS = maximal aerobic speed; Bench 1RM = one repetition maximum bench press.

Table 10. Effect of fixed factors on carries (90% CI).

Carries	**Coefficient**	**90% CI**	**df**	***t*-value**	η^2
Intercept	0.072	0.59, 0.74	195	12.691	
Body Mass (kg)	0.002	-0.12, 0.17	195	0.359	0.03
Skinfolds (mm)	-0.001	-0.33, -0.06	195	-2.712	-0.19
Bench 1RM (kg)	0.000	-0.13, 0.15	195	0.173	0.01
Pull-up (kg)	-0.001	-0.20, 0.08	195	-0.860	-0.06
F_0 (m·s^{-1})	-0.028	-0.27, 0.01	195	-1.872	-0.13
CMJ (cm)	-0.003	-0.25, 0.03	195	-1.573	-0.11
10 m Split (s)	-0.474	-0.27, 0.01	195	-1.826	-0.13
30 m Split (s)	0.116	0.01, 0.28	195	2.117	0.15
Mom10 (kg m·s^{-1})	0.000	-0.16, 0.12	195	-0.260	-0.02
MAS (m·s^{-1})	-0.068	-0.28, 0.00	195	-2.004	-0.14

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; Bench 1RM = one repetition maximum bench press; F_0 = theoretical maximum force; CMJ = countermovement jump; Mom10 = momentum over 10 m; MAS = maximal aerobic speed.

Table 11. Effect of fixed factors on total tackles (90% CI).

Total tackles	**Coefficient**	**90% CI**	**df**	***t*-value**	η^2
Intercept	0.091	0.44, 0.63	195	9.024	
Body Mass (kg)	0.002	-0.09, 0.19	195	0.763	0.05
Skinfolds (mm)	-0.002	-0.26, 0.02	195	-1.720	-0.12
Bench 1RM (kg)	0.000	-0.16, 0.12	195	-0.294	-0.02
Pull-up (kg)	-0.001	-0.16, 0.12	195	-0.281	-0.02
F_0 (m·s^{-1})	-0.049	-0.26, 0.02	195	-1.697	-0.12
CMJ (cm)	-0.003	-0.20, 0.08	195	-0.864	-0.06
10 m Split (s)	-0.316	-0.26, 0.01	195	-1.669	-0.12
30 m Split (s)	0.100	-0.07, 0.21	195	0.958	0.07
MAS (m·s^{-1})	-0.040	-0.20, 0.09	195	-0.639	-0.05

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; Bench 1RM = one repetition maximum bench press; F_0 = theoretical maximum force; CMJ = countermovement jump; MAS = maximal aerobic speed.

Table 12. Effect of fixed factors on collisions (90% CI).

Collisions	**Coefficient**	**90% CI**	**df**	***t*-value**	η^2
Intercept	0.230	0.67, 0.81	138.831	13.306	
Body Mass (kg)	0.007	-0.08, 0.26	130.828	1.097	0.10
Skinfolds (mm)	-0.001	-0.31, 0.11	85.779	-0.819	-0.09
Bench 1RM (kg)	0.000	-0.21, 0.22	84.926	0.065	0.01
Mom30 (kg m·s^{-1})	0.000	-0.30, 0.17	68.534	-0.457	-0.06
MAS (m·s^{-1})	0.063	-0.10, 0.19	181.014	0.577	0.04

Note: CI = confidence interval; df = degrees of freedom; η^2 = effect size correlations; Bench 1RM = one repetition maximum bench press; Mom30 = momentum over 30 m; MAS = maximal aerobic speed.

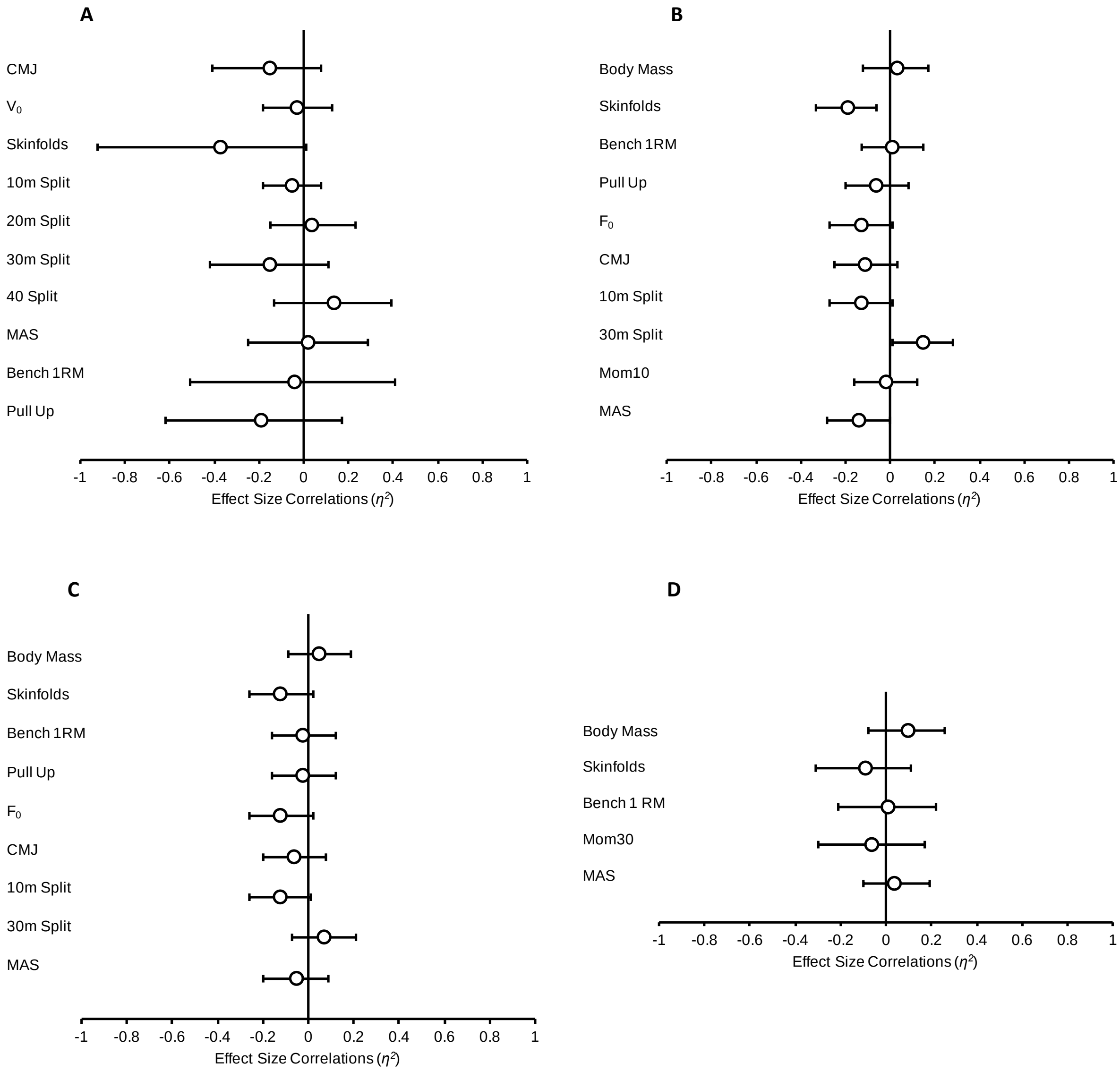

Figure 5. Effect size correlations for clean breaks (A); carries (B); total tackles (C); and collisions (D) (90% CI).

Body mass was positively associated with carries (η^2 = 0.03), tackles (η^2 =0.05) and collisions (η^2 = 0.10). Bench 1RM was positively associated with carries (η^2 = 0.01) and collisions (η^2 = 0.01), but negatively associated with tackles (η^2 = -0.02). Pull-up and F_0 were both negatively associated with carries (η^2 = -0.06, 0.13, respectively) and tackles (η^2 = -0.02, -0.12, respectively). Skinfolds and Mom30 were negatively associated with collisions (η^2 = -0.09, -0.06, respectively), while MAS was positively associated (η^2 = 0.04).

Chapter 5.0 – Discussion

This is the first study to examine relationships for key performance indicators (KPIs) and running loads of female rugby union matches, with combinations of physical abilities and morphological variables. Our results show that several relationships exist between physical abilities and match activities.

Maximal aerobic speed (MAS) had a positive relationship with the number of sprints, total distance, total distance < 3 $m \cdot s^{-1}$, total distance 3 to 5.5 $m \cdot s^{-1}$, and total distance > 5.5 $m \cdot s^{-1}$ performed in games (η^2 = 0.31, 0.22, 0.02, 0.14, 0.18, respectively). This confirms that MAS, as a measure of aerobic fitness, is positively related to the distance covered and number of sprints performed in female rugby union, as previously highlighted in other male team sports (Stone & Kilding, 2009; Helgerud et al., 2001; Bishop & Spencer, 2004; Swaby et al., 2016). The relationship with the selected KPIs (which were coach selected based on the associated links to performance; Watson et al., 2017) is less clear, as trivial relationships were found between MAS and clean breaks and collisions (η^2 = 0.02, 0.04, respectively), whereas trivial and small negative relationships were found for total tackles and carries (η^2 = -0.05, -0.14, respectively). Hence, MAS relates well to movement variables but other physical qualities, unrelated to MAS, are more likely to explain variance in collision activities. Moreover, it was unanticipated that bench 1RM and pull-up, which are reliable measures of upper-body strength (MacMaster et al., 2016; Jones et al., 2018), had trivial and small relationships with clean breaks (η^2 = -0.04, -0.19, respectively), carries (η^2 = 0.01, -0.06, respectively) and total tackles (η^2 = -0.02, -0.02, respectively) performed in games. In addition, the number of collisions performed in games had a trivial, positive relationship with bench 1RM (η^2 = 0.01), but no relationship with pull-up. It is important to note, the KPIs used in this study were not related to success on the pitch, such as tackle completion. Therefore, future research should attempt to make comparisons between physical abilities and successful performance.

Countermovement jump height was positively associated with all kinematic variables: accelerations (η^2 = 0.12), decelerations (η^2 = 0.09), sprints (η^2 = 0.28), total distance (η^2 = 0.21), total distance below 3 $m \cdot s^{-1}$ (η^2 = 0.01), total distance from 3 to 5.5 $m \cdot s^{-1}$ (η^2 = 0.23) and total distance greater than 5.5 $m \cdot s^{-1}$ (η^2 = 0.26). This suggests that improvements in CMJ correlate with locomotor activity performed in games. A relationship between jump height, speed and match accelerations in male and female rugby athletes has been reported (Cronin & Hansen, 2005; Cunningham et al., 2016b; Jones et al., 2016) – although this finding is yet to be confirmed in female rugby union. In contrast, CMJ had negative correlations with KPI variables, including clean breaks, carries and total tackles (η^2 = -0.15, -0.11, -0.06, respectively). Therefore, the present findings suggest that CMJ positively correlates with match running loads but negatively with match involvements via these KPIs.

The magnitude of the relationship between CMJ and kinematic variables was dependent of the intensity of the activity. That is, match activities with greater intensities had stronger relationships with CMJ. The stretch-shortening cycle (SSC) contributes to positive work done and vertical displacement during the CMJ, and is essential for performance during intense, explosive activities, such as sprinting and jumping (Kubo et al., 2000; Kyröläinen & Komi, 1995). The SSC describes the activity of the muscle, whereby an eccentric muscular contraction (a stretch) is immediately followed by an explosive, concentric muscular contraction (Harrison et al., 2004). An athlete can increase force production and power output, augmenting the concentric contraction, by increasing elastic energy from the eccentric contraction; hence, increasing the stretch (Cavagna et al., 1968; Komi & Bosco, 1978; Van Ingen Schenau et al., 1997). Acceleration ability is characterised by the effectiveness of concentric and propulsive contractions, whereas deceleration ability is characterised by the effectiveness of the eccentric and breaking component of the SSC (Kopper et al., 2014). The effectiveness of the SSC is influenced by the rate and magnitude of the stretch, muscle tendon stiffness, the change in muscle length during the stretch, and the time between eccentric and concentric phases (Anderson, 1996; Harrison et al., 2004). Therefore, it is likely that through these mechanisms, the positive relationship between CMJ and high-intensity, explosive locomotor activities, during matches, can be explained – such as accelerations, decelerations, sprints and total distance greater than 5.5 $m\cdot s^{-1}$. However, it is suggested that running and hopping may provide a better representation of force generation during an SSC activity, due to a greater contribution of the stretch reflex, augmenting the concentric and propulsive phase, more so than vertical tests (Komi & Gollhofer, 1997). Thus, horizontal acceleration and deceleration tests may have added more to the finding of CMJ, as well as ensuring greater specificity of movement in relation to rugby union, which is predominantly running-oriented.

Alongside CMJ, body mass was the only other determinant of accelerations and decelerations performed in games (η^2 = -0.06, -0.26, respectively). Research has shown that excess mass reduces power-to-weight ratio and increases energy expenditure, therefore decreasing horizontal and vertical acceleration (Duthie et al, 2003; Withers et al., 1986). Moreover, an athlete's acceleration and force production capabilities are reduced with excess mass ($F = m \cdot a$; Barr et al., 2014). Furthermore, higher lean body and lean muscle mass, and lower body fat mass, increases power (Duthie et al., 2003; Olds, 2001; Dacres-Manning, 1998). The negative relationship of body mass with accelerations and decelerations in the present study would suggest that declines in the number of accelerations and decelerations performed in games can be partly explained by increased excess (fat) mass, as opposed to increased muscle mass. It is therefore surprising that skinfolds did not significantly change the maximum likelihoods for both accelerations and decelerations, consequently being excluded from the models.

Small effects were found for the relationship between the number of sprints performed in games and 10 m split time (η^2 = -0.22), suggesting that a one second increase in 10 m split time (i.e. slower time) corresponds with a 1.876 decline in sprint count per min. Duthie et al. (2006b) suggest that the mean duration of sprints in professional men's rugby union lasts between 2.5 and 3.1 s, which corresponds with split times up to 20 m for elite male players (Cross et al., 2015). This would suggest that players perform greater number of sprints over shorter distances, as opposed to longer distances, > 20 m (Duthie et al., 2006b; Austin et al., 2011). Furthermore, Suarez-Arrones et al. (2014b) reported that in elite female rugby union, the average sprint distance during games was 12.0 ± 3.8 m; however, this study used a small sample size (*n* = 8) and the 'elite' classification of players is questionable. Therefore, this suggests that improving the 10 m split time of elite female players positively correlates with the number of sprints performed in games; thus, the best accelerators perform more sprints, irrespective of any other capacity. However, the sprint patterns in the female game are, as of yet, uncertain and need to be clarified.

The relationship between sprints performed in games and 10 m split time could be explained by fixed thresholds for game kinematic variables. It has been shown that forwards and backs have different 10 m speeds (Cross et al., 2015; Quarrie et al., 1996), which has also been reported across positional groups. For example, Smart et al. (2013) showed that outside backs produced the fastest split times up to 30 m. Furthermore, the GPS units used in the current study were programmed to categorise sprints or high-speed running as work done at > 5.5 $m{\cdot}s^{-1}$. In the present study, data entries for backs showed faster split times over 10 m (1.88 ± 0.10 *vs.* 1.96 ± 0.12 s) and 20 m (3.25 ± 0.15 *vs.* 3.44 ± 0.17 s) than data entries for forwards, excluding data entries for scrum-halves. Thus, backs would break the present threshold quicker than forwards and over a shorter distance for a similar relative intensity of work done – likewise in female rugby league players (Jones et al., 2016). In addition, in female rugby union, forwards' high-speed running outputs are hindered by the greater amount of time spent in close proximity to other players (Sheppy et al., 2019). This highlights the need for positional-related thresholds to categorise high-speed running and sprinting kinematics. Moreover, Reardon et al. (2015) showed that in professional male players, inter-individual variability within positional subcategories exist for maximal velocity and high-speed running. Therefore, individualised speed zones (Reardon et al., 2015) would provide a better and more representative understanding of running loads during matches.

A negative relationship was also found for momentum over 10 m and sprints (η^2 = -0.25), suggesting that an increase in momentum corresponds with a decline in sprint count per min. On one hand, variations in body mass could explain a sprint-momentum relationship, given that momentum is a function of mass and velocity ($p = m \cdot V$; Barr et al., 2014) and that excess fat mass reduces horizontal acceleration and sprint speed in elite rugby players (Hartmann Nunes et al., 2020; Duthie et al, 2003; Withers et al., 1986). However, our results showed a moderate, positive effect size for the relationship with skinfolds and sprints (η^2 = 0.34), suggesting that an increase in skinfold thickness corresponds with an increase in the number of sprints performed in games. Similarly, body mass did not significantly increase the maximum likelihood in the step-up model for sprints, suggesting that neither absolute mass, nor muscle mass (although this was not directly measured), had no relationship with the number of sprints. On the other hand, momentum over short distances is linked to low-velocity force actions, such as tackles, collisions, rucks, mauls and scrums (Hendricks et al., 2014a; Duthie et al., 2003), as opposed to high velocity sprinting. Thus, players with force-dominant F-V profiles are more likely to have greater momentum over 10 m in comparison to those that are velocity-dominant (Cross et al., 2015); therefore, this could provide an explanation for the current finding. It was unanticipated that momentum variables would show only two other, small relationships with KPIs and match running variables. In addition, like the relationship between sprints performed in games and 10 m split time, it is likely that the interpretation of the present results is limited by using fixed speed bands instead of individualised speed bands (Reardon et al., 2015). Hence, the relationship of momentum with match running and KPI in female rugby union games requires further research.

Skinfold thickness was also positively related to total distance ($\eta^2 = 0.40$), and with all distance-speed thresholds. This finding indicates that players with higher sum of skinfold thickness (in a squad range of 52.3 to 139.9 mm; 86.9 ± 17.0 mm) will cover more relative distance during matches, while being statistically controlled for their positional group. This contradicts previous research, which suggested that excess fat mass increases energy expenditure and reduces mobility (Duthie et al, 2003; Withers et al., 1986; Olds, 2001; Dacres-Manning, 1998). Similarly, Posthumus et al. (2020a) reported that, in elite male rugby union players, skinfold thickness had a large and negative relationship with yo-yo intermittent recovery distance. Furthermore, lighter and leaner players tend to run more during both male and female matches (Duthie et al., 2003; Suarez-Arrones et al., 2014b). Whilst this is largely attributed to the difference in match demands between forwards and backs, this study incorporated a statistical control for the variance caused by positional differences. Therefore, the reasons for this relationship are unclear but could be explained by the nature of current female rugby tactics and the individual physical player profiles, which require further discussion herein.

In comparison to the men's game, elite female players possess higher skinfold thickness and body fat (28.2 ± 2.4 *vs.* 16.6 ± 2.5 %; Posthumus et al., 2020a; Posthumus et al., 2020b). Moreover, the sample of Posthumus et al. (2020b) were leaner and heavier than previously reported elite female players (Kirby & Reilly, 1993; Hene et al., 2011; Hene & Bassett, 2013; Nyberg & Penpraze, 2016). This highlights the large variation in the reported physical characteristics of elite female ruby players. Furthermore, the homogeneity of players is greater in elite male rugby union squads than female squads, with females reporting greater percentage differences between forwards and backs for body mass (27.9 *vs.* 21.5 %), lean mass (19.0 *vs.* 17.6 %), fat mass (64.5 *vs.* 48.2 %) and body fat percentage (27.7 *vs.* 20.4 %) than males (Posthumus et al., 2020a; Posthumus et al., 2020b). Moreover, considering the sample used in the present study, a large variance within position groups could explain the unanticipated, positive relationship between skinfolds and total distance covered in games. For example, data entries for scrum-halves with less than 75 mm skinfold thickness reported a greater mean total distance than the data entries for scrum-halves with greater than 75 mm skinfold thickness (78.0 ± 11.0 *vs.* 72.1 ± 11.5 $m \cdot min^{-1}$). Therefore, the homogeneity of elite female rugby union squads requires investigation.

Successful teams in elite female rugby union tend to adopt a possession-based strategy, in comparison to men's teams who adopt a territory-based strategy (Hughes et al., 2017). Successful men's teams kick more frequently than women's teams (Hughes et al., 2017), possibly resulting in a more continuous, (passing, ball-carrying, frequent colliding) style of play for women's teams. If we assume that this is the case for the current players, it is plausible that greater skinfold thickness among females help to withstand the effects of repeated collisions (Zemski et al., 2015), while maintaining the associated intensity of continuous running demands. Therefore, players who are more heavily involved in repeated collisions during matches, such as front row forwards (MacLeod et al., 2018), who also cover considerable distance during matches (between 4,220 and 5,358 m; Cahill et al. 2013; Cunningham et al., 2016a), could partly explain the variance in the relationship between skinfolds and total distance covered. Whilst the playing style of female players requires further research, it would appear than higher skinfold thicknesses within the ranges reported here (52.3 to 139.9 mm; 86.9 ± 17.0 mm) support the ability to maintain match running intensity in the elite female game.

Chapter 6.0 – Conclusion

Using a large sample of players over a five-year period, the current study reports on the relationships between combinations of physical abilities and morphological variables, with KPIs and running loads in elite female rugby union. Countermovement jump demonstrated positive relationships with all kinematic variables and stronger relationships with high-intensity running loads such as sprints, accelerations and total distance > 5.5 $m \cdot s^{-1}$ performed and covered in games. Similarly, MAS had positive relationships with sprint and distance variables. A positive relationship between skinfold thickness and distance covered at all intensities was an unanticipated and novel finding. To understand this more thoroughly, future research should attempt to characterise the tactical and technical match demands of elite female rugby union. The relationships between physical abilities and success on a rugby pitch should also be determined.

Chapter 7.0 – Practical applications

The results of this study can be used to create a physical profile for international and elite level female rugby union players. The current results suggest that practitioners can potentially improve match running performance by improving certain physical abilities; namely, CMJ and MAS, irrespective of position, in female rugby union. Moreover, strength and conditioning coaches should look to improve vertical explosive power to increase the number of sprints and accelerations performed in games, as well as distance covered at high-speeds. Furthermore, aerobic fitness should be considered essential for relative intensity during matches and repeated high-intensity performance. The positive relationship of skinfold thickness and total distance covered is novel, requiring further research before advising players.

The present findings support the framework for the physical development of elite rugby union players by Duthie (2006); suggesting that improving strength, power and speed, and optimising body mass and composition are essential for ensuring the physical development and progression of elite rugby union players. Furthermore, it is suggested that a big challenge for practitioners is to develop aerobic fitness, alongside anaerobic qualities, so players can achieve and maintain high levels of performance during repeated high-intensity efforts; such as, clean breaks, carries, tackles and collisions. Whilst in the present study, few relationships were found between KPIs, physical abilities and morphological variables, improving an athlete's physical abilities remains of vital importance for rugby union performance and player development. Moreover, it is suggested that training physical abilities through sport-specific movements is more effective than training individual muscles in isolation, as it improves the functionality of the kinetic chain (Duthie, 2006; Gambetta, 1998). In addition, KPIs, such as the ones chosen for this study, have direct links to success on the pitch (Cunningham et al., 2018; Watson et al., 2017; Vaz et al., 2010; Den Hollander et al., 2016; Ortega et al., 2009). Therefore, practitioners should consider the importance of KPIs on performance when creating and implementing training programmes for players.

The present physical profile for international female rugby union players should be considered for the development of elite players, at both international and club level. Thus, the present findings could also be used to inform talent identification and selection from club to international playing level in female rugby union. For example, CMJ and MAS scores could be used to inform performance on the pitch and readiness for competition. In summary, the present findings could be used to better inform coaches, practitioners and players regarding player development, readiness and selection.

Chapter 8.0 – List of References

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