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REVIEW ARTICLE

Applied Sport Science of Rugby League

Rich D. Johnston · Tim J. Gabbett · David G. Jenkins

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Abstract Rugby league is a team sport in which players engage in repeated high-intensity exercise involving frequent collisions. Recent research, much of which has involved global positioning system (GPS) technology, has provided coaches and sport scientists with a deeper understanding of match demands, particularly at the elite level. This has allowed for the development of training programmes that prepare players for the most intense contact and running demands likely to be experienced in competition. At the elite level, rugby league players have well-developed aerobic and anaerobic endurance, muscular strength and power, reactive agility, and speed. Upper- and lower-body strength and aerobic power are associated with a broad range of technical and sport-specific skills, in addition to a lower risk of injury. Significant muscle damage (as estimated from creatine kinase concentrations) and fatigue occurs as a result of match-play; while muscle function and perceptual fatigue generally return to baseline 48 h following competition, increases in plasma concentrations of creatine kinase can last for up to 5 days post-match. Well-developed physical qualities may minimise post-match fatigue and facilitate recovery. Ultimately, the literature highlights that players require a broad range of physical and technical skills developed through specific training. This review evaluates the demands of the modern game, drawing on research that has used GPS technology. These findings highlight that preparing players based on the average demands of competition is likely to leave them underprepared for the most demanding passages of play. As such, coaches should incorporate drills that replicate the most intense repeated high-intensity demands of competition in order to prepare players for the worst-case scenarios expected during match-play.

R. D. Johnston (✉) · T. J. Gabbett
School of Exercise Science, Australian Catholic University,
1100 Nudgee Road, Brisbane, QLD 4014, Australia
e-mail: richard.johnston@acu.edu.au

T. J. Gabbett · D. G. Jenkins
School of Human Movement Studies, University of Queensland,
Brisbane, QLD, Australia

1 Rationale

Rugby league is an intermittent team sport played internationally by junior and senior players from elite to non-elite standards. During a match, players perform bouts of high-intensity activity (e.g. high-speed running and sprinting) separated by short bouts of lower-intensity activities (e.g. standing, walking and jogging) [1–8]. In addition to the numerous bouts of high-speed running, players also frequently engage in physically demanding collisions and wrestling bouts [9–11]. For information on the origin and rules of rugby league, readers are referred to a previous review [12]. The sport science and physiology of rugby league have been reviewed only three times; in 1995 [13], 2005 [14] and 2008 [12]. Since 2008, there have been a number of advancements in sport science technology and global positioning system (GPS) microtechnology devices in particular. GPS has been used in the Australian National Rugby League (NRL) since 2009 and in the European Super League (ESL) since 2010, providing more detailed information regarding the physical demands of the game. There has also been an exponential rise in applied rugby league research. In the 5 years since the last review (2008), a search of PubMed for the term "rugby league" returned 129 results, compared with the 48 results in the 5 years prior to 2008. Furthermore, various rule changes since 2008 are likely to have altered the demands of the game and therefore player preparation. The NRL and ESL reduced the number of interchanges permitted by each side from 12 to 10 in 2008 and 2012, respectively. In 2009, the NRL introduced two referees to officiate matches; ESL and international games are still officiated by a single referee [2]. Quantifying the demands of rugby league match-play is important in developing specific training drills to appropriately prepare players for the rigours of competition. Given the large body of literature that has been published since the last review, an update on the applied sport science literature relating to rugby league will provide practitioners and researchers alike with an overview of the game as it presently stands. Data referred to in the text are means ± standard deviation unless otherwise stated.

2 Physical Demands

2.1 Quantifying Demands

Much of the research described in the previous rugby league reviews [12–14] involved the manual coding of video footage, classifying activities into 'zones' based on subjective analysis of movements [3, 6, 7, 15]. While this approach is reliable [3, 7], coding is labour-intensive, which has limited these studies to small sample sizes. Recent developments in GPS technology have allowed the movement patterns to be assessed objectively and with greater ease, allowing large numbers of athletes to be monitored during competition. Published articles describing the competition demands of rugby league using GPS [2, 4, 5, 8, 16–27] have extended our understanding of the physical demands of the game. Despite these advances, there are some issues regarding the quantification of match demands. Firstly, the reliability and validity of GPS devices in measuring movements, particularly short, high-intensity activities, has been questioned, but as the technology (and sampling frequency) has developed, so too has the accuracy [28]. Secondly, different devices used across studies makes comparisons difficult, and may explain some of the disparities seen [29]. Finally, there is little consistency between researchers in the velocity zones used for low-speed (0–1.9, 1–3, 0–2.7, 0–3.3 and 0–5 m s^{-1}), moderate-speed (1.9–3.9, 2.7–5, 3–5 and 3.3–5 m s^{-1}), high-speed (3.9–5.8, 5–5.5, 5–6.1 and 5–7 m s^{-1}) and very high-speed/sprinting activity (>5.5, >5.6, >5.8, >6.1 and >7 m s^{-1}) [4, 8, 17, 18, 20, 24]. More information on GPS technology can be found in these recent reviews [28, 30–32].

2.2 Total Distance

The physical demands of rugby league competition have been analysed in elite (professional) [2, 4, 5, 8, 16, 17, 19, 20, 24, 26, 33], semi-elite (semi-professional) [21, 24, 27], non-elite (amateur) [34, 35] and junior players [19, 23, 24] (Table 1). Over the course of a match, players typically cover 4,000–8,000 m depending on playing position and standard [2, 8, 17, 19, 20, 24, 34, 35]. The outside backs cover the greatest distances (~5,500–8,000 m) followed by the adjustables (~6,000–7,000 m) and hit-up forwards (~3,500–6,000 m) [2, 8, 17, 19, 20]. Differences in absolute distance are less clear when expressed relative to playing time (Table 1). There are small differences between positions, with some [8, 17, 19, 24, 26], but not all studies [2, 19, 24] suggesting that forwards cover the greatest relative distances. These conflicting findings could be related to the style of play of individual teams rather than a reflection of the game as a whole. Similar playing intensities can be largely attributed to the forwards spending less time on the field than other positions, typically playing 40–50 min [2, 8, 26]. Elite NRL and ESL players typically cover 90–100 m min^{-1} [2, 5, 8, 19, 24, 26]. On average, semi-elite and junior elite players cover lower relative distances than elite players (88 vs. 95 m min^{-1}) [19, 21, 24, 36] (Table 1); the intensity of non-elite matches is lower once again (75–83 m min^{-1}) [23, 34, 35]. This could be due to reduced physical [37, 38] and skill qualities [39] in non-elite players leading to lower work rates, more errors and stoppages during competition and reductions in match intensity. Relative distance covered (or match intensity) appears important to the outcome of a match. In elite and semi-elite competition, greater relative distances are covered by winning sides [16, 21], suggesting that the ability to maintain high work rates is linked to match outcome. It is important to recognise that the average match intensity does not highlight the most demanding passages of match-play [27, 40–42]. Preparing players based on these average intensities is likely to result in players being underprepared for competition [40, 41]. Indeed, when only assessing ball in play time rather than the whole game (including stoppages), the match intensity is significantly greater (125 ± 16.1 vs. 86.7 ± 9.8 m min^{-1}) [27]. In addition, relative distance covered varies depending on field position and phase of play. Relative distance is greatest when defending in the 70–100 m zone compared with the 0–30 m zone [117.2 ± 29.1 vs. 100.4 ± 28.9 m min^{-1}; effect size (ES) = 0.65] [41]. As such, coaches should be mindful of these increased demands when prescribing the intensities of conditioning drills. Collectively, these data highlight the importance of players maintaining high match intensity, as well as possessing the ability to increase intensity at critical periods of the match.

2.3 High-Speed Running

Players are required to perform high-intensity activities at critical periods of a match [16, 36, 40]. Forwards cover the

Table 1 Movement demands of rugby league competition

Study	Group	Playing time (min)	Distance (m)	Distance (m min^{-1})	LSA (m)	HSR (m)	RHIE bouts (no.)
Austin and Kelly [17]	NRL forwards	–	5,964 ± 696	85 ± 4	4,655 ± 568	432 ± 127	–
	NRL backs	–	7,628 ± 744	86 ± 5	5,844 ± 549	749 ± 205	–
Gabbett et al. [2]	NRL hit-up forwards	38.0 ± 10.8	3,569 ± 1,177	94 ± 10	3,334 ± 1,082	235 ± 122	8.0 ± 5.2
	NRL wide-running forwards	58.5 ± 16.7	5,561 ± 1,579	96 ± 13	5,143 ± 1,474	418 ± 154	9.9 ± 6.4
	NRL adjustables	64.1 ± 23.0	6,411 ± 2,468	101 ± 19	5,974 ± 2,299	436 ± 198	8.6 ± 7.7
	NRL outside backs	73.5 ± 14.9	6,819 ± 1,421	93 ± 13	6,235 ± 1,325	583 ± 139	8.5 ± 5.4
Gabbett [19]	NRL forwards	50.7 ± 13.1	5,129 ± 1,652	105 ± 21	4,878 ± 1,541	251 ± 157	11.9 ± 6.2
	NRL adjustables	74.9 ± 14.6	7,834 ± 2,207	99 ± 8	7,513 ± 2,138	320 ± 176	14.3 ± 5.4
	NRL backs	77.8 ± 10.1	7,575 ± 850	94 ± 10	7,123 ± 830	452 ± 113	14.5 ± 5.4
McLellan et al. [20]	NRL forwards	–	4,982 ± 1,185	–	4,664 ± 1,165	232 ± 60	–
	NRL backs	–	5,573 ± 1,128	–	4,879 ± 1,339	440 ± 101	–
McLellan and Lovell [24]	NRL forwards	–	8,442 ± 812	98 ± 12	–	–	–
	NRL backs	–	8,158 ± 673	101 ± 8	–	–	–
Twist et al. [26]	NRL forwards	56.7 ± 16.4	4,948 ± 1,370	88 ± 8	–	–	–
	NRL adjustables	82.8 ± 8.9	7,973 ± 1,160	96 ± 8	–	–	–
	NRL backs	85.8 ± 3.9	7,381 ± 518	87 ± 6	–	–	–
Varley et al. [25]	NRL	64.9 ± 18.8	6,276 ± 1,950	96 ± 16	5,950 ± 1,845	327 ± 168	11.4 ± 5.9
Twist et al. [26]	ESL forwards	57.9 ± 15.8	5,733 ± 1,158	102 ± 14	–	–	–
	ESL adjustables	69.7 ± 23.4	6,766 ± 1,495	104 ± 27	–	–	–
	ESL backs	83.9 ± 12.9	7,133 ± 1,204	86 ± 11	–	–	–
Waldron et al. [8]	ESL forwards	44.2 ± 19.2	4,181 ± 1,829	95 ± 7	1,723 ± 743	513 ± 298	–
	ESL adjustables	65.2 ± 12.4	6,093 ± 1,232	94 ± 8	2,365 ± 667	907 ± 255	–
	ESL backs	77.5 ± 12.3	6,917 ± 1,130	89 ± 4	3,262 ± 505	926 ± 291	–
Gabbett [19]	NYC forwards	52.3 ± 25.4	4,866 ± 2,383	93 ± 9	4,641 ± 2,315	225 ± 90	7.5 ± 3.5
	NYC adjustables	71.3 ± 14.0	6,920 ± 1,481	97 ± 10	6,562 ± 1,297	320 ± 176	11.3 ± 6.6
	NYC backs	75.5 ± 15.8	7,172 ± 1,377	96 ± 11	6,767 ± 1,262	452 ± 113	8.1 ± 1.4
McLellan and Lovell [24]	NYC forwards	–	4,774 ± 564	82 ± 5	–	–	–
	NYC backs	–	5,768 ± 765	74 ± 11	–	–	–
Gabbett [36]	QC top 4 teams	69.3 ± 19.6	5,822 ± 1,654	86 ± 8	5,475 ± 1,516	348 ± 186	10.9 ± 5.1
	QC middle 4 teams	70.2 ± 19.0	5,823 ± 1,616	85 ± 7	5,461 ± 1,494	362 ± 193	10.6 ± 5.3
	QC bottom 4 teams	68.3 ± 18.4	5,880 ± 1,583	87 ± 7	5,547 ± 1,481	334 ± 166	11.4 ± 5.7
McLellan and Lovell [24]	QC forwards	–	6,701 ± 678	89 ± 8	–	–	–
	QC backs	–	7,505 ± 627	94 ± 8	–	–	–
Duffield et al. [35]	Senior non-elite players	74 ± 10	5,585 ± 1,078	75 ± 14	4,923 ± 935	661 ± 225	–
Johnston et al. [34]	Senior non-elite players	68.8 ± 11.2	5,919 ± 872	82 ± 7	5,562 ± 828	358 ± 125	1.6 ± 1.5
Gabbett [23][a]	Junior non-elite players	32.7 ± 8.4	2,673 ± 650	83 ± 12	2,529 ± 619	144 ± 82	4.5 ± 2.5

Data are reported as mean ± standard deviation

ESL European Super League (elite), *HSR* high-speed running, *LSA* low-speed activity, *NRL* National Rugby League (elite), *NYC* National Youth Competition (junior elite), *QC* Queensland Cup (semi-elite), *RHIE* repeated-high intensity effort (classified as 3 or more high acceleration, high speed or contact efforts with <21 s between efforts)

[a] Games were 40 min in duration

least distance at high speeds (513 ± 298 m) compared with adjustables (907 ± 255 m) and outside backs (926 ± 291 m) [8] (Table 1). The majority of these high-intensity efforts occur over short distances, with 75–95 runs over less than 10 m, depending on position, and as few as 1–3 runs over a 50 m distance [5]. Outside backs perform significantly more high-speed runs over 10–20 m than props, and over 20–30 m than adjustables and props [5]. Like soccer [43], there is variation in high-speed [coefficient of variation (CV) = 14.6 %] and very-high speed running (CV = 37.0 %) between games [44]. However, it is unclear how much of this variation is due to various match factors, such as opposition, or the reliability and validity issues surrounding the GPS devices used [45]. Despite this, it is clear that workloads between players and matches vary; coaches should be mindful of this when prescribing training following each game. There is little difference in the amount of high-speed running performed by winning and losing teams [16, 36]. However, it is unclear whether there is a difference in how players achieve these distances (e.g. good kick chase in winning teams vs. covering line breaks in losing teams). It appears less successful teams are equally equipped to perform high-speed running efforts, but perhaps not able to recover as quickly [16]. The amount of high-speed running players perform varies depending on field position and is 6–8 times higher when defending in the opposition's 30 m zone than the other two-thirds of the field [41]. As such, players require the capacity to perform large amounts of high-speed running during short periods of match-play.

2.4 Sprinting

The distribution of sprints is similar to high-speed runs, with almost 40 % of sprints performed over 6–10 m, and 85 % being shorter than 30 m. Furthermore, only 1.4 % of sprints are deemed high velocity (>7.0 m s^{-1}) with the remainder comprised of low (≤1.11 m s^{-2}), moderate (1.12–2.77 m s^{-2}) and high (≥2.78 m s^{-2}) acceleration efforts [4]. Players perform a range of different activities prior to sprinting, with standing (24.3 %) and forward walking (28.1 %) being the most common [4]. Training acceleration across all positional groups by performing short sprints, typically over 0–20 m, from a number of starting positions is vital. Longer sprints focusing on peak velocity are also important for the outside backs [4, 8].

2.5 Repeated High-Intensity Efforts

Given the frequency of sprints (>7 m s^{-1}) performed over a game (35 ± 2 irrespective of playing position) [4], it could be thought that repeated-sprint ability (RSA) is an important attribute. Research from field hockey reported that the majority of sprints either occurred with less than 21 s or more than 2 min between each sprint [46]. As such, repeated-sprint bouts are defined as three or more sprints with less than 21 s between each sprint [46]. However, these bouts rarely occur in rugby league competition, with players only performing 1 ± 1 (range 0–3) repeated-sprint bout during a match [4, 6]. This could be due to the infrequency of high-velocity sprints [4], as well as the numerous physical collisions that players perform over a match [9, 10, 47]. Wide-running forwards perform the greatest number of collisions (47 ± 12), followed by hit-up forwards (36 ± 8), adjustables (29 ± 6) and the outside backs (24 ± 6) [10]. However, when expressed relative to playing time, the greatest frequency of collisions occurs in the hit-up forwards (0.58 per min) [2, 5]. Whilst repeated-sprint bouts may be important to non-contact sports [46], they are unlikely to reflect the most demanding passages of play in contact sports due to the exclusion of other high-intensity activities such as high-speed running, accelerations and collisions. Indeed, the addition of contact to repeated-sprints results in greater reductions in sprint performance [9]. Therefore, recognising repeated-sprint bouts as the 'worst-case' demands or exclusively training RSA is likely to leave players underprepared for the most demanding passages of match-play [9, 40].

Based on these shortfalls, all high-intensity activities (collisions, high-speed running and maximal accelerations) have since been incorporated into repeated-sprint bouts to truly reflect the 'worst-case scenarios' termed repeated high-intensity effort (RHIE) bouts [2, 4, 40]. More specifically, a RHIE bout, adapted from the definition of repeated-sprints [46], is defined as three or more maximal acceleration, high speed or contact efforts with less than 21 seconds between each effort [2]. Research suggests that in the NRL, players perform in the region of 9–14 RHIE bouts per match (Table 2), with little difference between positions [2, 4, 16, 19]. RHIE bouts occur during important passages of play, suggesting that the ability, or inability, to perform these bouts may significantly influence the outcome of a game [16, 40]. The greatest frequency of RHIE bouts occurs when players are defending in their 0–30 m zone (ES = 0.75–0.85) [41], with 70 % of RHIE bouts occurring within 5 min of a try being scored [40]. Moreover, winning teams perform more RHIE bouts, and more efforts per bout, than losing teams [16]. At the elite level, the running demands are similar between NRL and National Youth Competition (NYC) players, whereas the RHIE demands are greater during NRL competition [19]. Taken together, it appears vital that both senior and junior players are conditioned for the most demanding RHIE bouts experienced during match-play. These RHIE bouts are complex in nature and comprised of different activities, effort numbers, recovery between efforts, and recovery between bouts. There are a number of studies that document the nature of these RHIE bouts [2, 19, 40], which are summarised in Table 2. This information can be used by conditioning staff to develop position-specific RHIE drills to replicate the 'worst-case scenarios' of competition.

Table 2 Repeated high-intensity effort demands of National Rugby League competition[a]

	Hit-up forwards	Wide-running forwards	Adjustables	Outside backs
Total bouts (no.)	8–12	10–12	6–14	5–15
Maximum bout duration (s)	64	64	64	49
Mean efforts per bout (no.)	4–6	4–6	4–6	4–6
Maximum efforts per bout (no.)	6	6	6	7
Mean effort duration (s)	1.2–2.1	1.2–1.8	0.9–1.6	1.0–1.5
Maximum effort duration (s)	4.9–6.0	4.9–5.6	3.9–4.7	5.1–5.5
Effort recovery (s)	6.3–6.4	5.9–6.3	5.9–7.0	5.9–6.3
Bout frequency	1 every 4.8 min	1 every 6.3 min	1 every 5.2–7.7 min	1 every 5.4–9.1 min
Minimum bout recovery (s)	42	42	55	55

[a] Data from Gabbett [19], Gabbett et al. [2] and Austin et al. [40]

2.6 Activity Cycles

A recent study assessed 5 min periods of competition in NRL and NYC adjustables [42]. During the peak period for total distance, the ball was in play for significantly longer (peak: NRL = 251 s, NYC = 241 s; subsequent: NRL = 175 s, NYC = 185 s; mean: NRL = 184 s, NYC = 175 s), players covered greater total distance, and had a greater skill rating, compared with the subsequent and mean 5 min periods. While this study provides some information on the most demanding 5 min periods of play in adjustables, only using 5 min periods may not capture, and therefore underestimate, the most demanding passages of play. Indeed, the longest time the ball is in play for in NRL and NYC matches has been reported as over 11 min [1]. The average longest activity cycle is greater in the NRL (318.3 ± 65.4 s vs. 288.9 ± 57.5 s) and there is a smaller proportion of short-duration activity cycles (<45 s) than longer activity cycles (>91–600 s) than in NYC matches [1]. Furthermore, Top 4 NRL teams have a greater proportion of long activity cycles than Bottom 4 NRL teams [48]. Activity cycles of 'State-of-Origin' competition between the states of Queensland and New South Wales in Australia even exceed those of NRL matches, with a greater proportion of long-duration activity cycles [49]. Collectively, these data highlight the importance of performing prolonged high-intensity exercise (>10 min) and the ability to recover during short rest periods.

2.7 Phase of Play

The demands of defending are generally higher than attacking with greater total distance (106 vs. 82 m min^{-1}), low-speed distance (104 vs. 78 m min^{-1}), collision frequency (1.9 vs. 0.8 per min) and RHIE frequency (1 every 4.9 min vs. 1 every 9.4 min) [41]. Moreover, there may be stages when players are required to defend for a number of sets (e.g. concede a penalty or drop-out) at these elevated intensities. Coupled with the fact that fatigue causes reductions in tackling technique [50], the ability or inability to maintain these elevated match intensities, and minimise reductions in tackling technique, could determine whether a try is conceded. Although the demands of attack are lower than defence [41], players are required to maintain possession of the ball to create try-scoring opportunities, which may occur under high levels of fatigue [42]. Therefore, it is important that players are prepared for the most demanding running and contact demands of competition, whilst being able to maintain skill execution in both attack and defence. Given the increased physical demands of defence and the large physical cost associated with collisions [9, 47], teams that have performed large amounts of defence during a game may require additional recovery following competition. The emphasis on recovery may be increased further if the match was won, as these matches are associated with greater physical demands [16].

2.8 Pacing and Match Fatigue

Over the course of a game, players experience transient fatigue [5, 21, 22, 42] and display pacing strategies to permit the completion of the game whilst remaining in a reasonable physical state [21, 22]. Whilst low-speed activity is maintained over a game, there are reductions in high-speed running of 20.0 ± 21.4 and 30.5 ± 20.2 % in the final 20 min of each half [5], indicative of fatigue [51, 52]. Furthermore, adjustables exhibit reductions in distance covered and skill involvements in the final 10 min of the match [42]. This suggests that fatigue develops over the course of a game and results in reductions in physical and technical performance towards the end of each half of match-play. Utilising interchange players in the closing minutes of each half may attenuate the decline in match intensity [21, 22].

Although fatigue may manifest towards the end of each half, players also employ pacing strategies depending on their role within the match (whole-match vs. interchange players) [21, 22]. Whole-match players only show reductions in high-speed running in the final quarter (~21 %) [22], which is in accordance with others [5], highlighting the gradual onset of fatigue. Furthermore, whole-match players appear to employ a pacing strategy to manage energy expenditure so they can adequately complete game tasks, yet finish the match in a reasonable physical state. On the other hand, interchange players initially pace at a higher intensity than whole-match players [21, 22]. Waldron et al. [22] found that during the first interchange bout, players were able to maintain a greater match intensity than whole-match players for approximately 15 min. However, during their second bout, interchange players paced at a similar intensity to whole-match players so they maintain enough energy to produce an 'end-spurt' in the final minutes of the match [22]. Interchange players appear to cover a greater distance per minute and greater distances at low speeds, as well as greater RHIE bout frequency than whole-match players [21]. Collectively these data highlight that pacing occurs during rugby league match-play and interchange players set higher pacing strategies than whole-match players. If the aim of the interchange is to increase match intensity, coaches should acknowledge that the interchange player may only be effective for the first 15 min (depending on their individual physical capacity and the nature of the game) [22]. Despite this, more research is required in order to ascertain whether interchange players set different pacing strategies depending on the length of time they are likely to be on the field.

Pacing strategies also differ depending on match outcome for both whole-match and interchange players [21]. Whole-match players in winning teams maintain greater match intensity and cover greater distances at low speeds than players on losing teams [21], which is in accordance with others [16]. There is no difference in interchange players' match intensity between winning or losing teams, except for in the final quarter, where losing players produce an 'end-spurt', most likely in an attempt to force a positive result for their team [21]. These studies [21, 22] highlight that the competition demands differ between whole-match and interchange players, as well as winning and losing teams. Therefore, when conditioning interchange players, a greater emphasis can be placed on short, high-intensity exercise bouts.

3 Physiological Responses During Match-Play

Since the previous review [12], the internal load during competition has been assessed using heart rate [8, 22]. Elite players show average heart rates similar to those from semi-elite players [53], with little difference between the backs (83.5 ± 1.9 %), adjustables (81.5 ± 4.1 %) and forwards (84.1 ± 8.2 %) [8]. Average heart rate is reduced in elite players in the second half, which is likely to be explained by second-half reductions in playing intensity [22]. Although the relative intensity of a match appears to be similar between positional groups, the internal load, highlighted by training impulse, is greater in the outside backs [279.4 ± 71.8 arbitrary units (AU)] than the forwards (198.3 ± 82.3 AU), but not different to the adjustables (270.6 ± 63.5 AU) [8]. Whilst greater playing times experienced by the adjustables and outside backs could explain these differences [8], greater overall and high-speed running distances also heavily influence the rating of perceived exertion [54].

Table 3 Anthropometric characteristics of rugby league players by playing standard

Playing standard	Height (cm)	Body mass (kg)	∑7 Skinfolds (mm)
Senior elite [62, 63, 95]	183.9–184.2	94–97.6	47.0–60.8
Senior semi-elite [62, 86]	183.1	93.4–98.0	65.3
Senior non-elite [39, 129]	174.0–180.1	78.0–92.2	83.2–90.7
Junior elite [37, 56, 57, 61, 65, 130, 131]	171.0–182.0	75.2–95.1	64.3–68.5
Junior non-elite [37, 57, 64, 65]	169.6–176.0	69.7–76.3	75.1–76.4

4 Physical Qualities

Based on the complex demands of the game, players require a broad range of physical qualities [55, 56]; normative data are highlighted in Tables 3 and 4.

4.1 Body Composition

Due to the physical contact during a match, body mass and in particular lean mass are important (Table 3) [57]. Forwards are heavier and have greater skinfold thickness than other positional groups [56, 58–61]. Recent studies report no difference in body mass between elite and semi-elite players [62, 63] but show lower skinfold thickness as playing standard increases [57, 62–65], indicating greater lean mass in elite players. Low skinfold thickness is one of the most important discriminators between national and regional junior [57] and selected and non-selected senior elite players [63]. Furthermore, low skinfold thickness is associated with improved vertical jump ($r = -0.345$), 30 m sprint ($r = 0.417$), 505 agility ($r = 0.391$) and maximal aerobic power ($\dot{V}O_{2max}$) ($r = -0.464$) [66]; conversely, high skinfold thickness is associated with fewer playing minutes in elite players [63]. These data indicate that whilst high body mass is important, low body fat is vital

Table 4 Physical performance standards of rugby league players by playing position and standard[a]

Playing standard	Yo-Yo IRT (m)	Predicted $\dot{V}O_2$max (mL kg^{-1} min^{-1})	10 m sprint (s)	40 m sprint (s)	505 agility test (s)	Squat 1 RM (kg)	Bench 1 RM (kg)	Vertical jump (cm)	Squat jump peak power (W)	Bench throw peak power (W)
Senior elite	1,656–1,789	54.9–55.9	1.60–1.78	5.19–5.32	2.20–2.26	171–201	125–143	37.3–64.7	1,709–2,227	341–635
Senior semi-elite	1,506–1,564	53.2	1.60–1.74	5.13–5.29	2.27–2.32	150–155	111–144	60.8–69.0	1,701	515–694
Senior non-elite	1,080	45.0–47.6	1.82–2.19	5.69–6.14	2.34–2.69	145	105–134	41.0–62.0	–	506
Junior elite	1,440–1,488	46.4–51.7	1.61–2.06	5.15–5.83	2.30–2.47	133–145	101–133	43.5–52.8	1,897	–
Junior non-elite	1,340	32.1–50.6	1.79–1.95	5.52–5.93	2.31–2.48	145	70–115	42.5–58.2	1,315–1,552	255–554

Data taken from previous publications [37, 39, 56–59, 62–64, 70–72, 77, 79, 80, 85–91, 95, 96, 98, 107, 131–134]

1 RM 1 repetition maximum, *IRT* intermittent recovery test (level 1), $\dot{V}O_2$max maximal aerobic power

[a] Data are presented as means

so that performance is not compromised. With appropriate training and nutrition, players can expect to see gains in body mass and reductions in fat mass during the pre-season [60]; however, these gains may be difficult to maintain over the competitive period [67, 68], which may be explained by reduced training load during this time [69].

4.2 Speed and Acceleration

The majority of sprints performed during competition are over short distances (e.g. 0–20 m), and, as such, acceleration is a key attribute [4]. Acceleration is particularly important for forwards, who have the greatest proportion of short sprints [4]. Older studies (pre-2008) indicate no difference in speed qualities between standards [39, 59, 70], whereas more recent reports (post-2008) find elite players to be faster [57, 62–64], which may be due to advancements in the training methods of elite players (Table 4). Furthermore, 20 m sprint speed is an important discriminator between national and regional junior players [57]. Backs are significantly faster than forwards, especially over longer sprints [56, 71]. Developing speed, and in particular acceleration, from an early age should be a priority.

4.3 Agility

The ability to change direction at speed in rugby league is thought to be important [4, 72]. Despite this, there appears to be little difference in pre-planned change of direction speed performance between senior playing standards [59, 62, 72, 73] or positions [74]. However, in juniors, national players outperform regional players on the 505 agility test [57] and props are significantly slower than the other positional groups [66]. Although pre-planned agility is unable to distinguish between playing standard and position in senior players, when players are required to change direction in response to a sport-specific stimuli (i.e. reactive agility), there are clear differences [72, 73, 75]. Reactive agility performance is poorly correlated with 505 or L-run agility test performance [72]. This suggests that factors other than change of direction speed (e.g. visual scanning, anticipation, pattern recognition and situation experience) influence reactive agility performance and that they are distinct and separate qualities. With this in mind, it may be important for junior players to first master the ability to change direction and the specific movement skills required; as they develop, they need to be able to make decisions and change direction in response to specific stimuli (i.e. reactive agility).

4.4 Muscular Strength and Power

As discussed in a recent review paper [76], muscular strength and power are vital for success in contact sports. Upper- and lower-body maximal strength and power have consistently been shown to increase with playing standard [37, 63, 70, 77–81]. Muscular strength has been most commonly assessed with the back squat for the lower body, and bench press for the upper body, either testing 1 repetition maximum (RM) [82–85] or 3 RM [86–88]. Elite players have a 1 RM back squat ranging from 170 to 201 kg (1.78–2.05 kg kg^{-1}) [70, 85] compared with 150 kg (1.64 kg kg^{-1}) for semi-elite players [70]. Furthermore, 3 RM squat was significantly greater in selected semi-elite players than in non-selected players [86]. Muscular power is typically assessed in the lower body via vertical jump height [37–39, 59, 62, 63, 65, 74, 89–91] or peak power from jump squats [70, 78, 80, 87, 89] and bench throws for the upper body [77, 78, 80, 87].

Some studies report increases in vertical jump height with playing standard [63, 65, 90], whereas others do not [39, 62, 91]. Despite this, jump squat and bench throw peak power consistently increases with playing standard [70, 77, 78, 87, 89]. Forwards tend to be stronger and more powerful than the backs in absolute terms, but not when expressed relative to body mass [89]. Baker and colleagues reported that stronger players produce greater power outputs during the bench throw [77], and strength is associated with power production [87]. Increasing lower-body strength via multi-joint exercises (e.g. back squat) appears to translate into improvements in sprint speed over 0–20 m [85] and jump squat performance [92]. This is not surprising given that power is the product of force and velocity, and if the force-generating potential increases, then so will power. Despite this, low-strength individuals still possess the ability to improve power, highlighting that adaptations other than maximum strength are important for improving power [92, 93]. With this in mind, specific programmes need to be implemented using multi-joint exercises to maximise gains in strength and power.

4.5 Aerobic Power

Given the duration of a rugby league match, the distances covered at low speeds [2] and the need for rapid recovery following high-intensity exercise [94], it would be expected that well-developed aerobic power is important for performance. In accordance with the previous review [12], senior elite players have well-developed $\dot{V}O_{2max}$ in the range of 54.9–55.9 mL kg^{-1} min^{-1} [63, 95] with little difference between positions [38, 59, 74], and increasing with playing standard [63]. Despite this, $\dot{V}O_{2max}$ does not relate to any measure of match performance [95–97], which questions the utility of assessing $\dot{V}O_{2max}$ in an applied setting. However, in junior players, $\dot{V}O_{2max}$ is the strongest discriminator between playing rank [57]. This suggests that a well-developed aerobic capacity is vital at a young age, before developing more specific qualities, such as high-intensity running and RHIE ability, that appear more important for performance [97].

4.6 High-Intensity Running Ability

There are passages in play where players are required to perform large amounts of high-speed running in a short period of time [41, 42]. As such, well-developed high-intensity running ability is required in order to compete during these periods. Methods for testing this quality are inconsistent; some studies have used the Yo-Yo Intermittent Recovery Test [86, 98, 99], while others have used a prolonged high-intensity running ability test [63, 95, 97]. Gabbett and colleagues [63] reported no difference in prolonged high-intensity running ability and RSA between starters, interchange and non-selected players. Atkins [98] found no difference in the Yo-Yo test (Level 1) distance between elite (1,656 ± 403 m) and semi-elite players (1564 ± 415 m). In contrast, the distance covered on the Yo-Yo test (Level 1) was greater in selected (1,506 ± 338 m) than in non-selected (1,080 ± 243 m) semi-elite players [86]. In addition, greater high-intensity running ability is associated with greater playing minutes ($r = 0.32$) [63], as well as greater total and high-speed distance [97]. Whilst high-intensity running ability is a key attribute, the lack of differences between playing standard may reflect that these measures of anaerobic endurance fail to incorporate any form of contact, and therefore do not adequately replicate the demands placed on players. Indeed, the lack of association between Yo-Yo performance and RHIE performance highlights this point [86, 100]. As such, one attempt has been made to develop a specific RHIE test [100]. Although this test detected changes in RHIE performance, sprint time was the only dependent variable used, and did not take into account changes in tackle technique during the test. Given the complex nature of RHIE bouts, and the poor association with a number of physical qualities [86], determining an outcome measure is particularly difficult. More research is required regarding the nature of RHIE bouts in order to develop a specific test to assess this complex quality.

5 Technical Skills

It is clear that technical skills are also vital for successful rugby league performance, with elite players having superior tackling technique [63, 101], dual-task draw and pass proficiency [63, 102, 103], and anticipatory skill [72]. Furthermore, better tackling technique results in fewer missed ($r = -0.74$) and more dominant tackles ($r = 0.78$) during competition [101]. Despite this, the reliability of technical assessments, at least in junior players, has been questioned; it is important that when assessing a squad, the same expert assessor is used for all players [104]. Draw and pass performance (single-task) does not distinguish players of a different standard, whereas under dual-task conditions, elite players are better able to maintain performance [102, 103]. These findings suggest that the attentional demands of performing a successful draw and pass are lower (or, alternatively, the skill is more automated) in elite performers. Therefore, when these players are faced with this situation in a match, under pressure and fatigue, they are more likely to deliver a successful outcome. Indeed, greater off-field performance on these tasks is associated with a greater number of try assists, line break assists, fewer missed tackles, and more dominant tackles [95, 101]. As such, it is important for players to improve skills under single- and dual-task conditions. Fatigue also appears to impact on skill performance, with technical performance being reduced following the 5 min peak periods of NRL and NYC matches in the adjustables positional group [42]. Given that success in a game is governed by the number of tries scored or conceded, improving match-specific skills through training in both fatigued and non-fatigued states is likely to transfer to improvements of these skills during match-play.

6 Physical Qualities, Performance and Injury

Given the demanding nature of competition, it is not surprising that physical qualities influence match performance [95]. Sprint performance over 40 m is associated with evasive skills, such as beating a player ($r = -0.48$), offloading ($r = -0.45$) [39] and tackles completed during match-play ($r = 0.44$) [95]. Force generated over a 10 m sprint is positively associated with successful ball carries in junior players [96]. Reactive agility is associated with evasive skills and line break assists ($r = 0.29$) [39, 95]. Lower-body relative power is associated with sprint performance over 5, 10 and 30 m [88] and dominant tackles during match-play ($r = 0.27$) [95]. Lower-body strength appears vital for performance, with a greater 3 RM squat being associated with greater distances covered at both low and high speeds, as well as a greater number of RHIE bouts during match-play [86, 99]. It is likely that strong players are better able to utilise the stretch-shortening cycle [105], resulting in less neuromuscular fatigue [106] when moving at high speeds or effecting tackles, allowing them to execute these high-intensity activities more frequently [99]. Improving back squat strength appears to translate into improvements in sprint performance, particularly over 5 m where large forces are required during initial acceleration [85]. Based on this information, developing speed, agility and lower-body strength and power in rugby league players is vital for successful performances.

Given the high frequency, tackling is arguably one of the most important skills required of rugby league players. The greatest predictors of tackling technique in high-performance players are playing experience (ES = 1.59; $r = 0.70$) and lower-body power (ES = 0.49; $r = 0.38$) [62]. In addition, skinfold thickness (ES = 1.30–1.81; $r = -0.59$ to -0.68) and acceleration (ES = 0.82–2.30; $r = 0.41$–0.60) are also associated with tackling technique [62, 107]. Whilst playing experience is likely to improve tackling technique directly, greater acceleration, lean mass and lower-body power could allow a player to generate more force in the tackle, potentially leading to more dominant tackles [101]. Well-developed agility ($r = 0.68$) and aerobic power ($r = -0.63$) are associated with smaller fatigue-induced decrements in tackling technique [50]. This is likely to reduce the number of ineffective tackles in a match, particularly in the final stages of each half when fatigue is evident [22].

As highlighted earlier, the ability to perform repeated efforts is vital for performance [16, 40, 41]. Players with well-developed prolonged high-intensity running ability spend more time on the pitch, and cover greater total distances at both low and high speeds [97], and recover faster following match-play [99]. However, players with poor prolonged high-intensity running ability perform more collisions and RHIE bouts [97]. This highlights that while high-intensity running ability is vital for running performance and minimising post-match fatigue [99], it does not translate to RHIE performance, where the ability to perform contact efforts is vital. As such, it is clear that while running ability needs to be developed, specific contact and running drills that reflect the most intense RHIE bouts must also be incorporated into training.

Skill qualities do not appear to influence injury risk [108], whereas a number of physical qualities do [109, 110]. Faster 10 and 40 m sprint times, greater $\dot{V}O_{2max}$, high-intensity running ability, body mass and upper-body strength are all associated with lower injury risk [109, 110]. Although speculative, there are numerous factors that could explain these relationships. Firstly, contact injuries are the most common type of injury sustained in rugby league [111, 112]. Therefore, light players will produce less momentum when carrying the ball into the defensive line and slow players are more likely to be tackled than faster players [39], both of which are likely to increase injury risk. Secondly, players with lower aerobic power are likely to exhibit greater decrements in tackling technique [50], which in turn could increase contact injury risk. Thirdly, players with greater upper-body strength are more likely to 'win' the tackle in both attack and defence, potentially minimising injury risk. A broad range of physical qualities, such as speed, strength and aerobic power, need to be developed to minimise injury risk.

7 Post-Match Fatigue

Players experience immediate and delayed symptoms of fatigue that persist for a number of days following match-play. Studies have reported impairments in whole-body neuromuscular function [34, 35, 113–116], increases in markers of skeletal muscle damage [34, 99, 115–118] and reductions in perceived well-being [34, 113, 116] following rugby league matches. Due to the recovery time between matches, typically 5–10 days, coaching staff need to be mindful of the recovery time course in order to prepare optimally for the subsequent match.

The majority of studies quantifying post-match fatigue in rugby league players have utilised the countermovement jump to detect impairments in neuromuscular function [34, 35, 99, 113–116, 119]. Following competition, there are transient reductions in neuromuscular function typically lasting 24–48 h, evidenced by decreases in peak power and jump height [114–116]. Peak force appears less sensitive at detecting fatigue, showing little change following both single games [115] and an intensified competition [34]. As such, lower-body fatigue variables including a velocity component, such as peak power, offer high reliability and sensitivity for detecting changes in neuromuscular function [120]. Training aimed at developing speed and power qualities should be avoided for 48 h after competition.

There is evidence that upper-body muscle fatigue occurs following matches [34, 99]. Plyometric push-ups have been shown to offer good reliability in rugby league players [47]. Various studies have shown reductions in power and force following competition [34, 99, 119] and game-based training [47]. Furthermore, upper-body fatigue is only evident following physical contact [47]. These findings indicate that physical contact is largely responsible for upper-body fatigue following training and competition; assessing lower-body fatigue alone may underestimate the fatigue response.

The most effective way to determine fatigue is to utilise direct tests of muscle function. Despite this, numerous studies have utilised blood or plasma creatine kinase (CK) as an indirect marker of muscle damage in an attempt to understand the underlying physiological mechanisms [34, 99, 115–118]. Under normal, homeostatic conditions, CK is located within the myofibrils [121]; exercise induces varying degrees of mechanical muscle damage [122], which is thought to cause the release of intracellular components, including CK, into the extracellular fluid [123, 124]. Current evidence highlights that CK is elevated immediately post-match, with a peak at around 24 h after competition [115–118], and may remain elevated for up to 120 h following competition [115, 117], long after neuromuscular function has recovered [114, 117]. Physical collisions appear to be largely responsible for these increases in CK, with strong correlations between increases in CK and the number of collisions performed [116, 118]. Furthermore, larger increases in CK were seen following small-sided games involving contact, compared with non-contact small-sided games [47]. Although CK is widely used as a marker of muscle damage, its utility has often been questioned [125, 126]. However, recent research from rugby league [34, 119] and Australian football [127] suggests that high blood CK, indicative of muscle damage, is associated with reductions in match performance. In spite of this, regular assessment of players' CK is difficult, given the cost, time, variability in responses and invasive nature of the tasks [128]. More information regarding monitoring fatigue in rugby league can be found in a previous review [128].

8 Conclusions

The aim of this article was to offer a comprehensive and updated review of the literature regarding applied sport science in rugby league. There are now numerous studies that highlight the demands of the game in great detail from elite to non-elite competitions, indicating that as playing standard increases so too do the demands of the game, and in particular the RHIE demands. Winning in rugby league is associated with significantly greater match intensities, and repeated-effort demands. Lower-body strength and power as well as speed are positively associated with match performance and match-specific skills. High-intensity running ability is related to greater running performance during competition, but not RHIE performance. As such, players need to train specifically to replicate the most extreme RHIE demands of competition. As well as physical qualities, a number of technical skills also impact on successful tackles, line break assists and try assists.

Significant fatigue and muscle damage occurs following matches. Reductions in muscle function and perceptual fatigue typically return to baseline within 48 h of competition, although CK can remain elevated for up to 5 days. Well-developed high-intensity running ability and lower-body strength may reduce post-match fatigue. Markers of fatigue are exacerbated during periods of intense competition. Physical contact is largely responsible for increases in CK and upper-body fatigue. Increased blood CK prior to competition is associated with reductions in high-speed running and RHIE bouts. As such, players need to have well-developed physical qualities and allow sufficient time for recovery between games in order to maintain playing performances.

It is clear that in rugby league, physical and technical qualities are closely linked to successful performances. In junior players, low skinfolds, $\dot{V}O_{2max}$, agility and speed appear to be the most important physical qualities. In senior players, muscular strength and power, low skinfolds, high-intensity running ability, reactive agility and acceleration are vital to performance. Tackling technique and dual-task draw and pass ability appear to be the most important technical skills. Ultimately, these data highlight the need for specific training that aims to develop both physical and technical qualities.

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