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The effect of training mode on the validity of training load measures for quantifying the training dose in professional rugby league

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by

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Abstract

Establishing the accurate quantification of the training load is a key focus for researchers and sport scientists to maximise the likelihood of appropriate training prescription. In the field, there are numerous methods adopted to quantify the physiological, physical, mechanical, and other loads placed on team sports athletes, including global positioning systems, accelerometry, heart rate and session rating of perceived exertion. Each method can be classified within one of two theoretical constructs: the external or internal training load. Due to the lack of a gold standard criterion, previous research has investigated validity through relationships with criterion measures of load or dose-response associations with chronic changes in physical fitness. The current research designs within investigations into the validity of those methods have failed to consider the influence of the mode of training on the validity of the measures. As strength and conditioning coaches utilise a variety of training modes to stress the various physiological systems to promote the adaptations required to succeed in competition, investigating the influence of training type on training load validity is warranted.

To achieve this, the research (Chapters 3-6) was conducted within two professional rugby league clubs, where training load data (global positioning system, accelerometry, heart rate, session rating of perceived exertion) were collected across three twelve week pre-season preparatory periods. Training sessions were demarcated by training mode. The results of the first study showed that meaningful differences in the distances covered within arbitrary speed- and metabolic power-derived-thresholds exist between field-based training modes (small-sided games, conditioning, skills, speed). These differences in external load also led to differences in the perceptual- and heart-rate-derived internal load response. Establishing how those differences in demands influence the relationships between multiple external and internal training load methods is important to establish the validity of individual methods across different modes of training. In our case study approach in study two, the main finding was that when session rating of perceived exertion (sRPE) demonstrated trivial differences across multiple skills training sessions, large variation was present (coefficient of variation range 31-93%) in other training

load methods (individualised training impulse [iTRIMP], Body Load™, Total Number of Impacts, high-speed distance) which reduced (coefficient of variation range 3-78%) when sRPE demonstrated trivial differences during small-sided games. This provided initial evidence that training load measures provide different information which might be influenced by the training mode. However, a more comprehensive investigation was needed. In the third study we aimed to examine the influence of training mode on the variance explained between measures of external (arbitrary high-speed distance, Body Load™, total-impacts) and internal (iTRIMP, sRPE) training load over two twelve week pre-season preparatory periods. This was replicated in our fourth study, across a shorter period of training from a different team utilising different methods in which to represent the external (individualised high-speed distance, PlayerLoad™) and internal (heart rate exertion index [HREI], sRPE) training load. During both investigations, we determined the structure of the interrelationships of multiple internal and external load methods via a principal-component analysis (PCA). Within the findings of both investigations, the extraction of multiple dimensions (two principal components) in certain modes of training suggests a single training load measure cannot explain all the information provided by multiple measures used to represent the training load in professional rugby league players. Therefore, if a single measure is used this could underrepresent the actual load imposed onto players. However, establishing the 'dose-response' associations between training load and the changes in training outcomes, such as physical fitness is also needed to establish validity. As a result, during study five, we aimed to determine the influence of training mode on the 'dose-response' relationship between measures of external (PlayerLoad™) and internal (sRPE, HREI) training load and acute changes in physical performance (countermovement jump, 10- and 20-m sprint, Yo-Yo intermittent recovery test level 1) following conditioning and speed training. sRPE was the only training load measure to provide meaningful relationships with changes in Yo-Yo intermittent recovery test level 1 performance. This provides the first evidence of the acute dose-response validity of the sRPE method. No measure provided meaningful relationships with all changes in performance. Therefore, further investigation is warranted to establish whether a combination of measures reflect better those changes than individual measures. The findings of the thesis suggests that practitioner should consider the implementation of both external and internal training load methods within their monitoring practices and researchers should establish multivariate and mode-specific relationships between training load methods to elucidate appropriate evidence of validity.

1. Introduction

Rugby league is an international sport that originated in Northern England in the 1890s. The game is now played in several countries worldwide, including Australia, New Zealand, United Kingdom, France and Papua New Guinea (Meir, Arthur & Forrest, 1993; Gabbett, King & Jenkins, 2008). Currently, there are two predominant full-time professional competitions: The European Super League (ESL) and the National Rugby League (NRL). Whilst the game is arguably more popularity in Australia, as reflected in the turnovers of the two competitions (NRL: £104.3 million v Super League: £21.9 million), rugby league remains one of the most watched sports in the United Kingdom (UK) (The Rugby Football League, 2012; The National Rugby League, 2012). The recent and improved TV deal between the Rugby Football League (RFL) and Sky (Sky Sports, 2014) together with the introduction (2014-2015 season) of an innovative promotion and relegation structure (The RFL, 2015), means that more money is at stake for individual clubs. This should increase the pressure to perform and increase the commitment of coaches and sport scientists to advance current practices. The hope is that these pressures will ultimately enhance the spectacle of the game and draw more people to watch it.

One of the reasons people enjoy watching rugby league is the physical contact between players. As such, rugby league has been described as a collision based sport. It is played over two 40 minute (min) halves (at senior level) separated by a 10 min rest interval. While players are subjected to high-impact collisions, they also engage in short duration high-intensity bouts (e.g. running, passing, sprinting, tackling, hit-ups) separated by low intensity exercise (e.g. standing, walking, jogging) and the sport therefore, is of a prolonged intermittent nature (Gabbett et al., 2008). Each competing team consists of 13 players, with a limited interchange rule of 10 (from a selection of four substitutes). These 13 players are commonly divided into two predominant playing groups: forwards and backs. Individual positions include: prop, hooker, second row, lock, halfback, five-eighth, centre, wing and fullback (Austin & Kelly, 2013). The aim of the game is to advance the ball (in the hands) into the field position of the opposition and place the ball behind the opposition's 'try' line (Gabbett et al., 2008). Each team has a set of six tackles in which to score a try. After this, the ball is immediately given to the opposition to commence their set of six tackles. The duration of a rugby league match (80 min) is comparable to other sports such as soccer (90 min) and hockey (70 min) whilst being substantially shorter in duration than Australian rules football (120 min). The area of a rugby league pitch (261 m^2 per player) is considerably smaller than that of Australian rules football (436-516 m^2 per player) and soccer (375 m^2 per player) (The RFL, 2011). Due to the shorter playing duration and pitch area, the total locomotor distance demands of rugby league (~6000-7600 m) (Austin & Kelly, 2013) are lower than that of soccer (~9000 to 12000 m) (Carling, Bloomfield, Nelson & Reilly, 2008) and Australian rules football (~12,000 to 16,000m) (Gray & Jenkins, 2010). Lower-speed actions, which are evasive in nature, are commonplace within the game and are regularly contested in confined spaces due to the 10-metre distance that separates attack and defence lines. This is coupled with frequent physical collisions in an attempt to advance or restrict field position which include tackling, bumping, off-the ball decoy running and hit-ups and occur between 28 and 42 times per match (Gabbett, Jenkins & Abernethy, 2012). This interplay between running and collision-based activities between positions impose both a high magnitude and variety of physiological 'stress' or 'load' onto players (Johnston et al., 2014a; Soligard et al., 2016). To tolerate these varied loads and maximise performance, players require a wide range of well-developed physical qualities such as speed, agility, muscular strength, power, repeated sprint ability and maximal aerobic fitness (Gabbett et al., 2012; Johnston, Gabbett & Jenkins, 2014). To improve these qualities, practitioners need to appropriately prescribe multiple modes of training including conditioning, small-sided-games, skills, speed and wrestling training.

Enhancing the physical performance of players whilst ensuring they are available to compete are key considerations within team-sport training prescription. At the most abstract level, Bannister (1991) proposed that performance at any given time could be broken into two distinct components; a positive function (fitness impulse) and a negative function (fatigue impulse), in which performance results from the difference between the two (fitness minus fatigue) (Bannister, 1991; Morton, 1990). Therefore, a player with high fitness function but also high fatigue would produce a poor physical performance. On the other hand, a player with low fatigue but low fitness would also produce a poor physical performance. The magnitude of difference between the fitness-fatigue impulses occur as a direct result of the load imposed during competition or training (Gabbett, 2016). Therefore, given the congested fixture schedules over the calendar year, the prescription of these training modes must be carefully managed to ensure the optimal balance between fitness and fatigue (Twist, Waldron, Highton, Burt & Daniels 2012; McLellan, Lovell & Gass, 2011; Morgans, Orme, Anderson & Drust, 2014). This balance must also be managed to avoid negative training outcomes such as injury (Gabbett, 2016).

However, team sport training is complex as players are frequently trained in group settings designed to develop team physical fitness status and technical-tactical skills (Manzi et al., 2013). The danger is that typical group training reduces the likelihood of subjecting players to training doses that are specific and appropriate to their individual physiological capabilities and needs (Impellizzeri et al., 2005). Numerous factors such as an athlete's starting fitness level have previously been suggested to influence their internal training load and response to a given training stimulus (Bouchard & Rankinen, 2001). Therefore, group training practices might result in inappropriately prescribed internal loads, which could increase the risk of fatigue or injury if the training load is too high, or reductions in physical performance if the training load is too low (Alexiou & Coutts, 2008; Colby, Dawson, Heasman, Rogalski & Gabbett, 2014; Rogalski, Dawson, Heasman & Gabbett, 2013). As a result, consideration must also be given to the inter-individual variability in internal response to a given external training load (Borresen & Lambert, 2009).

Therefore, understanding the 'stress' or load that players are exposed to during training and competition is a fundamental consideration for practitioners. The International Olympic

Committee consensus statement on load in sport and risk of injury (Soligard et al., 2016, p.66) defined 'load' as:

'the sport and non-sport burden (single or multiple physiological, psychological or mechanical stressors) as a stimulus that is applied to a human biological system (including subcellular elements, a single cell, tissues, one or multiple organ systems, or the individual)'.

Therefore, to achieve this understanding as scientists, there is a need to develop valid measurement (s) that can be used in practice to represent the theoretical construct of the load imposed. Based on this definition, it appears the strive towards a valid representation of load should represent the magnitude imposed on multiple physiological (e.g. neuromuscular, musculoskeletal, and cardiovascular), mechanical and psychological systems across all training types within the overall training process (Bannister, 1991; Chiu & Barnes, 2003; Avalos et al., 2003).

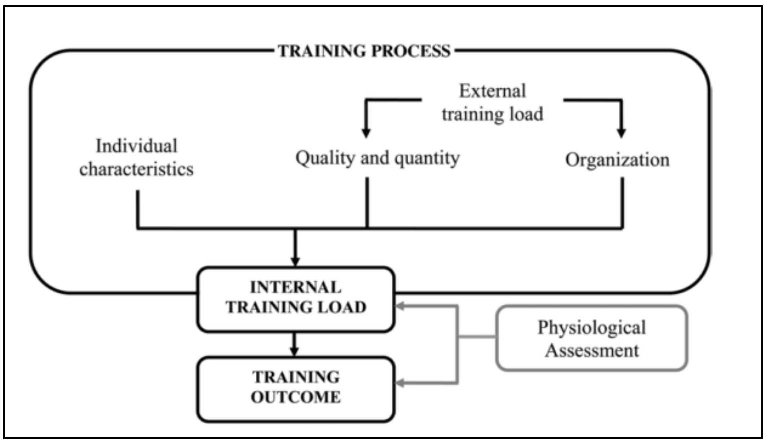


Figure 1.1. The training process (Impellizzeri et al., 2005).

More specifically, the overall training load imposed on athletes has two distinct components: the external training load, which is the training load that is independent of individual internal characteristics, such as the distance covered, or the internal training load, which is the psycho-physiological stress elicited predominately as a result of the external load (Impellizzeri et al., 2005; Scott, Black, Quinn & Coutts, 2013). There are a number of different methods used to quantify the training load in athletes, including the session rating of RPE, numerous training impulse (TRIMP) monitoring methods based on heart rate (internal training load) or more recently global positioning systems (GPS) and accelerometers (Borresen & Lambert, 2009).

The model by Impellizzeri et al. (2005) (Figure 1.1) shows that, theoretically, the internal load forms the basis for the training induced adaptations that are required to succeed in competition. The measurement of the internal load as mentioned previously has been largely based on heart rate-based TRIMP methods (Banister, 1991; Edwards, 1993; Lucia, Hoyos, Santalla, Earnest & Chicharro, 2003) and a perceptual-based method sRPE (Foster et al., 2001; Lovell, Sirotic, Impellizeri & Coutts, 2013). Establishing the agreement of practical measurements such as these to its true value (i.e. internal load) is a key consideration for sports scientists (Hopkins, 2000) and as a result, researchers establish the validity of a training load measure by investigating its relationships with a criterion method (Alexiou & Coutts, 2008; Kelly et al., 2015).

The sRPE has been suggested to be a valid measure of internal training load because of the large associations with a number of heart rate-based measures, such as Banister's TRIMP (Banister, 1991) and Edwards TRIMP (Edwards, 1993). For example, large associations have been reported between sRPE and Banister's TRIMP ($r = 0.73$; $r^2 = 0.53$) and Edwards TRIMP ($r = 0.77$; $r^2 = 0.59$) during in-season professional soccer training (Scott et al., 2013), despite the coefficient of determination showing that 40%-50% of the variation in heart rate-based methods is still unaccounted for by sRPE. The 'criterion' methods outlined above have also been previously been criticised (Akubat et al., 2012) for their lack of specificity to team sports as a result of using mean heart rate (Banister, 1991), the use of generic weightings based on sex and not individualised characteristics (Banister, 1991) or linear weighting factors which do not reflect the physiological response to intermittent exercise (Edwards, 1993).

Therefore, rather than examining the validity of sRPE by examining its relationship with other measures of training load, a dose-response study should provide a more robust approach to inferring validity. That is, changes in fitness and/or performance should be correlated against sRPE over a period of training or following individual training sessions. Recently, Gil-Rey et al. (2015) examined the relationships between differential (respiratory and muscular perceived exertion) sRPE and changes in physical fitness following 9 weeks of in-season training and competition in 34 youth soccer players. *Most likely* very large associations were found between respiratory (r = 0.71 [90% CL: ± 0.19]) and muscular (r = 0.69 [90% CL: ± 0.20]) sRPE and changes in aerobic fitness (time to exhaustion test). Although Gil-Rey et al. (2015) reported dose-response validity for differential sRPE, other studies using global sRPE have not (Gabbett & Domrow, 2007; Akubat et al., 2012). As a result, questions remain over the validity of the sRPE method to quantify the internal load, as sRPE has only been validated against the previously criticised methods of measuring the training load and only one study has reported a dose-response relationship to changes in fitness and/or performance.

The individualised training impulse (iTRIMP) was developed because of the criticisms levelled at previous heart rate methods and to further individualise the quantification of the heart-rate based internal training load (Manzi, Iellamo, Impellizzeri, D'Ottavio & Castagna, 2009; Akubat, Patel, Barrett & Abt, 2012; Manzi, Bovenzi, Impellizzeri, Carminati & Castagna, 2013). The iTRIMP uses a weighting factor, which is calculated using each players individual blood lactate-heart rate profile, with the weighting factor applied to each heart rate and then summated. The dose-response relationship between the mean weekly iTRIMP and changes in fitness have been reported in recreational runners and professional youth and professional senior football players (Manzi et al., 2009; Akubat et al., 2012; Manzi et al., 2013). However, to date no study has assessed the validity of the iTRIMP method across different modes of training in professional rugby league.

More importantly, it would also be logical to question the capability of a single criterion method to represent the true value of the internal load imposed given the definition of load highlighted previously. This might be even more important to consider in sports such as rugby league, that include a high frequency of collision-based activity. The recent development of GPS (and inbuilt inertial sensors) systems has allowed sports scientists to more easily quantify the external loads placed on team sports players, which have been shown to provide additional useful information to the outcomes of training. For example, whilst speculative, current internal training load measures such as iTRIMP, might underrepresent the internal neuromuscular and musculoskeletal cost of collisions, which have been shown to elicit significant damage to the muscle fibre structures and elicit neuromuscular fatigue and decrements in performance (McLean et al., 2010; McLellan et al., 2011; McLellan & Lovell, 2012). In contrast, accelerometer-derived external load measures have previously been reported to reflect the variability in these responses (McLellan et al., 2011; McLellan & Lovell, 2012; Oxendale et al., 2014). As a result, in collision sports such as rugby league a combination of measures might provide a better representation of the total load of training rather than individual measures alone. However, this type of investigation in professional rugby league is limited.

These questions are confounded further when considering the variety of training modes used in rugby league, which can range from skills to wrestling, and involve different session aims and organisational constraints (e.g. volume and intensity). Using a variety of training modes are likely to impose a diverse range of stresses on the various physiological systems (e.g. cardiovascular, neuromuscular, and musculoskeletal) in order to provoke an array of complementary adaptations within an eclectic player development programme (Lovell et al., 2013; Soligard et al., 2016). However, there is currently limited information examining the differences in external and internal load structures of different training modes commonly used in professional rugby league. A greater knowledge of these training structures would provide extremely useful information for practitioners in the development of periodised training programmes. Further, the influence of the training mode on the variance explained by a single training load method has yet to be considered. Whilst not the primary aim of their study, Lovell et al. (2013) reported that the strength of the relationships between sRPE and other measures of training load (e.g. total distance, Banister’s TRIMP, Body Load™) was altered across different training modes in professional rugby league training. For example, the mean within-individual correlation reported between sRPE and Banister's TRIMP during skills-conditioning training was r = 0.75 (90% CI: 0.58 to 0.86) while during skills training this relationship reduced to r = 0.45 (90% CI: 0.18 to 0.66). While these relationships were statistically significant, the wide confidence intervals highlighted above show the imprecision and uncertainty in those relationships. Again, the coefficient of determination for these relationships show that sRPE accounts for only 56% of the variance in Banisters TRIMP during skills-conditioning whilst this reduces to 20% during skills training. Consequently, this provides initial information that the training mode influences the validity of a single training load measure (such as sRPE) to quantify the training load in rugby league players. Therefore, a current limitation of traditional training load research is that although practitioners and researchers collect multiple methods concurrently (e.g. sRPE; GPS; tri-axial accelerometer; HR), the standard statistical analysis techniques employed (e.g. Pearson correlation) do not acknowledge the multivariate aspects of the dataset and instead focus on single variables to represent the training load construct. Nevertheless, it is unknown whether more than one training load variable is needed to accurately reflect the training stress more appropriately across different modes of training. As a result, the major aim of this thesis is to determine the influence of training mode on the validity of currently adopted external and internal training load methods in professional rugby league.

1.2. Aims

The aims of this thesis are:

- To determine the differences in external and internal training load per minute of training time between training modes in professional rugby league.
- To examine the variation in external and internal training load measures when a single measure of internal load (sRPE) demonstrates trivial differences across an acute period of training.

- To examine the influence of training mode on the variation explained by common measures of external and internal training load during a chronic period of training in professional rugby league.
- To examine the influence of training mode on the dose-response relationships between measures of training load and acute changes in physical performance.

2. Literature Review

The aims of the literature review are: (1) to provide an overview of the physical and physiological demands of professional rugby league and the qualities that professional players need to possess to succeed. This will provide context against which the methods (training modes) can be evaluated; (2) to examine the role of training load monitoring, with special reference to the influence of training load on both the positive and negative outcomes of training; and (3) to critically examine the current knowledge base relating to the validity of individual measures of both external and internal training load to highlight unconsidered areas within the literature.

2.1. The Locomotor and Physiological Demands of Rugby League Competition

Time motion analysis has been utilised extensively to determine the locomotor demands and movement characteristics of professional rugby league match play (Waldron, Twist, Highton, Worslford & Daniels, 2011; McLellan et al., 2011; McLellan & Lovell, 2013; Austin & Kelly, 2013). The results of time-motion analysis studies provide important information to applied sport scientists on the demands of training and competition, which can assist practitioners to evaluate whether the training prescribed is comparable to the demands imposed during competition (Gabbett et al., 2012). Prior to the introduction of GPS in the NRL and ESL, much of the research describing the demands of rugby league match play used manual coding of video footage from matches (King, Jenkins & Gabbett, 2009; Sirotic, Coutts, Knowles & Catterick, 2009; Sirotic, Knowles, Catterick & Coutts, 2011; Meir et al., 2001). However, whilst reliable (King et al., 2009; Sirotic et al., 2009), the laborious nature of manual video time-motion analysis has now been replaced with the development of GPS technology. Large volumes of data can be analysed very quickly from multiple players, which negates the issues of single player analysis, small sample sizes and consistency within and between observers using video analysis techniques (Macleod, Morris, Nevill & Sunderland, 2009). While the reliability and validity of early GPS devices (1 Hz & 5 Hz) to quantify high-speed movements have previously been questioned, the continued development (10 Hz & 15 Hz) of the technology has improved its accuracy (Aughey, 2011; Scott, Scott & Kelly, 2015) which will be discussed in Section 2.3.1.1 of the literature review.

The recent approval for the use of GPS units (and accompanied HR data) within professional level rugby league competition has allowed researchers to quantify the locomotor and physiological demands of competition over longitudinal periods (McLellan et al., 2011; Sykes et al., 2011; Waldron et al., 2011; Gabbett, 2012; Austin & Kelly, 2013; Gabbett, 2013a; Gabbett, 2013b; McLellan & Lovell, 2013; Waldron et al., 2013; Varley, Gabbett & Aughey, 2013; Austin & Kelly, 2014; Twist et al., 2014). Therefore, the aim of this section of the review is to determine the current demands of professional rugby league match play with particular reference to the locomotor, contact and physiological demands. Due to the difficulties in comparing the results of video-based and GPS based time-motion analysis and the current level of this research within this area, the following review of the locomotor demands will focus solely on time-motion analysis studies using GPS.

2.1.1. Locomotor Demands

Quantification of the locomotor demands of rugby league match play has largely centred on the distances covered at various arbitrary speed thresholds (McLellan et al., 2011; Waldron et al., 2011; Gabbett, 2012; Austin & Kelly, 2013; McLellan & Lovell, 2013; Austin & Kelly, 2014). However, a number of factors have to be considered when interpreting and comparing locomotor demands. First, the thresholds used for low speed (0 to 1.9; 1 to 3; 0 to 2.7; 0 to 3.3; 0 to 5 $m \cdot s^{-1}$), moderate-speed (1.9 to 3.9; 2.7 to 5; 3 to 5; 3.3 to 5 $m \cdot s^{-1}$), high-speed (3.9 to 5.8;

5 to 5.5; 5 to 6.1; 5 to 7 $m \cdot s^{-1}$) and very high-speed/sprinting (> 5.5; > 5.6; > 5.8; > 6.1; > 7 $m \cdot s^{-1}$) differs widely across studies (McLellan et al., 2011; Waldron et al., 2011; Gabbett, 2012; Austin & Kelly, 2013; McLellan & Lovell, 2013; Austin & Kelly, 2014). These wide variations makes comparisons between individual studies difficult. Second, the number of players and number of matches analysed is an important consideration. Differences in sample size must be accounted for in the interpretation of the results, as large between-match variability in distances covered at high and sprint speed have previously been reported (Kempton, Sirotic & Coutts, 2013). The co-efficient of variation (CV%) for total distance, high-speed running (> 15 $km \cdot h^{-1}$) and very-high speed running (> 21 $km \cdot h^{-1}$) from 345 individual match samples was 3.6, 14.6 and 37.9%, respectively (Kempton et al., 2013). This is logical as tactical differences between different oppositions, match outcomes and changes in within-game tactics of the team are likely to influence the locomotor demands of the match (Hulin, Gabbett, Kearney & Corvo, 2015).

Table 2.1. Locomotor demands of professional rugby league competition**.**

Study	Group	Playing time (min ± SD)	Distance (m ± SD)	Distance ($m{\cdot}min^{-1}$ ± SD)	LSR (m ± SD)	HSR (m ± SD)
Austin & Kelly (2013)	NRL FOR	-	5964 ± 696	85 ± 4	4655 ± 568	432 ± 127
	NRL BAC	-	7628 ± 744	86 ± 5	5,844 ± 549	749 ± 205
Gabbett et al. (2012)	NRL HUF	38 ± 10.8	3,569 ± 1,177	94 ± 10	3,334 ± 1,082	235 ± 122
	NRL WRF	58.5 ± 16.7	5,561 ± 1,579	96 ± 13	5,143 ± 1,474	418 ± 154
	NRL ADJ	64.1 ± 23.0	6,411 ± 2,468	101 ± 19	5,974 ± 2,299	436 ± 198
	NRL OB	73.5 ± 14.9	6,819 ± 1,421	93 ± 13	6,235 ± 1,325	583 ± 139
Gabbett (2013a)	NRL FOR	50.7 ± 13.1	5,129 ± 1,652	105 ± 21	4,878 ± 1,541	251 ± 157
	NRL ADJ	74.9 ± 14.6	7,834 ± 2,207	99 ± 8	7,513 ± 2,138	320 ± 176
	NRL BAC	77.8 ± 10.1	7,575 ± 850	94 ± 10	7,123 ± 830	452 ± 113
McLellan et al. (2011)	NRL FOR	-	4,982 ± 1,185	-	4,664 ± 1,165	232 ± 60
	NRL BAC	-	5,573 ± 1,128	-	4,879 ± 1,339	440 ± 101
McLellan and Lovell (2011)	NRL FOR	-	8,442 ± 812	98 ± 12	-	-
	NRL BAC	-	8,158 ± 673	101 ±8	-	-

Twist et al. (2014)	NRL FOR	56.7 ± 16.4	4,948 ± 1,370	88 ±8	-	-
	NRL ADJ	82.8 ± 8.9	7,973 ± 1,160	96 ±8	-	-
	NRL BAC	85.8 ± 3.9	7,381 ± 518	87 ±6	-	-
Varley et al. (2013)	NRL	64.9 ± 18.8	6,276 ± 1,950	96 ± 16	5,950 ± 1,845	327 ± 168
Twist et al. (2014)	ESL FOR	57.9 ± 15.8	5,733 ± 1,158	102 ± 14	-	-
	ESL ADJ	69.7 ± 23.4	6,766 ± 1,495	104 ± 27	-	-
	ESL BAC	83.9 ± 12.9	7,133 ± 1,204	86 ± 11	-	-
Waldron et al. (2011)	ESL FOR	44.2 ± 19.2	4,181 ± 1,829	95 ± 7	1,723 ± 743	513 ± 298
	ESL ADJ	65.2 ± 12.4	6,093 ± 1,232	94 ± 8	2,365 ± 667	907 ± 255
	ESL BAC	77.5 ± 12.3	6,917 ± 1,130	89 ± 4	3,262 ± 505	926 ± 291

Abbreviations: ESL, European Super League; NRL, National Rugby League; FOR, forwards; ADJ, adjustables; BAC, backs; OB, outside backs; LSR, low-speed running; HSR, high-speed running.

The total distance covered during a game is a frequent variable reported in research studies. As can be seen in Table 2.1, rugby league players typically cover between 4000-8000 m during the course of an 80-minute match, which is dependent on both the standard of competition, and playing position. Outside backs typically cover the greatest distances (~5,500-8000 m) followed by the adjustables (~6000-7000 m) and hit up forwards (~3500-6000 m).

While profiling the total distance travelled during a match is useful, it is also blunt in the information it provides for practitioners in regards to the structure and intensity of this external activity. Therefore, a comprehensive evaluation of the demands of competition or training is difficult unless taking into account additional variables such as the distance covered within various speed zones as it is likely that players can cover similar total distance whilst achieving this in vastly different ways. In regards to the high-speed locomotor demands, it has been established that players perform high-speed activities during critical periods of a match (Austin, Gabbett & Jenkins, 2011; Gabbett, 2013a; Gabbett, 2013b). Generally, forwards cover the least distance at high-speeds (14 to 17 $km \cdot h^{-1}$) (513 ± 298 m) compared with adjustables (907 ± 255 m) and outside backs (926 ± 291 m) (Waldron et al., 2011) (Table 2.1). Many of the high-intensity efforts performed during a match are over short distances, with as many as 75-95 less than 10 m and only 1-3 greater than 50 m (Sykes et al., 2011). Outside backs perform significantly more high-speed running over 10-20 m when compared to the props and significantly more over 20-30 m compared to both the adjustables and props (Sykes et al., 2011). This distribution is similar when investigating the sprinting demands of competition, where only 40% of sprints were found to be greater than 6-10 m with 85% shorter than 30 m (Gabbett, 2012). The mechanisms behind findings such as these have previously been suggested (Waldron et al., 2011). For example, the outside backs have a much larger area of space in which to progress at higher speeds from game situations such as kick-returns and positions during attacking plays. This is in contrast to the hit-up forwards who are very close (~10 m) to the opposition gain line and focused on winning the collisions and advancing the team's pitch position in both attack and defence. As a result, the availability of periods within a match to reach higher speeds is severely limited in this positional group. Moreover, it is possible that forwards are slower than both backs and adjustables (Meir et al., 2001), suggesting a greater difficulty or even lack of accelerative capability within the match-related spatial confinements, to attain a speed that is greater than the arbitrary sprint thresholds used in previous studies. Collectively, these findings highlight the benefits of adopting more than one variable to understand the external load demands of competition. This benefit is also transferable to understanding the external load demands of training.

Despite this, it is possible that rugby league players do not reach speeds that are necessary to be quantified as high-speed as frequently as in other sports such as soccer, as differences in pitch dimensions and rules (i.e. 10 m rule in rugby league) and the resulting spatial confinements are likely to limit the frequency of efforts at high-speed in rugby league. However, one cannot assume that a reduced frequency of efforts at high-speed as quantified by certain speed thresholds means that the metabolic cost of locomotor activity in rugby league match play is lower than that of soccer. As described later in the literature review, the metabolic cost of locomotor activity can be high, even though the speed of the activity is low (Osgnach et al., 2010). Interestingly, only 1.4% of sprints reported by Gabbett (2012) during professional NRL competition matches were deemed to be high speed (> 7.0 $m \cdot s^{-1}$), with the remainder of bouts classified as low (≤ 1.11 $m \cdot s^{-2}$), moderate (1.12 to 2.77 $m \cdot s^{-2}$) and high (≥ 2.78 $m \cdot s^{-2}$) acceleration efforts (Gabbett, 2012). Consequently, the sole use of speed-derived methods to quantify the external load may lead to an underestimation of the high-intensity dose that rugby league players are subjected to during match play. It is possible that this underestimation could also occur in the quantification of the high-intensity locomotor dose during training. If the training prescription by the strength and conditioning staff is individualised to the positional demands detailed by Austin and Kelly (2013), there is likely to be wider variation in the organisation of the external training load between positional groups and across training modes, which could exacerbate this underestimation. This could lead to sub-optimal quantification of the training dose and potentially inappropriate inferences made in regards to the process of training (Impellizzeri et al., 2005).

2.1.2. Collision Demands

In addition to the locomotor demands, rugby league players require the capability to execute and tolerate physical collisions during both defensive and attacking aspects of match play (Gabbett, Jenkins & Abernethy, 2011). The ability of a rugby league player to perform a tackle optimally during defence and to 'win' the tackle contest may be crucial for determining the outcome of the match (Gabbett, 2013a). Similarly in attack, the ability to dominate the physical collision contest during hit ups is important for optimising the distance gained and subsequent team field position.

The frequency of collision events in professional rugby league match play has previously been reported (Gabbett et al., 2011; Cummins & Orr, 2015; Kempton, Sirotic & Coutts, 2015). For example, Gabbett et al. (2011) observed that the total number of physical collisions performed in NRL competition matches was highest in the wide running forwards (47 [95% CI, 42 to 52]), which was significantly greater ($P < 0.05$) than the hit-up forwards (36 [95% CI, 32 to 40]), adjustables (29 [95% CI, 26 to 32] and outside backs (24 [95% CI, 22 to 27]. This finding, where hit-up and wide-running forwards perform a higher number of collisions than the adjustables and outside backs has been reported to occur consistently in professional rugby league competition (Gabbett et al., 2011; McLellan et al., 2011; Gabbett et al., 2012; Cummins & Orr, 2015).

However, despite the interesting findings, a full profile of collisions cannot be provided unless there is a description of not just the frequency of collisions but also the magnitude of collisions (Gabbett et al., 2012; Cummins & Orr, 2015). Quantifying the magnitude of collisions was previously impossible using video analysis techniques. However, with the introduction of GPS-housed accelerometers, the potential to quantify the magnitude of collisions during match play has led to the development of this emerging area of research. Gabbett et al. (2012) aimed to quantify the number of collisions at mild, moderate and heavy magnitudes using a tri-axial accelerometer sampling at 100 Hz, which was built into the MinimaxX GPS unit (Team 2.5, Catapult Innovations, Melborune, Australia). The hit-up forwards (42 [range: 35 to 48]) and wide-running forwards (45 [range: 38 to 52]) completed a significantly ($P < 0.05$) greater total number of collisions when compared to the outside backs (28 [range: 23-32]) but not the adjustables (28 [range: 23 to 32]).. However, the hit-up forwards (16 [range: 14 to 18]) and wide-running forwards (17 [range: 15 to 20]) completed a significantly greater ($P < 0.05$) number of heavy collisions when compared to the adjustables (11 [range: 9 to 14]), but not the outside backs (14 [range: 12 to 16]). These findings highlight the demanding additional aspects of collision-based activity when compared to other team sports such as football. Whilst the physiological responses to these activities will be discussed later, it is possible that a failure to consider this demanding aspect of rugby league training and competition will underestimate the load imposed on players, which is likely to reduce the chance of positive training outcomes.

2.1.4. Physiological Responses to Match-Play

Researchers investigating the physiological responses during rugby league matches have focused on within-game (Coutts, Reaburn & Abt, 2003; McLellan et al., 2011; Waldron et al., 2011) and post-game (McLellan et al., 2011; McLellan & Lovell, 2012; Twist et al., 2012; Oxendale et al., 2015) time periods. The within-match physiological responses have received limited attention, with researchers predominately measuring heart rate (Coutts, Reaburn & Abt, 2003; McLellan et al., 2011; Waldron et al., 2011) and blood lactate (Coutts et al., 2003). This is due to the current lack of non-invasive techniques to quantify the physiological response (apart from heart-rate) during a match. The mean heart rates reported in 12 professional ESL players across 12 competitive matches were 82 ± 4%, 84 ± 2% and 84 ± 8% of maximal heart rate (HR_{max}) for adjustables, outside backs and forwards groups, respectively (Waldron et al., 2011).

McLellan et al. (2011) confirmed the mean heart rates observed by Waldron et al. (2011) in 22 NRL players across five competitive fixtures. In addition, no significant differences were reported between the mean and maximum heart rate of forwards and backs or between first half and second half periods (McLellan et al., 2011).

Although there were no significant differences in the mean heart rate between forwards and backs, McLellan et al. (2011) reported that forwards spent a larger percentage of time during both halves of the match with a heart rate exceeding 170 $b{\cdot}min^{-1}$ (>85% HR_{max}). This is consistent with previous research in semi-professional rugby league players (Coutts et al., 2003). Despite differences in the standard of competition and refereeing structures between the two elite level competitions of the NRL and ESL, there appears to be comparability in the aerobic demands between the two competitions. Furthermore, Coutts et al., (2003) aimed to describe the blood lactate, heart rate and estimated energy expenditure responses of seventeen semi-professional rugby league players competing in the Queensland Cup in Australia, which is a surrogate reserve grade competition for the NRL. Heart rate responses were demarcated into low (< 70% HR_{max}), moderate (70-85% HR_{max}) and high-intensity (> 85% HR_{max}) zones. Estimated energy expenditure was calculated by extrapolating an individual's match play heart rate combined with the heart rate-VO_2 regression equation derived from an incremental treadmill test. The mean blood lactate concentration during a semi-professional match was reported to be 7.2 ± 2.5 $mM{\cdot}l^{-1}$. The blood lactate response during the first half (8.4 ± 1.8 $mM{\cdot}l^{-1}$) was significantly higher ($P < 0.05$) than during the second half (5.9 ± 2.5 $mM{\cdot}l^{-1}$). An elevated blood lactate concentration suggests a substantial involvement from the glycolytic system (Duffield et al., 2009), with lactate production being higher than lactate removal leading to a net increase measured in the blood. The observation of a decrease in blood lactate concentration between first and second half periods could be due to a reduction in high-intensity activity and subsequent anaerobic energy production during the second half, due either to accumulated fatigue (Reilly, 1997) or changing tactics. A reduction in blood lactate as the match progresses has also been observed in soccer practice matches (Krustrup et al., 2006). However, time-motion analysis was not conducted by Coutts et al. (2003), so it is not possible to ascertain whether this was the case in that study. The invasive nature and logistical difficulties of blood lactate collection have limited the use of this measure at the elite level. Regardless, the data from the above studies reaffirms the traditional perspective that there is both a large aerobic and anaerobic glycolytic component to rugby league match play (Meir et al., 1993; Meir et al., 2001).

The difficulty in obtaining measurements in the field setting during professional competition has led research to focus on the post-match physiological responses in order to understand the mechanisms and time-course of post-match fatigue (McLellan et al., 2011; McLellan & Lovell, 2012; Twist & Highton, 2013; Oxendale et al., 2015). This information is essential to inform periodisation strategies and to avoid negative outcomes such as injury risk and decreases in performance (Twist & Highton, 2013). The focus on post-match responses is logical, given the likelihood that within a periodised training regime competitive matches will likely contribute to the highest proportion of the total weekly stimulus imposed on players. It is outside of the scope of this thesis to comprehensively review the literature on post-match responses in rugby league players. Rather the aim of this section is to highlight the variety of fatigue mechanisms that arise because of rugby league competition in order to provide context for why monitoring the load imposed on players during competition and training is integral to optimise the training process. For a comprehensive review of the mechanisms of fatigue in professional rugby league, please see Twist & Highton (2013).

A major mechanistic cause of post-match fatigue is exercise-induced muscle damage (EIMD), which manifests itself as decreases in neuromuscular function (Byrne, Twist & Eston, 2004; McLellan & Lovell, 2012; Twist et al., 2012) and the proliferation of plasma myofibrillar proteins (McLean et al., 2010; McLellan et al., 2011) (Table 2.2). In addition, whilst not directly investigated in rugby league, depletions of the key energy substrate in intermittent activity, muscle glycogen, might also have a mechanistic influence on post-match fatigue. Evidence in other team sports with similar metabolic demands and game durations (i.e. football) (Krustrup et al., 2006) support this notion. These changes, coupled with the previously reported relationships between the number of collisions and blood markers of muscle damage (Twist et al., 2012; McLellan et al., 2011; Oxendale et al., 2014), suggests the demands of professional rugby league competition (Sections 2.1.1 to 2.1.3), such as collisions, lead to a multitude of mechanisms of fatigue. The manifestation of fatigue-related characteristics after competition has important implications for the periodisation and subsequent quality of training after competition, given the likelihood that increases in muscle soreness might reduce for example, exercise tolerance (Marcora, Staiano & Manning, 2009). Consideration of the influence of fatigue effects after both competition and training on the importance of periodisation of training will be discussed later (section 2.2.).

Table 2.2. Summary of research on the physiological and perceptual responses post-rugby league competition**.**

Authors		Fatigue Method	Results
		Blood & Salivary	
McLellan et al. (2011)	17 professional NRL players	Plasma Creatine Kinase ($U \cdot L^{-1}$)	Significant ↑ 24, 48, 72, 96, 120 hours post-match
		Salivary Cortisol ($\mu g \cdot dL^{-1}$)	Significant ↑ 24 hours post-match
Twist et al. (2012)	23 professional ESL players	Whole Blood Creatine Kinase ($U \cdot L^{-1}$)	Large ↑ 24 & 48 hours post-match
Oxendale et al. (2015)	17 professional ESL players	Whole Blood Creatine Kinase ($U \cdot L^{-1}$)	*Most likely* large ↑ 12 & 36 hours post-match
		Neuromuscular Performance	
Twist et al. (2012)	23 professional ESL players	CMJ Flight Time (Seconds)	*Forwards & Backs*: Large ↓ at 24 hours post-match *Forwards*: Moderate ↓ at 48 hours post-match Backs: Small ↓ at 48 hours post-match
Oxendale et al. (2015)	17 professional ESL players	CMJ Flight Time (Seconds)	*Very likely* large ↓ at 12 and 36 hours post-match
		Repeated Plyometric Push-Up (Seconds)	*Possibly* small ↓ at 12 hours post-match. Likely moderate ↓ at 36 hours post-match.

McLellan & Lovell (2012)	22 professional NRL players	CMJ Peak Rate of Force Development ($N \cdot s^{-1}$)	Significant ↓ 30 minutes and 24 hours post-match
		CMJ Peak Power (W)	Significant ↓ 30 minutes and 24 hours post-match
		CMJ Peak Force (N)	Significant ↓ 30 minutes post-match
Perceptual Responses			
Twist et al. (2012)	23 professional ESL players	Muscle Soreness	Forwards: Very large ↑ at 24 hours post-match Backs: Large ↑ at 24 hours post-match
Oxendale et al. (2015)	17 professional ESL players	Muscle Soreness	*Most likely* large ↑ at 12 and 36 hours post-match

Abbreviations: NRL, national rugby league; ESL, European Super League; CMJ, countermovement jump; ↑, increase; ↓, decrease.

2.1.5. Summary

- Rugby league players cover ~4000-8000 m during the course of an 80-minute match, which is dependent on both the standard of competition, and playing position.
- Of this distance, ~250 to 950 m is covered at high-speed, although the speed thresholds used to demarcate high-speed running have varied between studies.
- The sole use of total distance to represent external load demands is likely to limit the understanding of competition and training.
- Rugby league players participate in ~24 to 47 demanding collisions per match with 9 to 15 collisions at high magnitude (>10 *g*).
- Game-related spatial confinements substantially limit the frequency of sprints greater than 20 m, which is dependent on player position.

- The demands of competition summarised above impose a high metabolic stress on players, which, coupled with the volume of acceleration, deceleration and collision events elicit fatiguing effects. A variety of fatigue effects occur that reduce a player's functional capacity particularly in the 48 hours following competition. These fatiguing effects must be considered in the subsequent planning of training.

2.2. The Training Process

Due to the complex demands of rugby league match play reviewed above, players require a wide range of physical qualities (Meir et al., 2001; Till, Cobley, O'Hara, Chapman & Cooke, 2013). For example, due to the duration of a rugby league match (80 min), the previously highlighted distances covered at low speeds (Table 2.1) and the need for fast recovery after high-intensity bouts (Buchheit, 2013a), the development of a player's aerobic power and repeated-high-intensity-effort capacity (Austin et al., 2011; Johnston et al., 2014a) is an important consideration for optimal performance. Conversely, rugby league players must also be able to express the ability to move quickly to position themselves in attack and defence (Gabbett, 2005). The importance of speed and acceleration to match performance has been previously investigated with 40 m sprint performance associated with evading players ($r = -0.48$), offloading the ball ($r = -0.45$) (Gabbett, Kelly & Pezet, 2007) and the number of tackles completed during competition ($r = 0.44$) (Gabbett et al., 2011). Subsequently, the development of a variety of physical qualities such as body composition, speed and acceleration, agility, muscular strength and power, aerobic power, and technical skills are a particular focus for coaches and sports scientists in order to maximise the performance of their teams (Johnston et al., 2014a).

The process of training focuses on the concurrent development of specific attributes across multiple modes of training (e.g. small-sided games, traditional conditioning, speed and skills training) with the aim of enabling rugby league players to execute the variety of skills and physical outputs required for successful performance (Gabbett et al., 2012; Lovell et al., 2013). Attributes not only include physical development but technical skills and tactical awareness, psychological characteristics and resistance to injury (Bompa & Haff, 2009). The capability to produce a high level of technical skill during rugby league performance is vital. This has previously been shown as elite players possess superior tackling technique (Gabbett et al., 2011), dual-task draw and pass proficiency (Gabbett et al., 2011), and anticipatory skill (Gabbett, Kelly & Sheppard, 2008). Those findings show that physical and technical qualities are closely linked to successful performance. In order to acquire and further develop the aforementioned attributes, the optimisation of rugby league players physical performance throughout a competitive season requires an appropriate, individualised training schedule.

Professional rugby league training and competition exposes players to a multitude of physiological stressors, which can vary in both volume and intensity (Gabbett, Jenkins and Abernethy, 2012). The classic general adaptation syndrome (GAS) model by Selye (1956) and later the fitness-fatigue model by Banister (1991), highlight the maintenance of homeostasis as the fundamental driver to the training induced adaptations that result from the interactions of a variety of physiological perturbations (Manzi et al., 2009). Fundamentally, the GAS model by Selye (1956) details a generic response to a given stressor that includes three phases in which training induced adaptations take place. Firstly, there is a negative response, termed the 'alarm phase' which is related to the reduction in physiological function following a given training stimulus. Secondly, the 'resistance phase' whereby an athlete returns to homeostasis, often with a higher status of physiological function. Finally, the 'exhaustion phase' can occur when the elicited stress is of greater magnitude than the adaptive capabilities of the individual. It is during this stage where negative outcomes of the training stress occur, such as increases in injury risk.

Whilst Selye (1956) suggested that all stressors result in similar responses, the fitness-fatigue model proposed by Banister (1982) refined this paradigm and suggests that different training stressors elicit a variety of physiological responses and therefore differentiate the actions of a given stressor on individual physiological systems. Within this model, he proposed that training induces two effects, a positive effect (fitness) and a negative effect (fatigue) in which the interaction of the two determines the change in performance after a given training stimulus (Banister, 1982; Chiu & Barnes, 2003). Generally, the fatigue effect is large in magnitude but short in duration which produces the initial decreases in performance within the ‘alarm stage’ as first described by Selye (1956). Banister (1991) hypothesised that fatigue decays three times faster than fitness, after which training induced adaptations and enhanced performance take place.

The magnitude and duration of the fitness and fatigue effects are dependent on the stimulus applied as quantified by the training impulse (TRIMP) or internal training load (Banister, 1991; Chiu & Barnes, 2003; Impellizzeri et al., 2005). As discussed in section 2.1.4 of the literature review, the demands of competition lead to a variety of fatigue effects in players. Despite this, the fatigue effects elicited because of the concurrent training practices in professional rugby league are poorly understood. From Banister’s model (1982), it is possible that different training stimuli, and therefore different modes of training will elicit multiple fitness and multiple fatigue effects within a given training period in professional rugby league players (Chiu & Barnes, 2003). Variations in the intensity and duration of training are likely to elicit different stimuli to muscle fibres, neural activation and utilisation of different energy pathways (White, Spurway & MacLaren, 2006; Buchheit & Laursen, 2013a; Buchheit & Laursen, 2013b), which in turn are likely to elicit different fitness effects. For example, aerobic training results in adaptations such as an increased concentration of myoglobin, mitchondrial enzyme activity, increased respiratory capacity as well as increased cardiac output (Viru & Viru, 2001). On the otherhand, short duration sprint training with maximal recovery elicits morphological adaptations such as increases in fibre cross-sectional area, with other findings showing a decrease (Dawson et al., 1998) or no change in citrate synthase activity (Linossier et al., 1997), a key enzyme of the aerobic energy system. However, whilst different, these effects are likely to elicit a cumulative effect and in particular, the accumulation of fatigue effects with insufficient recovery might lead to an increase in negative training outcomes (Chiu & Barnes, 2003; Colby et al., 2014). Indeed, the capability of an athlete to dissipate the fatigue effects and adapt to the stressors imposed by training and competition is a crucial factor in the achievement of optimal performance levels in professional rugby league.

As highlighted in Figure 1.1, practitioners manipulate the fundamental principles of training (e.g. frequency, intensity and duration) within the design of the external training load (e.g. distances, speeds) to elicit the aforementioned physiological responses and subsequently an individual's internal training load (Impellizzeri et al., 2005). However, the typical group training approach within team sports training, coupled with a large squad of players, reduces the likelihood that players will be subjected to training loads that are individual to their requirements. This could lead to inappropriate fitness-fatigue effects and over longitudinal periods, inappropriate training outcomes such as injury (Gabbett 2004a; Gabbett 2004b; Colby et al., 2014). This is exacerbated further when considering the inter-individual variability in response to a given external training load (Impellizzeri et al., 2005; Borresen & Lambert, 2009). This inter-individual variability in response is likely to lead to a variety of players having an 'under-dosed', 'over-dosed' or 'appropriately-dosed' training programme if prescription is the same between players.

Numerous studies across both individual and team sports have investigated the influence of the fundamental principles of training (e.g. volume, intensity and frequency) on performance. Performance generally increases with increases in training load (Foster et al., 1996; Stewart & Hopkins, 2000), and assuming appropriate recovery. In individual sports, positive relationships have been observed between both training intensity (Mujika et al., 1995) and performance and training volume (Foster, Daniels & Yarbrough, 1977) and performance. However, given the multitude of factors that could influence successful match performance in team sports, it is unsurprising that the relationship between training load and match performance in team sports is currently poorly understood. Regardless, the training process-outcome relationship in team sports has been investigated in other areas with previous studies reporting the association between training load and training injury rates (Gabbett, 2004a; Gabbett 2004b; Gabbett & Ullah, 2012; Colby et al., 2014; Hulin et al., 2016).

To consider the fitness and fatigue impulses within load-injury analyses, Gabbett (2016) proposed the acute- and chronic-training-load ratio. The acute aspect of the ratio is calculated by the 7-day rolling average of a given single training load method which represents the fatigue impulse (Gabbett, 2016). On the other hand, the chronic aspect of the ratio is calculated by the 30-day rolling average of a given single training load method which represents the fitness impulse. The acute:chronic workload ratio is calculated by dividing the acute training load by the chronic training load which provides the relative magnitude of the acute training load compared with the chronic training load. A value of greater than 1 represents an acute training load greater than chronic training load and vice versa.

The ratio derived from a single training load method has been used as a single predictor variable in binary logistic regression analyses with injury incidence as the dependent variable. For example, Hulin et al. (2016) found a very-high (≥ 2.11) total-distance A:C ratio was very likely associated with a 3.4 times (95% confidence interval [CI]: ×/÷ 2.0) greater relative risk of injury than a low ratio (0.31 to 0.66) in professional rugby league players. The negative impact of injuries on team success (Hägglund et al., 2013), coupled with the influence of training load in improving physical qualities (e.g. higher aerobic capacity) and their subsequent influence in reducing injury likelihood (Gabbett & Domrow, 2005) highlights the importance of managing both the acute and chronic training load to minimise negative training outcomes. However, in every study that has investigated the association between the acute- and chronic-training-load-ratio and injury incidence, researchers have adopted numerous single training load variables such as total-distance, high-speed-distance and session rating of perceived exertion (sRPE) into the analyses (Bowen, Gross, Gimpel & Li, 2016; Murray, Gabbett, Townshend, Hulin & McLellan, 2016; Malone, Roe, Doran, Gabbett & Collins, 2016). Given the definition of load highlighted within the introduction of the thesis (Soligard et al., 2016), it is possible that a single method might not be optimal to reflect the actual total load imposed and multiple variables might be required. Given there are numerous methods available to quantify both the external and internal training load these will now be discussed in sections 2.3 and section 2.4.

2.3. Methods of Quantifying the External Training Load

Practitioners have been attempting to quantify the external load for decades. While the quantification of steady-state exercise is relatively simple (e.g. recording the duration of exercise or the distance covered) (Borresen & Lambert, 2009), the external load has previously been difficult to quantify in team sports due to their random intermittent nature (Bloomfield et al., 2007). This is further confounded when considering the labour intensive nature of video-based notational analysis methods that limits their use in both research and applied settings, particularly in regards to the quantification of training (Gabbett et al., 2012). However, the use of GPS technology to monitor the training load within team sports is now extremely common with a number of external load parameters collected (Aughey, 2011). The accurate quantification of the quantity and organisation of the external load is a key focus due to its contribution to the internal training load, which provides the stimulus in which training induced adaptations take place (Impellizzeri et al., 2005). Further, following the basic principle of training specificity, quantification of the external load is essential to quantify whether the response to training (internal load) is caused by an external training dose that is specific to the athletes competition needs. The following section will review current methods that are utilised to quantify the external training load, with particular focus on GPS and accelerometer technology.

2.3.1. Global Positioning Systems (GPS)

The global positioning system (GPS) is a satellite-based navigational technology that was originally developed for military purposes within the United States (Cummins, Orr, O’Connor & West, 2013). GPS devices possess an inbuilt receiver that communicates with a network of 27 orbiting satellites to determine the location of the unit (Scott, Scott & Kelly, 2015). Each satellite contains an atomic clock, which synchronises with the clock in the GPS receiver and emits information at the speed of light to the GPS receiver (Larsson, 2003). The geographical location of the player is determined by the travel time of the radio frequency signals that are emitted (Larsson, 2003). By comparing the time given by the satellite with the time within the GPS receiver, the signal travel time (i.e. displacement of the GPS unit) is calculated. The lag time that is determined by comparing the time given by a satellite and the time within the GPS receiver, is used to determine the distance from the GPS receiver to the satellite by multiplying the signal travel time with the speed of light (Larsson, 2003). A three-dimensional position and altitude of the GPS receiver can be determined trigonometrically by calculating the distance from the GPS receiver to at least four satellites (Shutz & Chambaz. 1997; Terrier et al., 2001). The GPS receiver compares the time a signal was transmitted by a satellite with the time it is received with the difference in time calculated by the GPS receiver to determine the distance to the satellite (Shutz & Chambaz, 1997; Terrier & Shutz, 2005; Townshend, Worringham & Stewart, 2008). Typically, speed profiles are determined by the Doppler Shift method, which is the measurement of the rate of change of the satellite signal frequency due to movement characteristics and relative speed between the satellite and the GPS receiver (Shutz & Chambaz, 1997; Terrier & Shutz, 2005; Townshend et al., 2008). The recent miniaturisation of GPS technology has permitted wider application of this technology to extend to team sport settings to enable sports scientists and coaches with detailed real-time analysis of player performance during competition and training. The increasing popularity of GPS has led to an increase in the number of research studies investigating the reliability and validity of the devices. Assessing the validity and reliability of the GPS unit is important to determine prior to applying the technology as a method of quantifying the external training load. The use of GPS technology within team sport applications focuses primarily on the quantification of an athlete’s total distance and the distances covered in various speed zones during training and competition. Consequently, establishing the validity and reliability of the technology to quantify both distance and speed is essential.

2.3.1.1. Validity and Reliability of GPS

Sampling rate, which is the frequency in which the GPS technology receives satellite signals, appears to be a major contributor to the validity of GPS devices to quantify the external load. Rapid progressions in sampling have been observed (5, 10 & 15 Hz) since its initial inception at 1 Hz. It would be logical to assume that as sampling rate increases, the precision of the technology to quantify short, rapid minimal duration efforts such as accelerations, decelerations and sprints will increase. The accurate quantification of these movements is essential, given their predominance within professional rugby league competition (Gabbett, 2012). However, the advanced microchip technology along with manufacturer specific algorithms aimed at increasing the measuring accuracy of GPS receivers also needs to be accounted for (Witte & Wilson, 2004; Buchheit et al., 2013). For example, two GPS receivers from different manufacturers, each with specific algorithms but both sampling at 5 Hz showed differing levels of accuracy (Petersen et al., 2009). As a result, it appears that a combination of improvements in both the sampling rate and chipset technology will provide greater sensitivity in the quantification of the measures. It is important as 'improved' devices emerge, that we continue to evaluate their validity and reliability.

The first validation study of commercially available GPS technology designed for team sports (GPSports, SPI-10, Canberra, Australia) was published by Edgecomb and Norton (2006). One athlete was fitted with a 1 Hz GPS unit that was worn at the anatomical site between the scapulae. The participant was requested to move at a self-selected speed around a marked circuit with 59 trials completed. The distance recorded by the GPS device was then compared to the distance measured via a calibrated trundle wheel. The results revealed that the distance covered by the GPS unit was highly correlated with, but significantly different to, the criterion distance ($r = 0.998$, $P < 0.001$), with the mean error reported to be 4.8 ± 7.2%. While a simple study with a very limited sample size, the work of Edgecomb and Norton (2006) introduced the first data to highlight the potential applications of GPS technology as a method of external training load quantification within team sport activity. The rapid increase in the utilisation of GPS technology within professional sport since that study, coupled with simultaneous advances in the technological capability of the devices, has led to a surge in research investigating the use of GPS in the recording of activity within sport (Petersen et al., 2009; MacLeod et al., 2009; Coutts & Duffield, 2010; Jennings et al., 2010; Castellano et al., 2011; Varley et al., 2011; Waldron et al., 2011; Johnston et al., 2014c). However, despite the increasing research attention in this area, there appears to be little consensus in regards to the 'gold standard' criterion method used to determine validity of the technology across studies. Criterion measures used in previous studies have included trundle wheels, pedometers, VICON and theodolite systems (Edgecomb & Norton, 2006; MacLeod et al., 2009; Gray et al., 2010; Coutts & Duffield, 2010; Barbero-Alvarez et al., 2010; Portas et al., 2010). Further, the variability in exercise bouts, GPS devices and sampling rates makes direct comparisons between studies difficult (Aughey, 2011). Despite this, given the history behind speed and distance measurement, the confidence that these criterion measures represent the true value is high (Hopkins, 2000).

5 Hz GPS units appear (Table 2.3) to display good validity for the quantification of straight-line (Portas et al., 2010), curvilinear (Petersen et al., 2009) and multidirectional movements (Johnston et al., 2012; Portas et al., 2010) during walking and running bouts over moderate to large distances. However, the validity of the device is greatly reduced during running and sprinting over shorter distances (Jennings et al., 2010; Petersen et al., 2009). Despite this and similar to 1 Hz devices, 5 Hz devices demonstrated the capability to quantify distance over a team sport simulation circuit with good validity (Jennings et al., 2012; Johnston et al., 2012).

At present, relatively few studies have compared the validity and reliability of 10 and 15 Hz GPS devices to accurately quantify distance and speed (Castellano, Casamichana, Calleja-Gonzalez, Roman & Ostojic, 2011; Akenhead, French, Thompson & Hayes, 2014; Johnston, Watsford, Kelly, Pine & Spurrs, 2014c). 10 Hz GPS has been reported to possess acceptable validity for quantifying distance during short sprints (15 m mean SEM = 11%, 30 m mean SEM = 5%) (Castellano et al., 2011). Similarly, Vickery et al. (2014) reported that distance measures were not significantly different from the criterion measures during a cricket fielding and fast bowling protocol. Further, Rampinini et al. (2014) reported good accuracy of 10 Hz GPS for measures of total distance (CV = 1.9%) and high speed running distance (CV = 4.7%) during intermittent shuttle running over moderate distances (70 m). The accuracy deteriorated however, during very high-speed running (CV = 10.5%). From the research reported to date, it appears that 10 Hz GPS devices are capable of quantifying short to moderate distances with greater accuracy compared to 1 Hz and 5 Hz devices. Therefore, the increase in sampling rate to 10 Hz should be preferred in team sport environments. In regards to reliability, 10 Hz devices appear to possess good intra-unit (CV: < 5%) and inter-unit (CV: 0.7-1.3%) reliability during 15 and 30 m sprints (Castellano et al., 2011). Good inter-unit reliability was also reported for total distance (TEM = 1.3%, ICC = 0.51), low speed running (TEM = 1.7%, ICC = 0.97) and high-speed running (TEM = 4.8%, ICC = 0.88) during a team sport circuit (Johnston et al., 2014c). However, this reliability appears to decrease with further increases in speed (TEM = 11.5%) (Johnston et al., 2014c).

Johnston et al. (2014c) expanded on the work of Castellano et al. (2011) to investigate the differences in validity and interunit reliability of both 10 Hz and 15 Hz devices. However, it must be stated that the 15 Hz GPSports unit (SPI-Pro XII) sampling rate is calculated by supplementing a 10 Hz GPS receiver with accelerometer data (Aughey, 2011), such that the remaining 5 Hz is interpolated. During a team sport circuit, no significant differences were observed between the criterion distance and the total distance as quantified by either the 10 Hz or 15 Hz unit (Johnston et al., 2014c). Conversely, 15 Hz devices appear to possess good to moderate intra-unit reliability in measures of total distance (CV: 3%), low speed running (CV: 2%) and high-speed running (CV: 6%). The interunit reliability however, becomes poor when quantifying very high-speed running distances (TEM = 12.1%) (Buchheit et al., 2014; Johnston et al., 2014c).

Table 2.3. Summary findings of GPS validity research within team sports.

Authors	GPS Device	Activity & Criterion (Variables)	Results	Conclusions
Edgecomb & Norton (2006)	1 Hz SPI-10	Multidirectional course *Distance*: 125 to 1386 m Trundle Wheel (Distance)	***SEE (%)*** + 4.8 ± 7.2	- Overestimation of distance by 5-7% - As trial distance increased so did the accuracy
Petersen et al. (2009)	5 Hz MinimaxX 5 Hz SPI Pro 1 Hz SPI 10	Linear cricket protocol *Distance:* 20 to 8800 m *Speed:* Various speeds from walk to sprint Timing Gates (Distance) Athletics Track	***Pearson's Correlation*** 0.99 ($P < 0.001$) **SEE (%) for walk to stride (1 to 5 $m \cdot s^{-1}$):** *1 Hz SPI 10*: 0.5 to 2.1 *5 Hz SPI Pro*: 0.4 to 3.7 *5 Hz MinimaxX*: 1.7 to 3.8 **SEE (%) for sprinting (> 5 $m \cdot s^{-1}$)** *1 Hz SPI 10*: No result *5 Hz SPI Pro*: 2.6 to 10.5 *5 Hz MinimaxX*: 5.3 to 23.8	- Accuracy of GPS is reduced at higher locomotion speeds and during changes of direction - Devices should not be used interchangeably

MacLeod et al. (2009)	1 Hz SPI Elite	Team Sport Circuit *Distance*: 8.5 to 6818 m *Speed:* Walk to Sprint ~ 5.5 – 13.2 km·h^{-1} Timing Gates (Mean Speed) Trundle Wheel (Total Distance)	**Mean Difference ± LOA** Total Distance: 2.5 ± 15.8 m Mean Speed: 0.0 ± 0.9 km·h^{-1}	- Validity influenced by COD and speed - Changes in satellite configuration at different times of day did not noticeably influence GPS accuracy
Coutts & Duffield (2010)	1 Hz SPI-10 1 Hz SPI Elite 1 Hz WiSPI	Team Sport Simulation *Distance*: 128.5 m *Speed*: Walk to Sprint Measuring Tape (Distance) Timing Gates Stopwatch	**Bias (%):** *1 Hz SPI-10:* -4.1 ± 4.6 *SPI Elite:* -2.0 ± 3.7 *WiSPI:* +0.7 ± 0.6	- 1 Hz GPS is not suitable to quantify high-speed movements or short-duration maximal efforts - Between model differences but with same sampling rate suggests different devices cannot be used interchangeably
Jennings et al. (2010)	1 Hz MinimaxX 5 Hz MinimaxX	Linear, Multidirectional and Team Sport Circuit *Distance:* 10 to 140 m	**SEE (%)**: <u>*Linear*</u> *1 Hz MinimaxX:* 9.6 ± 2.0 to 32.4 ± 6.9 *5 Hz MinimaxX:* 9.8 ± 2.0 to 30.9 ±	- Error increases when distance is shorter and at higher speeds - GPS may not possess adequate accuracy in the

		Speed: Walk to sprint speed Tape (Distance) Timing Gates	5.8 <u>*Multidirectional*</u> *1 Hz MinimaxX:* 9.0 ± 2.3 to 12.7 ± 3.0 *5 Hz MinimaxX:* 8.9 ± 2.3 to 11.7 ± 3.0 <u>*Team Sport Circuit*</u> *1 Hz MinimaxX:* 3.6 ± 0.6 *5 Hz MinimaxX:* 3.8 ± 0.6	quantification of short duration high speed locomotor movements - Sample rate increase GPS accuracy - 1 Hz and 5 Hz units underestimate distance
Waldron et al. (2011)	5 Hz SPI Pro	*Distance:* 10, 20 and 30 m sprint *Speed*: 0 to ~27 km·h^{-1} Tape (Distance) Timing Gates (Mean Speed)	**Distance (CV%)** 5.0 to 8.1% **Mean Speed (CV%)** 6.6 to 9.8%	- GPS underestimates distance when compared to criterion
Varley et al. (2011)	10 Hz MinimaxX	Linear *Distance:* No clear distance reported *Speed:* Constant speed, acceleration, deceleration (1 to 8 m·s^{-1})	**CV% [correlation]** <u>*Constant Velocity*</u> 1 to 3 m·s^{-1} : 8.3 ± 0.27 [0.96] 3 to 5 m·s^{-1} : 4.3 ± 15 [0.95] 5 to 8 m·s^{-1}: 3.1 ± 0.13 [0.92] <u>*Acceleration*</u> 1 to 3 m·s^{-2} = 5.9 ± 0.23 [0.98]	- 10 Hz units 2-3 times more accurate than 5 Hz units at detecting change in velocity - Underestimation of instantaneous velocity in both 10 Hz and 5 Hz units

		50 Hz Lazer (Instantaneous Velocity)	3 to 5 m·s^{-2} = 4.9 ± 0.21 [0.95] 5 to 8 m·s^{-2} = 3.6 ± 0.18 [0.92] *Deceleration* 5 to 8 m·s^{-2} = 11.3 ± 0.44 [0.98]	
Castellano et al. (2011)	10 Hz MinimaxX	Linear & Multidirectional *Distance:* 15 & 30 m *Speed:* Maximal Sprinting Tape (Distance) Timing Gates	**SEM (%)** 15 m: 1.9% 30 m: 5.1% **Bias (%)** 15m:-11.9% [95% CI: 12.9 to 13.6 m] 30m: -6.5% [95% CI: 28.4 to 27.7 m]	- More accurate over longer distances and compared to other 5 Hz MinimaxX devices
Johnston et al. (2014c)	10 Hz MinimaxX 15 Hz SPI-ProX	Team Sport Simulation *Distance:* 8 x 165 m (1320 m) Tape Measure (Distance) Timing Lights (Peak Speed)	**TEM (%)** *Total Distance* *10 Hz MinimaxX:* 1.3% *15 Hz SPI-ProX:* 1.9% *Peak Speak* *10 Hz MinimaxX:* 1.6% *15 Hz SPI-ProX:* 8.1%	- Comparisons cannot be made between 10 Hz and 15 Hz GPS units - 10Hz measured movement demands with greater validity and interunit reliability than 15 Hz - Both 10 Hz and 15 Hz improve the validity in

					comparison to 1 Hz and 5 Hz devices.

2.3.1.2. Applications of GPS to Quantify the External Load

The capability of GPS technology to measure speed and distance has enabled sport scientists to group player locomotor data into specific distance categories. Categories of locomotor movement are typically centred on the distances covered at walking, jogging, running and sprinting speeds as highlighted in the locomotor demands of rugby league competition earlier in the literature review (Section 2.1.1.). Descriptors such as this have been used for a number of years (Reilly & Thomas, 1976) although the methods used to do so have evolved. The determination of these speed-derived locomotor categories are typically based on either absolute or relative thresholds.

With absolute thresholds, a single speed is used for each category, and applied to the whole team, which is useful in allowing comparisons to be made between individuals and to determine a global external training load profile. Relative thresholds determine locomotor movement based on an objective measure that is specific to the individual. These can be performance based, such as the maximal running speed attained during routine fitness tests (e.g. speed at the completion of the 30-15 intermittent fitness test) (Buchheit, 2008) or based on physiological justification (e.g. speed at the second ventilatory threshold [VT_2]) (Abt & Lovell, 2009). Relative thresholds allow intra-player comparisons to take place, which might provide a more sensitive reflection of the true high-speed demands of an individual when compared to group-based absolute thresholds (Abt & Lovell, 2009). This benefit will be enhanced when considering the application as a specific method of quantifying an individual's external load during training, as the monitoring of the training load should focus on the individual.

Two speed-derived locomotor classifications that predominate within the literature are the total distance covered and the distance covered at high-speed. The focus on high-speed running distance has repeatedly been suggested to be critical to elite performance and to occur at crucial times during a match (Dawson, Fitzsimmons & Ward, 1993; Sirotic et al., 2009). For example, research by Mohr, Krustrup and Bangsbo (2003) reported that high-standard international football players, determined via FIFA national team ranking, performed more high-speed running (28%) and sprinting (58%) than their lower FIFA-ranked counterparts. Furthermore, despite the substantial differences between these measures, only a minor difference in the total distance covered between the players (5%) was reported, which highlights the potentially insensitive nature of the total distance measure to distinguish the external load between soccer players. Therefore, it appears that the distance run at high-speed might be a better measure of the external load. Given the high physiological stress imposed on players during high-speed running, the monitoring of this variable can allow coaches to evaluate the external training dose given to players to ensure the quality of the session is meeting the demands of competition (Gabbett et al., 2012). In regards to the application of high-speed distance as a valid measure of the external load, it must be stated that the theoretical external load must encompass both the volume and intensity of the whole external training stimulus (Impellizzeri et al., 2005).

Although it is the theoretical internal training load that is the direct governor of the outcomes of the training process (Impellizzeri et al., 2005), the external training load has been suggested to be a major contributor to the internal training load (Impellizzeri et al., 2005) and therefore, it is likely that measures quantifying the external training load will also provide useful information relating to the outcomes of training. Indeed, of the limited information available on the association between the external training load and the outcomes of training in team sports, Gabbett and Ullah (2012) highlighted the utility of measures of external training load to chronic training outcomes. Within their study, 34 professional rugby league players' locomotor movements were quantified by GPS (Figure 2.2.) along with the incidence of lower body soft-tissue injury over the course of one season. The risk of injury was reported to be 2.7 (95% CI: 1.2-6.5) times greater when sprinting distances (> 7 $m \cdot s^{-1}$) exceeded 9 metres per session which highlights the practical usefulness in monitoring this theoretical construct. Relationships between GPS derived variables (e.g. total distance, high-speed running) and markers of fatigue (creatine kinase, perceptual muscle soreness) in professional rugby league players have also been reported (Oxendale et al., 2015). For example, total distance was significantly correlated (r = 0.86; 95% CI: 0.70 to 0.95) to changes in creatine kinase concentration after competitive rugby league match-play. Although not an aim of the studies mentioned above, the findings provide initial evidence of the dose-response validity and utility of GPS-derived measures of the external load to reflect both acute and chronic training outcomes (Gabbett & Ullah, 2012; Oxendale et al., 2015). This strengthens the rationale that external load measures could represent a proxy measure of the internal load and provide additional information to explain training outcomes.

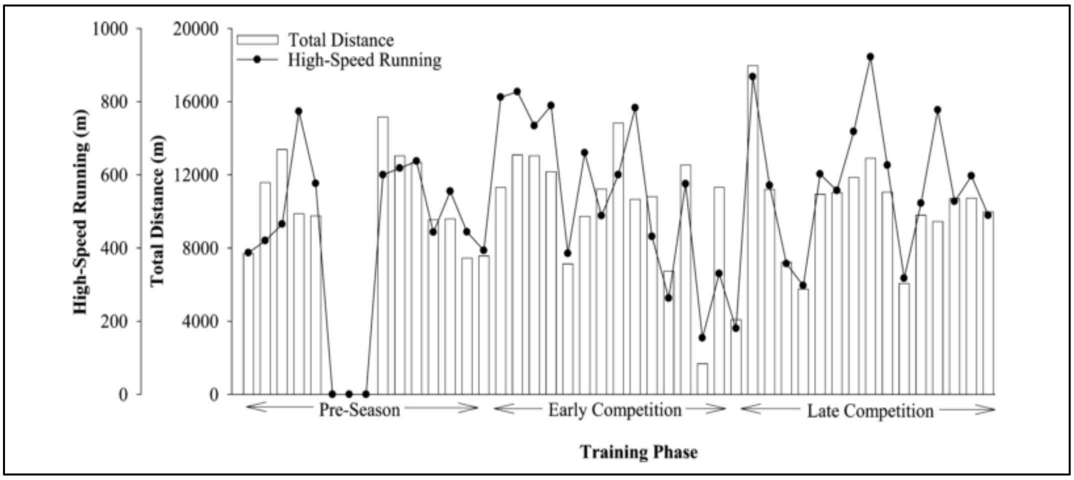


Figure 2.2 Weekly total training distance, and distance covered in high-speed running over the course of a professional rugby league season. *High-speed running includes all distances covered > 5 m·s^{-1}. Reproduced from Gabbett & Ullah (2012).

As presented in this literature review so far, the predominant focus of the quantification of the locomotor demands of training and competition have centred on speed-derived methods due to the traditional application and determined validity in soccer. However, the level of validity of speed-derived methods of external load quantification are specific to each sport. Unlike football, rugby league players are confined by the 10-m rule during both attacking and defensive phases in match play. It is possible that players will accelerate maximally and regularly for less than 20 m (Gabbett, 2012). Therefore, it is likely that rugby league players are unlikely to achieve the high-speed thresholds as frequently as in other team sports. Questions therefore arise as to the validity of high-speed thresholds to reflect all demanding locomotor aspects of rugby league competition and training, as they do not take into account instantaneous movements such as accelerations and decelerations (Osgnach, Poser, Bernardino, Rinaldo & di Prampero, 2010). Alongside the high stress imposed on players during high-speed running, rapid acceleration also imposes high physiological stress on players, even when the running speed is low (Osgnach et al., 2010). Failure to take into account the acceleration component when quantifying the external load could underestimate the total energy cost of training and competition, which may be exacerbated further in sports such as rugby league where spatial confinements are present. This is highlighted in the findings by Varley, Gabbett and Aughey (2014) who reported that professional rugby league players are involved in a greater number of relative accelerations when expressed per minute of playing time when compared to professional football and Australian rules football players. Therefore, it is likely that the valid quantification of the external load needs to measure the acceleration component of locomotor movement. Methods used to quantify the internal load must also be sensitive to reflecting this demanding aspect of training and competition.

Osgnach et al. (2010) aimed to reassess the metabolic demand of soccer players by determining the metabolic cost of acceleration, based on the work of di Prampero et al. (2005). Di Prampero et al. (2005) introduced the idea that accelerated sprinting on a flat terrain, as is the case during team sport games, is metabolically equivalent to uphill running at a constant speed. This is due to the equivalent angle that is formed between the ground and the forward lean of the athletes' body (e.g. centre of mass) during flat ground running and the upright position of the body during running in respect to the angle of the uphill terrain (di Prampero et al., 2005). From this model, Osgnach et al. (2010) was able to calculate the energy cost ($J \cdot kg^{-1} \cdot m^{-1}$) of accelerative running within professional soccer. That study reported marked increases in the calculated energy expended and match intensities during football matches when taking into consideration the accelerative component. For example, a movement that reaches a speed typically classified as low-speed by motion analysis thresholds (e.g. 9 km·h^{-1}), can have very similar metabolic demands to a constant run at 14 km·h^{-1} when the acceleration magnitude is increased (Osgnach et al., 2010). Therefore, the quantification of the locomotor aspects of the external load via the metabolic power method might have appropriate applications to rugby league training and competition, given the nature of the sport as previously described.

Further investigations using this method of external load quantification have been reported in football training (Gaudino et al., 2013; Gaudino et al., 2014) and rugby league competition (Kempton, Sirotic, Rampinini & Coutts, 2014). Given that the metabolic cost of running at a constant speed of 14 km·h^{-1} (typical high-speed distance threshold) has been previously reported to be 20 W·kg^{-1} (Osgnach et al., 2010), the current comparisons have centred on the differences in distance at these speeds or power (Gaudino et al., 2013; Kempton et al., 2014). Increases in the distances quantified at high power (> 20 W·kg^{-1}) when compared to high-speed (> 14 km·h^{-1}) have been reported (Gaudino et al., 2013; Kempton et al., 2014). For example, during rugby league competition, the percentage increases in distance as quantified by metabolic power-derived indices when compared to speed-derived methods have ranged from 37% higher in the outside backs positional group to 76% higher for the hit-up forwards (Kempton et al., 2014). The importance of those differences are highlighted when placing these findings into the context of the competitive nature of those positions. While the outside backs are typically positioned within wide, uncongested areas of the field, hit-up forwards are typically involved in the middle congested segments of the field. These game-related situations lend themselves to differences in locomotor activity as highlighted in Section 2.1.1 of the literature review where outside backs consistently cover greater distance at high-speed when compared to the hit-up forwards. However, the spatial confinements imposed on hit-up forwards due to the limited space between attacking and defensive lines limits the opportunities for this positional group to achieve speeds that are quantified as high-speed. However, the match role of this position requires frequent short-duration accelerative efforts. These findings provide initial evidence of the utility of metabolic power-derived measures of external load, particularly during activities with limited space for players to reach speeds quantified as high-speed. In addition, these differences will be evident between different training modes that are utilised in the training strategies of professional rugby league clubs, particularly in modes with limited spatial confinements such as skills training which aims to replicate aspects of competition to develop the skill and tactical qualities of rugby league players. This is an important notion to consider as the load may be underestimated during certain training modes when the quantification of the external training load is determined solely via speed-derived methods. However, the differences between metabolic power and speed-derived indices within different training modes in professional rugby league have yet to be investigated, as do the differences in the continuum of metabolic power thresholds (Table 2.4). This information is important to allow practitioners to gain a deeper understanding of the demands of professional rugby league training modes, which will assist in the optimisation of periodisation and thus positive training outcomes.

While the addition of metabolic power-derived variables might extend our understanding of the demands of team sports, the original energetics approach by di Prampero et al. (2005) is not without its limitations. More specifically, the assumption that the overall mass of the runner is located at the centre of mass fails to account for the motion of the limbs on the energetics of running (di Prampero et al., 2005), which could underrepresent the energetic demands of accelerative running. Further, the validity of the equation for assessing high equivalent slopes has yet to be determined, the influence of air resistance was neglected and eccentric work was not included in the development of this energetic model (di Prampero et al., 2005; Kempton et al., 2014). The quantification of deceleration and other events prevalent in rugby league competition and training, such as collisions need to be measured to provide a comprehensive overview of the demands during these activities. Therefore, additional measures of external load will be needed to achieve this. Metabolic power also has a limitation in common with speed thresholds, and that is the use of zones to delimit the magnitude of power. Similar to speed zones, a player's metabolic power will fail to reach the threshold for a particular zone. For example, one player generating 19.9 $W \cdot kg^{-1}$ will fail to reach the 'high' power zone, yet another player generating 20.1 W·kg^{-1} will be categorised into that zone. Yet, the metabolic consequences of 0.2 W·kg^{-1} is more than likely trivial.

Table 2.4. Metabolic Power thresholds (Osgnach et al., 2010).

Metabolic Power Category	**Metabolic Power Threshold**
Low Power (LP)	0 to 9.9 W·kg^{-1}
Intermediate Power (IP)	10 to 19.9 W·kg^{-1}
High Power (HP)	20 to 34.9 W·kg^{-1}
Elevated Power (EP)	35 to 54.9 W·kg^{-1}
Max Power (MP)	> 55 W·kg^{-1}

2.3.2. Accelerometry

Accelerometry has been used extensively to measure physical activity levels within clinical investigations (Eston, Rowlands & Ingledew, 1998; Brage et al., 2003; Strath, Brage & Ekelund, 2005; Fudge et al., 2007). More recently, researchers have begun to explore the potential of using accelerometry within sporting applications (Coe & Pivarnik, 2001; Sato, Smith & Sands, 2009; Gabbett et al., 2010; Lovell et al., 2013; Barrett, Midgley & Lovell, 2014). As previously discussed, acceleration and deceleration events are frequent within team sports where players are subject to a high metabolic and neuromuscular demand (di Prampero et al., 2005; Osgnach et al., 2010). The 'very poor' reliability of the 15 Hz GPS receiver reported for the determination of peak acceleration (CV = 10%), accelerations (> 3 m·s^{-2}, CV = 31%; > 4 m·s^{-2}, CV = 43%) and decelerations (> 3 m·s^{-2}, CV = 42%; > 4 m·s^{-2}, CV = 56%) (Buchheit et al., 2014) suggests that tri-axial accelerometry could overcome the limitations of GPS to quantify acceleration and deceleration events and would provide an additional benefit to the overall load monitoring process. Further, as previously described in section 1 of the literature review, rugby league players require the capability to execute and tolerate physical collisions during both defensive and attacking periods of play. Indeed, the ability to win the collision contest and to tolerate a number of collisions is a major contributor to success in the sport (Gabbett, 2013b). Therefore, subjecting players to a high number of collisions in training is needed to prepare players fully for the demands of the contest (Gabbett, Jenkins & Abernethy, 2010). However, as with all forms of training a sensitive balance needs to be struck between the minimum number of collisions that are needed to improve collision skill and the maximum tolerable number of collisions before inducing fatigue, micro-trauma and injury risk (Gabbett, 2013). Nevertheless, prior to the introduction of accelerometry in rugby league, the quantification of collisions was limited to its frequency, predominately via video-based analyses. Given the laborious nature of video-based methods, the number of players within a squad, and the frequency of skills sessions within a training year, the longitudinal collection of collision frequencies during training is unfeasible due to the high manual burden placed on practitioners. To allow a better understanding of the demands of collision events during training and competition, the acute and accumulated magnitude of those events also need to be quantified (Cummins & Orr, 2015). At present, there is likely to be considerable underestimation of the load imposed on professional rugby league players during training that is not being measured by current internal load methods.

Accelerometers record the frequency and magnitude of acceleration (Hendelman et al., 2000). An initial measurement derived from accelerometers were activity counts. This method measures the number of occurrences of acceleration above a set threshold within a given time period. However, a newer method that integrates activity count with the magnitude of acceleration has been proposed to capture both the frequency and intensity of a given activity bout. This method is commonly referred to as the vector magnitude, which summates the magnitude of each acceleration derived from the three biomechanical planes of motion (vertical, medio-lateral and anterior-posterior) (Boyd, Ball & Aughey, 2011). The vector magnitude method has been adopted by two of the most commonly used GPS companies, which are commonly referred to as PlayerLoad™ (MinimaxX, Catapult Innovations, Scoresby, Victoria) (Boyd et al., 2011) and Body Load™ (SPI Pro, GPSports, Canberra, Australia) (Lovell et al., 2013). These variables are expressed as the square root of the sum of the squared instantaneous rates of change in acceleration in each of the three planes and divided by 100 (Boyd et al., 2011; Barrett, Midgley & Lovell, 2014) and expressed in arbitrary units (AU). While the application of the vector magnitude method is relatively new in sporting applications, the vector magnitude or overall dynamic body acceleration method has been previously used as a proxy for energy expenditure in physical activity research (Levine et al., 2001; Rowlands et al., 2004; Fudge et al., 2007). Investigations using this method have also examined species other than humans (Laich, Wilson, Gleiss, Shepard & Quintana, 2011) to quantify the energy expenditure of farm animals (Miwa et al., 2015).

The tri-axial accelerometers housed within the two common GPS manufacturer units both sample at 100 Hz (Boyd et al., 2011; Kelly, Murphy, Watsford, Austin & Rennie, 2015) and during use, are positioned between the scapulae in a neoprene undergarment that houses the unit in an integrated pouch. These accelerometers collect data independently from the GPS system (Boyd et al., 2011), which allows data to be collected both indoors and outdoors, unlike GPS. This substantially increases the practical utility of the device, particularly when there is a possibility of future increases in the frequency of indoor venue use during professional team sports training. However, despite the common use of accelerometry in physical activity research (Eston, Rowlands & Ingledew, 1998; Brage et al., 2003; Brage et al., 2004; Fudge et al., 2007) and the now-common ubiquitous data collection in professional team sports, there is still a paucity of information detailing the static and dynamic reliability and/or validity of the devices currently used in professional sport (Boyd et al., 2011; Barrett, Midgley & Lovell, 2014; Kelly et al., 2015). Due to this, the aim of the following section is to review the current knowledge spanning both sporting and clinical research relating to the reliability and validity of 100 Hz tri-axial accelerometry. The current applications of this technology in team sports will then be discussed.

2.3.1.2 Reliability and Validity of Accelerometry

Research investigating the reliability of accelerometry has used highly repeatable mechanical devices such as shakers or agitators (Boyd et al., 2011; Kelly et al., 2015) or human testing using repeatable protocols (Barrett et al., 2014). Boyd et al. (2011) aimed to assess both the static and dynamic reliability of the MinimaxX tri-axial accelerometers (PlayerLoad™ vector magnitude) in both laboratory and field settings. First, static reliability was determined with ten minimaxX accelerometers positioned with the Z-axis aligned to vertical using a customised cradle. Six, 30 s trials with 2 minutes between each period were conducted. The devices showed good reliability both within (CV = 1.0%) and between devices (CV = 1.0%). To assess dynamic reliability eight accelerometers (MinimaxX 2.0, Catapult, Australia) were attached to a hydraulic testing machine (Instron 8501) which oscillated at two magnitudes (0.5 *g* and 3.0 *g*) to determine within and between-device reliability. A good level of within-unit (0.5 *g* CV = 1.01%; 3.0 *g* CV = 1.05%) and between-unit (0.5 *g* CV = 1.04%; 3.0 *g* CV = 1.02%) dynamic reliability was reported. Field-testing reliability was determined in nine Australian rules football matches, with good between-device reliability (CV = 1.9%) also reported. However, the laboratory dynamic protocol tested the reliability of the device to a maximum acceleration of 3.0 *g*, which is considerably lower than the accelerations frequently observed in professional rugby league training and competition (up to 12 *g*) (Cummins & Orr, 2015). Therefore, the dynamic reliability of the device at those magnitudes is yet to be reported.

Kelly et al. (2015) investigated the static and dynamic reliability of the GPSports SPI-Pro XII (GPSports, Canberra, Australia) housed tri-axial accelerometer (BMA150, Bosch, Germany) using similar methods to Boyd et al. (2011). However, rather than utilising a hydraulic shaker, Kelly et al. (2015) used a mechanical device that was capable of reproducing highly consistent (CV = 2.3%) impacts. The magnitude of impacts produced by the device peaked at 9.6 ± 0.23 *g* which is a considerably greater magnitude of acceleration than Boyd et al. (2011) used. No differences were reported for the 4 SPI-ProX II accelerometers during intra-device testing with the coefficient of variation ranging from 1.9 to 2.1% across more than 20 impact trials. Furthermore, using a continuous incremental treadmill protocol (1.94 to 4.4 $m \cdot s^{-1}$), Barrett et al.

(2014) reported good test-retest reliability (3 trials) for PlayerLoad™ when devices were positioned at the scapulae, with the coefficient of variation ranging from 13.1% at 2.22 $m \cdot s^{-1}$ to 4.6% at 4.4 $m \cdot s^{-1}$. The results seemed to indicate poorer reliability of the measure at lower speeds. The findings also suggest that accelerometers have very good within- and between-device reliability. As a result, devices utilising accelerometer data can be interchanged or compared with a good degree of confidence (Kelly, 2015).

In regards to validity, and similar to most validity research within the area, a lack of a 'gold standard' criterion has led to researchers using physiological criterion measures such as energy expenditure, heart rate and oxygen consumption in order to validate tri-axial accelerometers (Levine et al., 2001; Rowlands et al., 2004; Fudge et al., 2007; Barrett, Midgley & Lovell, 2014). Fudge et al. (2007) investigated the relationships between one tri-axial (100 Hz) and three uni-axial (10, 30 & 32 Hz) accelerometer counts and locomotor velocity, heart rate and VO_2. Accelerometers were fixed to the waist. During walking speeds (0.83 to 1.94 $m \cdot s^{-1}$), nearly perfect relationships for both uni- ($r = 0.95$ to 0.96) and tri-axial ($r = 0.96$) accelerometer counts were reported. However, differences in linearity between locomotor velocity and accelerometer counts were observed between uni- and tri-axial devices. Whilst the tri-axial accelerometer count continued to rise linearly at speeds up to 5.5 $m \cdot s^{-1}$ ($r = 0.89$), a plateau was observed when locomotor velocity increased to 3.88 to 4.4 $m \cdot s^{-1}$ in the uni-axial accelerometer. Strong relationships between tri-axial vector magnitude and increases in walking and running velocity (1.1 $m \cdot s^{-1}$ to 7.2 $m \cdot s^{-1}$) have also been reported (Rowlands et al., 2004). Differences in the strength of the relationships between uni-axial and tri-axial accelerometer counts and VO_2 were observed as the locomotor velocity increased from walking to running speeds (*uni-axial*: walking: $r = 0.70$ to 0.91; running: non-linear; *tri-axial*: walking: $r = 0.91$; running: $r = 0.87$). A similar picture emerged for HR (*uni-axial*, walking: $r = 0.49$ to 0.57; running = non-linear; *tri-axial*, walking: $r = 0.59$; running = 0.72) (Fudge et al., 2007). Tri-axial accelerometry vector magnitude has also been reported to have a very large relationships with VO_2 ($r = 0.79$ to 0.88)

(Rowlands et al., 2004). Therefore, it appears the validity of uni-axial accelerometry counts during running based activity is limited.

Conversely, the findings provide evidence that tri-axial accelerometers are capable of reflecting the variation in speed, VO_2 and HR across continuous walking and running bouts. Biomechanical differences between walking and running speeds has been proposed as a possible explanation for the differences observed. At higher speeds, there is a plateauing in the vertical plane magnitude and an increase in anterior-posterior and medial-lateral movement (Fudge et al., 2007). As uni-axial accelerometry only quantifies vertical acceleration, it appears incapable of quantifying these additional aspects at higher speed. The greater sampling rate of the tri-axial accelerometer will have also been a contributing factor in those differences (Fudge et al., 2007). Furthermore, an interesting additional finding of this study was that a combination of HR and tri-axial accelerometer counts (determined via multiple linear regression) explained more of the variance in VO_2 during running ($r^2 = 0.80$) than either accelerometer or HR alone. This finding provides initial evidence that a combination of training load measures might explain a greater proportion of variance than individual methods alone, with the magnitude of additional variance explained exacerbated by the training mode.

While investigations such as these provide useful evidence on the validity of accelerometry in team sports, differences in the placement of the accelerometers may influence the validity and reliability of the devices (Barrett et al., 2014). Given the predominant placement of the accelerometer is at the scapula in team sports environments, the position of accelerometers at the waist as investigated by Fudge et al. (2007) may make the transfer of the results to team sports difficult. However, with a 100 Hz tri-axial accelerometer specific to team-sports applications (Kionix: KXP94 housed within the MinimaxX Catapult GPS device) placed at the scapulae, almost perfect within-individual relationships between the vector magnitude PlayerLoad™ and VO_2 (mean r = 0.96) and HR (mean r = 0.98) were reported during a continuous incremental treadmill test (1.94 to 4.4 $m \cdot s^{-1}$) (Barrett et al., 2014). This was comparable to the same relationships when the device was placed at the centre of mass (VO_2: r = 0.96; HR: r = 0.98) (Barrett et al., 2014) which, coupled with previous findings (Rowlands et al., 2004; Fudge et al., 2007) suggests a comparable level of validity between the different locations of the tri-axial accelerometer and physiological criterion measures. However, a significant limitation of the above studies when applying the inferences to team sports is the use of continuous protocols. How those relationships change across different magnitudes of intermittent activity, which is common in both training and competition of team sports limits the conclusions drawn from the research discussed above. Different training modes are prescribed by practitioners within professional rugby league, which although yet to be investigated, are likely to show considerable variability in their level of intermittency. Therefore, establishing the relationships between the accelerometer derived vector magnitude method and physiological criterion methods across different magnitudes of intermittent exercise is essential to examine the validity of the method. However, to the author's knowledge, no research group has addressed this crucial research question, which warrants further investigation.

In addition to physiological criterion measures, researchers have investigated the potential validity of accelerometry to quantify specific activities in team sports such as collisions (Gabbett et al., 2010) and to quantify acceleration specifically (Tran, Netto, Aisbett & Gastin, 2010; Kelly et al., 2015). The dynamic validity of the GPSports 100 Hz accelerometer (BMA150, Bosch, Germany) has previously been assessed during drop landing and a countermovement jump using a force plate (Tran et al., 2010), with vertical ground-reaction force measured. Differences between the force plate criterion and the vector magnitude derived from the GPSports accelerometer ranged from 22.5% (CMJ) to 30.8% (drop landing) for unsmoothed accelerometer data. However, smoothed accelerometer data reduced the difference to 15.9% (CMJ) and 22.2% (drop landing) (Tran et al., 2010). The authors suggested that the results provide some supporting evidence for the validity of scapulae-positioned GPS housed tri-axial accelerometers to quantify jumping impacts. Kelly et al. (2015) investigated the validity of the GPSports Pro XII accelerometer using both a static and dynamic validity testing protocol.

A criterion reference accelerometer operating in a bandwidth of 0.1 to 3000 Hz was used. The magnitude of acceleration quantified by the GPSports accelerometer was significantly underestimated compared to the criterion accelerometer during static testing ($P = 0.001$) with large percentage differences observed (27.5 to 30.5%). Large percentage underestimation also occurred during dynamic testing (32 to 35%) when compared against the criterion accelerometer. To the author's knowledge, similar investigations examining the validity of the MinimaxX accelerometer to quantify peak acceleration are yet to be conducted. However, the results of the above studies suggest that GPSports XII devices possess poor validity for the measurement of acceleration, which could affect its usefulness as a method of external load quantification.

Furthermore, there is very limited research investigating the validity of GPS unit housed accelerometers to quantify impacts in team sports. The validity of a tri-axial accelerometer housed within a GPS unit to detect collisions (MinimaxX, Catapult Innovations, Melbourne, Victoria) was investigated in professional rugby league training (Gabbett et al., 2010). The relationship between the manufacturer derived PlayerLoad™ and coded video recordings of training were assessed in relation to detecting collisions. Gabbett et al. (2010) quantified collision severity into mild (contact made with player but able to continue forward progress/momentum out of tackle), moderate (contact made with player, forward progress/momentum continued until tackled) and heavy (contact made with player, forward progress/momentum stopped, and forced backwards in tackle). Collision events included tackles, hit-ups, decoy runs and support runs of which 237 events were recorded. No significant differences were reported in the number of collisions detected via the MinimaxX units and collisions coded from video. Mild collisions were reported to be the most difficult to detect using accelerometry ($r = 0.89$) when compared to moderate ($r = 0.97$) and heavy ($r = 0.99$). Regardless, this research suggests that the MinimaxX is able to detect the frequency and magnitude of collisions in rugby league training. However, the validity of the automatic collision detection of the GPSports tri-axial accelerometer to measure collisions in rugby league has yet to be reported.

In applied settings, researchers have attempted to establish the validity of the vector magnitude derived method by examining its relationships with other methods of training load quantification (e.g. sRPE) (Gomez-Piriz, Jimenez-Reyes & Ruiz-Ruiz, 2011; Lovell et al., 2013; Scott et al., 2013). Furthermore, Gomez-Piriz et al. (2011) investigated the relationship between sRPE and Body Load™ during SSGs. Whilst Gomez-Piriz et al. (2011) reported a weak relationship between RPE and Body Load™ during SSG's, Lovell et al. (2013) reported a large association (r = 0.64) between Body Load™ and sRPE during skills conditioning sessions which comprised solely of SSGs. Large relationships have also been reported between Catapult's accelerometer derived vector magnitude method (PlayerLoad™) and sRPE (r = 0.84), Banister's TRIMP (r = 0.73) and Edwards TRIMP (r = 0.80) (Scott et al., 2013). The results of the above studies suggest that accelerometer-derived measures may be valid to quantify the external training load. However, how those relationships alter between different training modes and the effect of session intermittency has yet to be fully investigated.

Although not the primary aim, the strength of the relationships between Body Load™ and sRPE have previously been reported to change across different training modes in professional rugby league (Lovell et al., 2013). For example, the relationship between sRPE and Body Load™ ranged from moderate (r = 0.45; $r^2 = 0.20$; variance explained = 20%) during wrestle training to large (r = 0.64; $r^2 = 0.41$; variance explained = 41%) during SSG (Lovell et al., 2013). This provides initial evidence that the training mode and the assumed differences in the organisation of the prescribed external training load influence the magnitude of variance explained by individual methods of quantifying the training load. However, how the relationships between other methods used to represent both the external and internal training load alter across different modes of training has yet to be investigated. Further, a closer examination of the correlations reported by Lovell et al. (2013) suggests a large amount of unexplained variance between the measures, which is also exacerbated by the training mode. In order to explain additional variance between the training load measures, a combination of training load methods might achieve this such as the results reported by Fudge et al. (2007). However, this has yet to be investigated.

2.3.2.2. Applications of Accelerometry to Quantify the External Load

Although accelerometer data has been used to describe collision events during professional rugby league competition as described earlier in the literature review (Section 2.1) (McLellan et al., 2011; Cummins & Orr, 2015), there is a dearth of information describing the accelerometer-derived methods within professional rugby league training or its associations with both acute and chronic training outcomes. Gabbett et al. (2012) described the differences in mild, moderate and heavy collisions across traditional conditioning, repeated high-intensity efforts, game-based and skills training. Differences in the frequency of mild, moderate and heavy collisions were observed between the training modes. However, how the overall accelerometer-derived vector magnitude (e.g. Body Load™/PlayerLoad™) differs between training modes has yet to be reported. Given the potential capability of accelerometers to quantify all external activities (e.g. accelerations, decelerations, collisions, locomotor activity), this information would be useful to the practitioner to determine the likely external loads placed on professional rugby league players.

While not the primary aim of these studies, researchers have now begun to report the technology's dose-response relationships with the outcomes of training and competition (McLellan et al., 2011; McLellan & Lovell, 2012; Colby et al., 2014). McLellan et al. (2011) and McLellan and Lovell (2012) examined the relationships between the volume and intensity of impacts recorded from a 100 Hz GPS-housed accelerometer (GPSports, Canberra, Australia), categorised into collision magnitude thresholds (Table 2.5.), with acute biochemical (McLellan et al., 2011), endocrine (McLellan et al., 2011) and neuromuscular (McLellan & Lovell, 2012) responses after professional rugby league match play. Large to very large positive associations were reported between the number of impacts categorised into zones four, five and six (Table 2.5.) and changes in plasma creatine kinase concentration 30 minutes (r = 0.61 to 0.63), 24 hours (r = 0.63 to 0.77), 48 hours (r = 0.59) and 72 hours (r = 0.55) post professional rugby league competition (McLellan et al., 2011). Further large to very large negative associations were reported between the same impact zones and changes in the peak rate of force development (PRFD) ($N \cdot s^{-1}$) and peak power (W) during a countermovement jump at 30 minutes (PRFD: r = -0.61 to -0.67; peak power: r = -0.60 to -0.73) and 24 hours (PRFD: r = -0.59 to -0.64; peak power: r = -0.59 to -0.64) after professional rugby league competition (McLellan & Lovell, 2012). The authors concluded that increases in skeletal muscle damage and reductions in neuromuscular function are related to the frequency of impacts in professional rugby league competition. Additionally, this data provides some evidence for the dose-response validity of accelerometer-derived data to reflect changes in acute responses and outcomes. However, the quantification of collisions only constitutes a small proportion, albeit a potentially important proportion, of the total external load that is imposed on players during training and competition. A valid method to quantify the total external load must quantify both the volume and intensity of all external activities (Impellizerri et al., 2005). However, there is limited information available detailing the applications of the accelerometer-derived vector magnitude method to quantify the external training load. Colby et al. (2014) investigated the relationship between an accelerometer-derived external load measure (force load) and injury risk in professional Australian football players. Force load is a cumulative measure that sums the forces produced from both foot strikes and collisions (Colby et al., 2014). Force load data and injury incidence were monitored across preseason and in-season phases. Multiple regression was used to compare cumulative (1-, 2-, 3-, and 4-weekly loads) and absolute changes (from previous-to-current week) in force load between injured and uninjured players. Odds ratios were calculated to determine the relative injury risk. During the in-season period only, 3-weekly cumulative force load (OR = 2.53 [95% CI: 1.09 to 5.87]; *P* = 0.031) was significantly associated with greater injury risk. In addition, this finding again shows some practical utility and dose-response validity of accelerometer-derived external load data to reflect chronic outcomes of training (e.g.

injury risk). However, the limited information means further research is warranted to establish those relationships with other accelerometer-derived vector magnitude methods.

Table 2.5. 100 Hz accelerometer derived (GPSports SPI Pro XII) impact classifications as described by McLellan et al., (2011)

Impact Zone	G Force	Impact Zone Descriptors
Light (1)	<5.0 to 6.0 *g*	Very light impact, hard acceleration/deceleration/change of direction
Light to Moderate (2)	6.1 to 6.5 *g*	Light to moderate impact, making tackle or being tackled at moderate velocity
Moderate-Heavy (3)	6.5 to 7.0 *g*	Moderate to heavy impact, making tackle or being tackled at moderate velocity
Heavy (4)	7.1 to 8.0 *g*	Heavy-impact, high-intensity collision with opposition player (s), making direct front on tackle on opponent travelling at moderate velocity, being tackled by multiple opposition players when running at sub maximum velocity
Very Heavy (5)	8.1 to 10.0 *g*	Very heavy-impact, high-intensity collision with opposition player (s), making direct front on tackle on opponent travelling at high velocity, being tackled by multiple opposition players when running at near maximum velocity.
Severe (6)	>10.1 *g*	Severe impact, high-intensity collision with opposition player (s), making direct front on tackle on opponent travelling at high velocity, being tackled by multiple opposition players when running at near maximum velocity

2.3.3. Summary

- Sample rate, speed, effort duration and the nature of the exercise task appear to influence the validity and reliability of GPS.
- 1 Hz, 5 Hz, 10 Hz and 15 Hz GPS devices are capable of quantifying the total distances covered.
- 1 Hz and 5 Hz have limitations in the capability to quantify short distance linear running.
- Despite limited research, 10 Hz and 15 Hz devices appear to overcome the limitations of 1 Hz and 5 Hz sampling rates, although the increase in sampling rate from 10 Hz to 15 Hz appears to provide no additional benefit and may actually reduce its validity and reliability compared to 10 Hz.
- Two common GPS housed 100 Hz tri-axial accelerometers (GPSports SPI Pro XII & MinimaxX) appear to possess good within- and between-unit static and dynamic reliability across instrumentation and human testing protocols. This suggests a highly repeatable quantification of the external load via this technology. However, the reliability of the devices at maximal acceleration magnitudes observed in professional rugby league competition has yet to be determined.
- 100 Hz tri-axial accelerometry appears to have large associations with physiological based criterion measures in continuous protocols. How those relationships change with different degrees of intermittent activity has yet to be established.
- Within field-based validity settings, limited research suggests that both the Catapult MinimaxX (PlayerLoad™) and GPSports SPI Pro XII (Body Load™) vector magnitude and GPS-derived measures of the external load appear to have large global relationships with other training load measures. However, how those relationships change across different modes of training in professional rugby league has yet to be established.
- Despite being a measure of external load, both GPS and accelerometer-derived variables appear to possess some evidence of dose-response relationships with the

variability in physiological responses to match-play and with other training outcomes such as injury risk.

- Despite its prevalent use to quantify the external loads of rugby league match play, there is limited information detailing the differences in a variety of external load variables across different modes of training in professional rugby league.

2.4. Methods of Quantifying the Internal Training Load

The internal training load is the theoretical construct used to describe the physiological stress imposed on athletes (Impellizzeri et al., 2005). While the technology used to measure external training load is advancing, direct measurement of the internal training load remains difficult in the applied team sport environment. Despite the difficulties, quantification of the internal training load is important for developing a greater understanding of the dose-response relationship between training and adaptation (Busso, 2003; Akubat et al., 2012). At present, there is no consensus on which methods are the most appropriate to reflect the internal load during intermittent team sport activity. The majority of the current literature has also only considered the implementation of single methods to quantify the internal load. However, given the likelihood that different training modalities will elicit varying loads on a variety of physiological subsystems (e.g. neuromuscular, cardiovascular, and musculoskeletal) (Buchheit & Laursen, 2013a; Buchheit & Laursen, 2013b; Soligard et al., 2016), investigating the influence of training mode should also be considered. Therefore, the aim of the following section is to review the current internal training load methods examined in the literature.

2.4.1. Heart Rate Based TRIMP

Heart rate (HR) is represented by the number of heart beats per minute ($b \cdot min^{-1}$) and has been used for many years to measure the cardiovascular response of athletes during exercise (Achten & Jeukendrup, 2003). Exercise intensity is commonly measured via HR (Coutts et al., 2009), which is based on the established linear relationship between HR and oxygen consumption (VO_2) over a varied range of steady-state submaximal loads (Astrand & Rodahl, 1986; Hoffman, 2002). The ability of HR to represent exercise intensity has allowed researchers to develop training impulse (TRIMP) monitoring methods by incorporating intensity, duration and an intensity-weighting factor in order to quantify an individual's training load.

The validity of HR has been commonly assessed against oxygen consumption (Thomson, 2010). Oxygen consumption (VO_2) is a frequently used, indirect method of calorimetry that measures the uptake, transportation and utilisation of oxygen. A linear relationship between VO_2 and HR exists over a range of sub-maximal intensities (Hoffman, 2002). However, this relationship might change during maximal intensity and intermittent activities. Esposito et al. (2004) investigated the validity of HR during soccer training. In this study, participants wore a portable gas analyser ($K4b^2$, Cosmed, Italy) and a HR monitor during a simulated soccer field test and during a laboratory treadmill test. The treadmill test was used to determine each individuals HR-VO_2 relationship while the simulated field test used running at various intensities, which incorporated activities with the ball to ensure appropriate simulation of soccer activity. The HR recorded during the simulated soccer circuit was then used to predict VO_2 and subsequently compared to the VO_2 determined by the gas analysis system. As seen in Figure 2.4. a nearly perfect association ($r = 0.99$) was found between the actual VO_2 recorded and predicted values that were collated via HR. Similar relationships have also been reported when using comparable methods during small-sided games and dribbling activities in soccer (Hoff et al., 2002). The results of the studies above indicate that HR can be usefully measured during soccer specific movements (Esposito et al., 2004; Hoff et al., 2002).

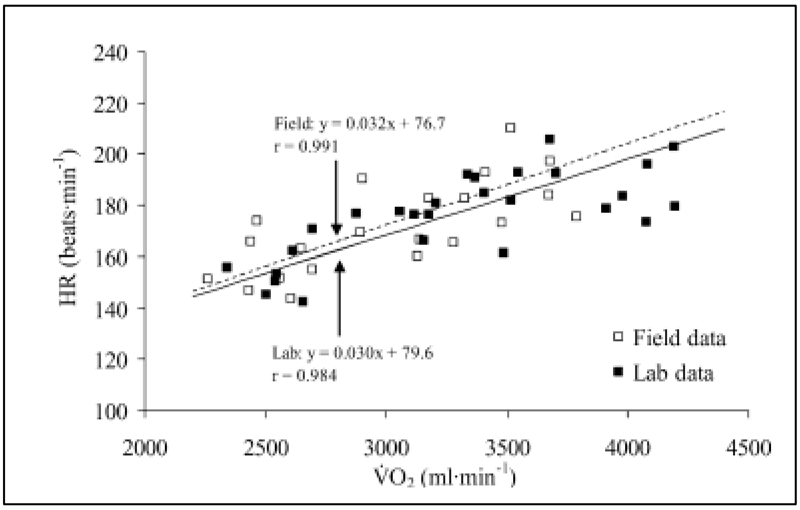


Figure 2.4. Scatter plot of the HR versus VO_2 data obtained from tests in the laboratory (*dashed line*) and on the field (*continuous line*). The regression equations represented in the figure were calculated using the average slopes and intercepts of the individual regressions of the seven amateur soccer players. Reproduced from Esposito et al., (2004).

As described within section 2.2 of the literature review, Banister first developed the 'training impulse' (TRIMP) as a method that would encompass the fundamentals of training (intensity and duration) in order to determine internal training load (Banister, 1991). Banister's TRIMP (bTRIMP) includes the HR reserve method (intensity component) and the duration of exercise (volume component). In any given training session, the mean HR is weighted, according to a generic sex-dependent relationship between HR and blood lactate. This value is then multiplied by the session duration. The sex-dependent weighting factor is designed to reflect the intensity of effort to negate a disproportionate importance given to long duration low intensity exercise compared to higher intensity exercise, which is of a typically much shorter duration.

As previously described, Banister (1991) proposed a statistical model describing an athlete's response to any given training stimulus (Avalos, Hellard & Chatard, 2003). Within this model, Banister proposed that performance could be broken into two distinct components; a positive function (fitness impulse) and a negative function (fatigue impulse) in which their difference (fitness-fatigue) could potentially predict performance (Banister, 1991; Morton, 1990). Banister suggested that fatigue decays at a threefold greater rate than fitness and it is this difference in decay rate that allows training adaptation and performance enhancement to take place. bTRIMP has previously been used to model the dose-response relationships of fitness and fatigue to performance in endurance based sports (Morton, 1990; Busso, 2003). Morton (1990) investigated the relationship between modelled predicted performances with the actual measured performances in two endurance athletes during a 28-day training period. The relationships were reported to be large (r = 0.71 & 0.96) as based on Hopkins (2002) qualitative descriptors of the correlation coefficients. However, as can be seen, the differences in correlation coefficients between the two subjects suggest there is also a large degree of individual variation. Given the small sample size (n = 2), it would be possible to suggest that the variation between the relationships could be much larger with a larger sample size. Manzi et al. (2010) investigated the dose-response relationship between bTRIMP and changes in measures of fitness in a group of recreational runners following an 8-week training period. This is one of only two investigations that have examined the dose-response relationship between bTRIMP (measured during training) and fitness/performance measures. Non-significant relationships between mean weekly bTRIMP and changes in running speed at 2 $mM \cdot L^{-1}$ of blood lactate ($r = 0.61$; $P = 0.11$) or 4 $mM \cdot L^{-1}$ of blood lactate ($r = 0.59$; $P = 0.12$) were reported. There were also no significant relationships between running performance measures of 5000 m ($r = -0.41$; $P = 0.31$) or 10000 m ($r = 0.54$; $P = 0.16$). This suggests bTRIMP does not act in a dose-response manner in recreational runners. The modelling used in the studies discussed so far have focused on endurance athletes. Questions remain as to its transfer to intermittent team sport activity, given the differences in training schedules and competition periods between the types of sports. As a result, it is logical to think that bTRIMP would lack sensitivity in intermittent sports such as rugby league due to its focus on mean HR. The use of mean HR in the bTRIMP method is problematic in intermittent sports as it is possible that mean HR will not reflect the frequent fluctuations in HR that occurs during intermittent exercise. Mean HR in rugby league competition has been reported to be 165 $b \cdot min^{-1}$ but can also peak at values close to an individual’s maximum at regular intervals (McLellan et al., 2011). Moreover, the use of only male and female factors within the equations suggests that sex is the sole determinant of differences in training load. This however, has previously been suggested to not be the case (Impellizzeri et al., 2005). As a result, Akubat et al. (2012) investigated the dose-response relationship of bTRIMP against measures of aerobic fitness in professional youth team soccer players in order to address this question. No significant relationships were reported between mean weekly in-season bTRIMP and percentage changes in the speed at lactate threshold ($r = 0.13$), speed at the onset of blood lactate accumulation ($r = 0.40$), heart rate at lactate threshold ($r = 0.20$) or heart rate at the onset of blood lactate accumulation ($r = 0.15$). Therefore, bTRIMP does not appear to be sensitive to changes in fitness. Despite its novel approach at the time, the limitations of bTRIMP cannot be ignored. The difficulty in analysing HR data at the time of the conception of bTRIMP possibly led to the use of mean HR. However, more recently, the improvements in software to analyse HR means much larger volumes of data can be analysed quickly. Therefore, other methods that can take advantage of this capability are needed. Despite its limitations, studies continue to use bTRIMP as a criterion measure in team sports to determine the validity of other measures of training load, particularly sRPE (Scott et al., 2013; Lovell et al., 2013).

Edwards (1993) proposed an alternative HR-based method to calculate the internal training load. Edwards demarcated five arbitrary heart rate zones which are multiplied by arbitrary coefficient weightings to produce a TRIMP value. The zones of the Edwards TRIMP are based on the percentage of an individual’s HR_{max}. Table 2.6 describes the five heart rate zones and their associated coefficients.

Table 2.6. Edwards TRIMP (2003) heart rate zones.

Heart Rate Zones	Coefficient
50-59% HR_{max}	1
60-69% HR_{max}	2
70-79% HR_{max}	3
80-89% HR_{max}	4
90-100% HR_{max}	5

Edwards TRIMP has proved popular, due in part to its use as the default setting on commercial HR telemetry and GPS systems. However, despite its popular use, the physiological justifications for the coefficients used within the Edwards TRIMP are currently lacking. Furthermore, the theoretical underpinning of this methodology is also questionable, as the heart rate zones are predetermined and are not related to any physiological thresholds. The weightings used in this methodology would imply a linear relationship between load and response measures. While some authors suggest this is the case (Kram & Taylor, 1990), others suggest an exponential relationship (Norton, Norton, and Sadgrove, 2010; Richardson et al., 1995). In addition, there are suggestions within the literature that small changes in intensity can influence training adaptations. Denadai, Ortiz, Greco and de Mello (2006) investigated the effect of two different high-intensity interval running training programmes (velocity at 95% VO_{2max} & 100% VO_{2max}) on measures of aerobic fitness (VO_{2max}, the velocity at VO_{2max} [vVO_{2max}]), velocity at OBLA, running economy, 1500 m time trial and 5000 m time trial) in well trained runners. No changes in VO_{2max} were observed in both groups. However, there was an improvement in the velocity at OBLA and 5000 m time trial performance in both groups. The most interesting finding is the significantly greater improvement in vVO_{2max}, running economy and 1500 m time trial performance in the participants who trained in the 100% vVO_{2max} group. Therefore, when the volume or duration is controlled and only intensity is manipulated, even to a small degree as in this study, training adaptations differ. This is an important consideration, as the use of HR zones, which include a large range of intensities, may lack the sensitivity and validity to truly reflect the internal training load. Using a larger range of intensity zones means that intensities within the same zone that induce different adaptations cannot be identified within the calculation of the training load. In the study by Denadai et al. (2006), the loads were controlled and manipulated. However, during team sports training and competition, where the activities are intermittent, the training durations within each of those intensity ‘zones’ will differ between individuals, between training sessions of the same mode, as well as between different training modes. Despite the lack of evidence suggesting sensitivity and validity as a measure of the training load, Edwards TRIMP continues to be used as fundamental criterion measure of the internal training load in team sport studies (Clarke, Farthing, Norris, Arnold, Lanovaz, 2013; Scott, Black, Quinn & Coutts, 2013; Rebelo et al., 2012).

Stagno, Thatcher and Van Someren (2007) attempted to develop a modified version of Banister’s TRIMP ($TRIMP_{mod}$) for use in field hockey. Instead of using a universal equation to reflect a generic blood lactate profile, direct blood lactate profiles were produced for each player. As a result, the weightings used in this method represented the blood lactate response to increasing exercise intensity for this specific cohort. Five HR zones were developed based on the lactate threshold, defined as 1.5 $mM \cdot L^{-1}$, and the onset of blood lactate accumulation (OBLA), defined as 4 $mM \cdot L^{-1}$. Team weightings for each zone were then produced for each of the five zones: 1.25, 1.71, 2.54, 3.61 and 5.16, respectively. The accumulated time in each HR zone was then multiplied by its given weighting factor to produce an overall $TRIMP_{mod}$ value. To investigate the sensitivity of this method, Stagno et al. (2007) examined the relationship between the $TRIMP_{mod}$ and measures of fitness during the course of a season. Significant relationships between the mean weekly $TRIMP_{mod}$ and changes in running speed at 4 $mM \cdot L^{-1}$ ($r = 0.67$; $p = 0.04$; ES = large) and VO_{2max} ($r = 0.65$; $p = 0.04$; ES = large) were reported. As previously described, Banister’s original TRIMP used the mean heart rate whereas Stagno et al. (2007) advanced this to include the time accumulated in different zones in order to reflect the wide range of intensities that team sport players are subjected to, compared to the more steady state and therefore less variable intensities that endurance athletes are subjected to. However, surprisingly the two methods were not compared (Stagno et al., 2007). A limitation in the method of Stagno et al. (2007) is the use of identical weighting factors for every heart rate within a given zone. For example, a zone including heart rates within the range 80-90% HR_{max} had the same weighting factor, and therefore a training session where an athlete responds with a HR of 81% HR_{max} would be allocated the same weighting factor as someone who responded with a heart rate of 79% HR_{max}. The physiological consequence of this difference in exercise intensity and the subsequent difference in adaptations is difficult to determine. Denadai et al. (2006) suggests that this difference in intensity will influence adaptation. Questions also arise as to the protocol that Stagno et al. (2007) used to produce the weighting factors. The oxygen consumption during intermittent and continuous exercise at the same mean intensity remains similar during low intensities (Bangsbo, 1994). However, at higher intensities oxygen consumption is significantly different (Bangsbo, 1994). The same authors also reported higher blood lactate concentrations for intermittent exercise when compared to continuous exercise at the same mean workload. Therefore, the continuous protocol used by Stagno et al. (2007) will limit the sensitivity of the weighting factors, particularly as the nature of hockey training and competition is very much an intermittent activity.

Leading on from this, Akubat and Abt (2011) aimed to investigate the effect of intermittent exercise on the HR-BL relationship and its influence on the weighting factors that are used to generate the TRIMP score. Twelve amateur team sport players undertook a vVO_{2max} test and then a continuous and intermittent trial, which comprised stages corresponding to 25%, 50%, 75% and 100% of vVO_{2max}. The trials were matched for distance and mean speed. Higher blood lactate concentration was reported during the intermittent trial at 75% vVO_{2max} ($P = 0.023$) and 100% vVO_{2max} ($P = 0.012$). This difference resulted in large changes to the TRIMP weightings at higher intensities during intermittent exercise (Akubat & Abt, 2011). This difference between intermittent and continuous protocols, particularly at higher intensities is logical, as high intensity intermittent exercise involves intense periods above the lactate threshold (Billat et al., 2000). The increase in TRIMP weightings at higher exercise intensities in this study was explained by the moderate to large increase in blood lactate found at these intensities rather than changes in ΔHR ($HR_{exercise}$-HR_{rest}/HR_{max}-HR_{rest}) (Akubat et al., 2011).

Despite the aforementioned limitations, the sensitivity to training responses also needs to be examined to provide a comprehensive evaluation of the validity of the training load measure. Akubat et al. (2012) compared the ‘dose-response’ relationship between $TRIMP_{mod}$ to changes in fitness as previously described. Despite significant correlations with mean weekly Banister’s TRIMP (r = 0.92; *P* < 0.001; 95% CI: 0.66 to 0.98), team TRIMP did not show any significant correlations with changes in velocity at LT (r = 0.20), velocity at OBLA (r = 0.28), heart rate at lactate threshold (r = 0.28), or heart rate at OBLA (r = -0.49). It has been suggested that only methods that show a relationship with changes in fitness or performance measures should be considered as appropriate measures of load for that specific cohort (Thomas, Nelson, & Silverman, 2005). Therefore, while this method provides a better degree of individualisation compared to previously discussed TRIMP methods, the $TRIMP_{mod}$ method lacks full individualisation of the internal training load. As a result, further individualisation is needed.

Further improvements in the sensitivity of the TRIMP method were attempted through the use of an individualised TRIMP (iTRIMP), firstly in distance runners (Manzi et al., 2009) and then in intermittent sports such as soccer (Akubat, Patel, Barrett & Abt, 2012; Manzi et al., 2013). The TRIMP weighting factor used within this method is based upon an individual’s own HR to blood lactate relationship observed during a standard incremental lactate threshold test. Therefore, this method uses individually determined weighting factors for the determination of the TRIMP score. Furthermore, unlike previous TRIMP methods, Manzi et al. (2009) did not use HR zones or mean HR. TRIMP values were calculated based on each HR reading and then summated to produce an overall TRIMP score. This is now possible with relative ease due to the advancement in software and data management capabilities. This individualisation is taken much further than individualisation by sex (Banister, 1991) or by team (Stagno et al., 2007).

Furthermore, the individualised weightings are a progression from arbitrary weightings used by Edwards (1993) and Lucia et al. (2003). This advancement was applied to address the previously discussed limitations of other TRIMP methods. Large and very large associations between improvements in percentage running speed at 2 mM·L^{-1} (r = 0.87; *P* = 0.005) and 4 mM·L^{-1} (r = 0.74, *P* = 0.04) blood lactate concentration with weekly iTRIMP values were observed in distance runners (Manzi et al., 2009). Strong associations were also reported in relation to iTRIMP and improvements in 5000 m (r = -0.77; *P* = 0.02) and 10000 m (r = -0.82; *P* = 0.01) track performances in the same subjects (Manzi et al., 2009). Moderate to large associations have also been reported between weekly iTRIMP and team sport specific changes in performance, including the Yo-Yo Intermittent Recovery Test 1 (r = 0.69, *P* = 0.009) in elite standard soccer players (Manzi et al., 2013) and with changes in the velocity at lactate threshold (r = 0.67; *P* = 0.04) in professional youth soccer players (Akubat et al., 2012). Comparisons between different proposed methods of training load have only previously been compared in one of the previously mentioned investigations (Akubat et al., 2012). Within this study, only iTRIMP was sensitive to any of the measures of aerobic fitness. sRPE or bTRIMP were not significantly related to the changes in fitness. The iTRIMP therefore appears to be an effective method to quantify the internal training load, given its previously determined dose-response relationship with changes in fitness parameters in both recreational runners and professional youth and adult soccer players. However, the training outcomes reported in Akubat et al. (2012) can be aligned with cardiovascular adaptations (e.g. Δ velocity at lactate threshold). The dose-response validity of the iTRIMP method with training outcomes across the variety of physiological stresses is still unknown. Further, given its suggested dose-response validity, detailing the differences in iTRIMP across different modes of training in professional rugby league would provide useful information to practitioners to establish the likely internal load imposed on players. However, given the previously discussed frequency of collision demands and its effects on training response (e.g. muscle damage), questions remain as to the usefulness of the iTRIMP method for reflecting the total internal load cost of training and competition in rugby league.

2.4.2. Session Rating of Perceived Exertion

Session RPE (sRPE) was proposed by Foster et al. (1998) as a measure of internal training load that incorporated both the intensity and duration of exercise. It is a perceptual scale that provides a single arbitrary unit (AU) of internal training load by multiplying the global rating of perceived exertion of the whole training session, (determined via Borg's CR10 scale), by the session duration (Impellizzeri et al., 2004; Alexiou & Coutts, 2008; Akubat et al., 2012; Casamichana et al., 2013; Clarke et al., 2013; Lovell et al., 2013; Scott et al., 2013; Haddad, Padulo & Chamari, 2014). The method has two components: a perceived exertion scale, which incorporates the intensity component, and session duration, which incorporates the volume component. The sRPE has previously been well documented as a simple, non-invasive and practical method to quantify the internal training load (Egan et al., 2006; Herman et al. 2006). Due to its ease of use and low cost, this method has been utilised by both coaches and researchers across a number of team sports including soccer, both rugby codes and Australian football as a 'global' measure of training load (Alexiou & Coutts, 2008; Hill-Haas, Coutts, Roswell & Dawson, 2008; Lovell et al., 2013). One of its suggested advantages is the inclusive nature of RPE, with many factors contributing to the perception of effort, including an athlete's psychological state (Morgan, 1994; Robertson & Noble, 1997), training status (Robertson & Noble, 1997; Martin & Andersen, 2000) and external training load (Impellizzeri et al, 2005; Coutts, Rampinini, Marcora, Castagna & Impellizzeri, 2009). Although, this also means that determining the contribution of those factors to the RPE obtained is problematic.

Table 2.7. Modified Borg CR-10 scale (Foster et al., 2001)

Rating	Descriptor
0	Rest
1	Very, Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	
7	Very Hard
8	
9	
10	Maximal

The intensity component, the rating of perceived exertion (RPE), has been used as a measure of exercise intensity for over 40 years (Doherty et al., 2001; Day et al., 2004). An athlete's perceived exertion is derived from a psychophysical foundation, which encapsulates numerous sensations and feelings of physical stress derived from the complex integration of a number of peripheral and central feedback and feed forward mechanisms (Borg, 1998; Haddad, Padulo & Chamari, 2014). It has been suggested that the afferent feedback from the physiological (cardiovascular, musculoskeletal, pulmonary) and neural (central pattern generator) stresses are the main determinants of perceptual exertion (Haddad, Padulo & Chamari, 2014). The reliability of the intensity component (the RPE scale) of sRPE has been well established in a range of modalities including running, cycling and resistance training (Doherty et al., 2001; Gearhart et al., 2002). The earliest reliability research on RPE (6-20 scale) assessed RPE in a variety of activities (walking, jogging, cycling and stepping), all of which showed strong test-retest relationships (r = 0.71 to 0.90) during randomised trials at steady state, wave form and incremental intensity bouts (Skinner et al., 1973; Stamford, 1976). The reliability of the RPE scale (6-20) was also investigated using repeated trials of treadmill running at four different gradients (Lamb et al., 1999). Stronger relationships were reported at lower intensities (r = 0.81) but the strength of the relationship reduced as the intensity of exercise increased (r = 0.60). Doherty et al. (2001) progressed this work further by investigating the reliability of RPE (6-20) during treadmill running at only high intensities. Three repeated supra-maximal (125% of VO_{2max}) trials were used to assess the within subject CV (4.4 to 6.0%) and ICC (0.78 to 0.79). The findings from these research studies suggest that the RPE scale is fairly reliable during graded and high-intensity exercise.

As previously stated, the RPE scale is a measure of exercise intensity and as a result is one component in the determination of the training load. Therefore, research that validates the RPE scale as a measure of intensity does not automatically mean that RPE is a valid measure of the training load. A limited number of studies have investigated the reliability of sRPE (CR10), which has focused on aerobic exercise, resistance training and in team sports (Day et al., 2004; Egan et al., 2006; Herman et al., 2006; Gabbett & Domrow, 2007). In terms of aerobic exercise, intra-athlete reliability was determined during aerobic exercise of either cycling or running modalities (Herman et al., 2006). Within this study, three pre-determined intensity zones were selected (easy: 40-50% VO_{2peak}; moderate: 60-70% VO_{2peak}; hard: 80-90% VO_{2peak}), of which the subjects completed two 30 minute bouts at each intensity. At least 2 days were permitted between exercise bouts. The standard error of estimate (SEE) was small (SEE = 1.2%) and the relationships between the repeated trials for sRPE was strong (r = 0.78). This suggests that sRPE is a reliable method for use in continuous exercise. However, despite demonstrating reliability in continuous activity, rugby league is an intermittent activity and therefore it is possible that the level of reliability will be altered, yet there is a paucity of sRPE reliability research in intermittent sports. Test-retest reliability was assessed in one study in rugby league players (Gabbett & Domrow, 2007). Reliability was assessed to ensure that sRPE had within-subject reproducibility to measure the training load (Gabbett & Domrow, 2007). Eleven rugby league players completed two identical training sessions with one week between sessions. Within-subject relationships were strong (ICC = 0.99, CV 4.0%) suggesting that the sRPE method is reliable for assessing training load in contact-based activity in rugby league.

Due to the lack of a gold standard criterion measure of load, research investigating the validity of sRPE has used other measures of load as the ‘criterion’ measure (Impellizzeri et al., 2004; Alexiou & Coutts, 2008; Scott et al., 2013; Lovell et al., 2013). Impellizeri et al. (2004) investigated the within-individual correlations between sRPE and the heart rate based methods of Banister (1991), Edwards (1993) and Lucia et al. (2003) in 19 youth soccer players during a 7-week training period. This training period included four training sessions and one match per week. The training sessions incorporated numerous training modes including physical conditioning, speed, interval training and small-sided games. They reported sRPE to correlate significantly with the Edwards method (r = 0.54-0.78), Banister’s TRIMP (r = 0.50 – 0.77) and Lucia’s TRIMP (r = 0.61-0.85). Large to very large correlations between sRPE and heart rate-based TRIMP methods have also been reported in other studies in football (Alexiou & Coutts, 2008; Akubat et al., 2012; Casamichana, Castellano, Calleja-Gonzalez, San Roman & Castagna, 2013) as well as across other team sports such as American football (Clarke, Farthing, Norris, Arnold & Lanovaz, 2013) and Australian rules football (Scott et al., 2013) (Table 2.8).

Table 2.8. Summary of sRPE validity research: correlations with criterion training load measures.

Authors	**Subject Number**	**Training Modes**	**Statistics**	**Criterion Measure/ Correlation [90% CI]**
Impellizzeri et al. (2004)	19 Male Football	Conditioning and SSG grouped together	WI Correlation	***Edwards TRIMP*** r = 0.54 [0.65 to 0.92] to 0.78 [0.56 to 0.90]; r^2 = 0.29 to 0.61; unexplained variance: 71 to 39% ***Banister's TRIMP*** r = 0.50 [0.14 to 0.74] to 0.77 [0.54 to 0.89]; r^2 = 0.25 to 0.59; unexplained variance: 75 to 41% ***Lucia's TRIMP*** r = 0.61 [0.29 to 0.81] to 0.85 [0.69 to 0.93]; r^2 = 0.37 to 0.72; unexplained variance: 63% to 28%

Alexiou & Coutts (2008)	15 Female Football	Conditioning, matches, speed, skills and resistance grouped together	WI Correlation	***Edwards TRIMP*** r = 0.50 [0.07 to 0.77] to 0.96 [0.90 to 0.98]; r^2 = 0.25 to 0.92; unexplained variance: 75 to 8% ***Banister's TRIMP*** r = 0.67 [0.32 to 0.86] to 0.95 [0.88 to 0.98]; r^2 = 0.45 to 0.90; unexplained variance: 55 to 10% ***LT_{zone} TRIMP*** r = 0.56 [0.16 to 0.80] to 0.97 [0.92 to 0.99]; r^2 = 0.31 to 0.94; unexplained variance: 69 to 6%
Waldron et al. (2011)	12 Male Rugby League	RL competition	Group Correlation	***Edwards TRIMP*** r = 0.62 [0.17 to 0.85]; r^2 = 0.38; unexplained variance: 62%
Akubat et al., (2012)	9 Male Football	Skills, Speed and Conditioning grouped together	Group Correlation	***Banister's TRIMP*** r = 0.75 [0.29 to 0.93]; r^2 = 0.56; unexplained variance: 44%

				iTRIMP No significant relationship. R not reported.
Casamichana et al. (2013)	28 male Football	SSG, conditioning and skills grouped together	Group Correlation	***Edwards TRIMP*** r = 0.57 [0.31 to 0.75]; r^2 = 0.32; unexplained variance: 68% ***Total Distance*** r = 0.74 [0.55 to 0.86]; r^2 = 0.54; unexplained variance: 46% ***PlayerLoad™*** r = 0.76 [0.58 to 0.87]; r^2 = 0.58; unexplained variance: 42%
Clarke et al. (2013)	20 Male American Football	Skills and conditioning grouped together	WI Correlation	***Polar Training Impulse*** r = 0.65 [0.36 to 0.83] to 0.91 [0.81 to 0.96]; r^2 = 0.42 to 0.82; unexplained variance: 58 to 18% ***Edwards TRIMP*** r = 0.69 [0.42 to 0.85] to 0.91 [0.81 to 0.96]; r^2 = 0.48 to 0.82; unexplained variance: 52 to 18%

Scott et al. (2013a)	21 Male Australian Rules Football	Skills	WI Correlation	***Banister's TRIMP*** r = 0.83 [0.66 to 0.92]; r^2 = 0.69; unexplained variance: 31% ***Edwards TRIMP*** r = 0.83 [0.66 to 0.92]; r^2 = 0.69; unexplained variance: 31% ***Total Distance*** r = 0.81 [0.63 to 0.91]; r^2 = 0.66; unexplained variance: 34% ***High-Speed Running*** r = 0.71 [0.46 to 0.86]; r^2 = 0.50; unexplained variance: 50% ***PlayerLoad™*** r = 0.83 [0.66 to 0.92]; r^2 = 0.69; unexplained variance: 31%
Scott et al. (2013b)	15 Male Football	Technical and SSG grouped together	WI Correlation	***Banister's TRIMP*** r = 0.73 [0.43 to 0.89]; r^2 = 0.53; unexplained variance: 47% ***Edwards TRIMP*** r = 0.98 [0.95 to 0.99]; r^2 = 0.96; unexplained variance: 4% ***Total Distance***

	r = 0.80 [0.55 to 0.92]; r^2 = 0.64; unexplained variance: 36%
	Low-Speed Distance
	r = 0.80 [0.55 to 0.92]; r^2 = 0.64; unexplained variance: 36%
	High-Speed Distance
	r = 0.65 [0.29 to 0.85]; r^2 = 0.42; unexplained variance: 58%
	Very High Speed Distance
	r = 0.43 [-0.01 to 0.73]; r^2 = 0.18; unexplained variance: 82%
	Playerload™
	r = 0.84 [0.63 to 0.93]; r^2 = 0.71; unexplained variance: 29%

Abbreviations: WI, within individual; SSG, small-sided games; TRIMP, training impulse

The inferences made within the above studies (Table 2.8) have concluded sRPE as a valid measure of the training load, despite a large proportion of unexplained variance which is exacerbated by the confidence intervals in these findings. In addition, investigating the validity of the sRPE method with ‘criterion’ heart rate methodology is problematic, given that those methods are not themselves the criterion method. This issue is further confounded due to the previously described criticisms of the HR-based criterion measures of training load used in previous studies. A measure cannot be deemed to be valid if the criterion measure used to determine validity has itself not been deemed to be a valid measure. In addition, given the varied psycho-physiological load imposed during training (Soligard et al., 2016), the capability of HR to reflect all of the actual internal load imposed is also limited. This highlights the limited validity information currently present within the literature and suggests the interpretation of the current research using those criterion measures should be preceded with caution.

As also mentioned previously, a valid measure of training load should possess a dose-response relationship with changes in fitness and/or performance. Brink, Nederhof, Visscher, Schmikli and Lemmink (2010) assessed the dose-response relationship of sRPE with performance and recovery. sRPE, total quality of recovery (TQR) and monthly interval shuttle run (ISRT) performance was monitored in youth elite soccer players over the course of a whole season. Daily session logs were recorded by players and coaches in order to report the training load after training sessions. The TQR scale was also recorded before the next session (Kentta & Hassmen, 1998). Multi-level modelling was applied to examine whether sRPE had the capability to predict performance and recovery. The number of training days was capable of predicting performance but sRPE or TQR was not able to predict performance. The apparent lack of dose-response validity of sRPE was also reported by Akubat et al. (2012) who investigated the dose-response relationship of sRPE with measures of fitness in professional youth soccer players. Interestingly, despite the strong correlations between sRPE and bTRIMP ($r = 0.75$) within their study, there was no significant relationship found between sRPE and the changes in fitness. Therefore, at present, whilst sRPE has displayed large relationships with other criterion measures of internal training load, there is a lack of dose-response validity with training outcomes and as such, the validity of this perceptual measure of internal training load has yet to be fully established.

The difficulty in establishing the validity of individual measures of internal training load is complicated further when considering the wide variety of training modes that rugby league players are required to participate in during their physical preparation programmes. Earlier in the literature review, the lack of research relating to the external and internal demands of the different training modes professional rugby league players undertake was highlighted. Previously, Gabbett et al. (2012) reported significant differences in total distance, mild, moderate and heavy collisions and repeated effort bouts between certain training modes (traditional conditioning, repeated high-intensity effort and skills training) in professional rugby league players. Differences in PlayerLoad™ between training modes (skills, small-sided games, tactical and match practice) have also been observed in Australian rules football (Boyd, Ball & Aughey, 2013). This provides initial evidence that the different training modes elicit different external loads on rugby league players during training. Although a comprehensive evaluation of the external and internal training load demands of a wide range of training modes utilised in professional rugby league training is warranted, it is possible that the manipulation of the organisation of the external training load by practitioners will influence the validity of individual measures of training load quantification. However, this has yet to be investigated.

As can be seen in Table 2.8 studies such as Impellizzeri et al. (2004) have grouped training modes together within their validity study. While these relationships might provide evidence for the global training load validity of sRPE, the strength of this validity may be altered when taking into account individual training modes. Within each training mode, practitioners manipulate the organisation (e.g. volume and intensity) of the external training load (e.g. distances) to elicit different magnitudes of physiological stress (internal load) onto predominately the cardiorespiratory, neuromuscular and musculoskeletal subsystems (Buchheit & Laursen, 2013). Therefore, the possible between-mode variability in the organisation of the external training load coupled with the inter-individual variability in internal training load response to a given external training load (Impellizzeri et al., 2005) might lead to different magnitudes of load imposed on the various physiological-subsystems during the overall training process (Buchheit & Laursen, 2013). This will be exacerbated during certain modes, such as SSG, where knowledge of bout duration has previously been reported to influence pacing strategies and therefore the external loads imposed on individuals (Gabbett, Walker & Walker, 2015). Therefore, a valid individual measure of training load should accurately reflect this variability across all types of training. However, a paucity of information is currently available that details the effect of the training mode on the validity, including dose-response validity, with training outcomes of individual training load measures.

Alexiou and Coutts (2008) were the first to describe the relationships between sRPE and criterion HR measures across different modes of training during professional women's soccer training. The relationships between sRPE and Banister's TRIMP, LT_{zone} training load and Edwards TRIMP were examined over 735 individual training sessions in fifteen elite women soccer players. Within-individual correlations were determined grouped across all training modes whilst group correlations were established between conditioning, matches, speed, technical and resistance training modes. While very large within-individual associations were reported between sRPE and Banister's TRIMP (0.84 ± 0.09; 95% CI: 0.80 to 0.89), LT_{zone} training load (0.83 ± 0.14; 95% CI: 0.74 to 0.92) and Edwards TRIMP (0.85 ± 0.12; 95% CI: 0.79 to 0.92), the training mode appears to alter the strength of the group level relationships between sRPE and HR-based training load methods as shown in Table 2.9. The stronger relationships reported during continuous based training modes (e.g. conditioning) compared with activities that are more intermittent (e.g. matches) provides initial evidence that the level of intermittency and rest period in the organisation of the external training load might influence the relationship between sRPE and HR-based internal training load methods.

Table 2.9. Between-subject correlation coefficients for sRPE and three HR-based TL methods demarcated by session type. Reproduced from Alexiou & Coutts (2008).

	Bannister's TRIMP		**LT_{zone}**		**Edwards TRIMP**	
Training Mode	**r**	**95% CI**	**r**	**95% CI**	**r**	**95% CI**
Conditioning	0.74	0.65 to 0.81	0.60	0.47 to 0.70	0.79	0.72 to 0.85
Matches	0.49	0.32 to 0.63	0.49	0.26 to 0.67	0.64	0.47 to 0.76
Speed	0.61	0.42 to 0.75	0.75	0.59 to 0.85	0.79	0.67 to 0.87
Technical	0.68	0.60 to 0.74	0.69	0.61 to 0.76	0.82	0.78 to 0.86
Resistance	0.25	0.13 to 0.36	0.34	0.21 to 0.46	0.52	0.42 to 0.61

Although the study by Alexiou and Coutts (2008) provided useful information about the influence of training mode on the validity of sRPE, this study only compared the relationships between sRPE and other measures of internal training load quantification. While the theoretical internal training load might be the most appropriate within the monitoring of training, in the model by Impellizzeri et al. (2005) a combination of the external training load, internal training load and individual characteristics make up the complete training process. Therefore, these three constructs of training might provide interchangeable or different information depending on the mode of training in professional rugby league. However, the relationships between internal and external training load have yet to be fully examined in professional rugby league training.

Table 2.10. Within-individual correlations for sRPE with various measures of load across different modes of professional rugby league training. Reproduced from Lovell et al., (2013).

Measure	Conditioning	Skills	SSG	Speed	Wrestling
N players	22	32	22	12	13
(n sessions)	(15.3 ± 2.9)	(34.3 ± 13.0)	(13.7 ± 2.2)	(10.8 ± 1.0)	(12.2 ± 1.4)
Distance (m)	0.80 ± 0.11	0.69 ± 0.10	0.88 ± 0.05	0.79 ± 0.12	0.37 ± 0.19
High-Speed Running (m)	-0.23 ± 0.20	0.53 ± 0.15	0.84 ± 0.08	0.43 ± 0.15	0.16 ± 0.21
Body Load (AU)	0.63 ± 0.15	0.51 ± 0.17	0.64 ± 0.14	0.58 ± 0.19	0.45 ± 0.22
Impacts (n)	0.69 ± 0.14	0.57 ± 0.11	0.75 ± 0.16	0.73 ± 0.15	0.30 ± 0.22
Banister's TRIMP (AU)	0.68 ± 0.19	0.45 ± 0.16	0.75 ± 0.23	0.56 ± 0.29	0.56 ± 0.20

As described in Section 2.3.2 of this literature review, while not the primary aim of the study, Lovell et al. (2013) reported the relationships between sRPE and other measures of load, including external load measures during various training modes (SSG, conditioning, wrestle, skills, speed) in professional rugby league training. The training mode was shown to alter the strength of the relationships reported (Table 2.9). For example, the association between sRPE and Body Load™ ranged from moderate ($r = 0.45$; $r^2 = 0.20$; unexplained variance = 80%) during wrestling to large ($r = 0.64$; $r^2 = 0.41$; unexplained variance = 59%) during skills conditioning. The large amount of unexplained variance in the relationships between sRPE and other measures of load provides initial evidence that the training mode influences the validity of sRPE to quantify load and that different measures provide different information of the load imposed. However, how the training mode influences the variance explained of multiple training load methods by a single method has not been previously investigated. Further, how the training mode alters the relationships between HR-derived training load, including a method that displays dose-response validity with training outcomes (i.e. iTRIMP) and external training load measures has also not been investigated.

2.4.3 Summary

- Comparable to external training load methods, the review of the methods used to represent the internal training load reveals that currently numerous methods exist.
- The limitations of those individual methods have been highlighted.
- Due to the lack of a gold-standard criterion measure of internal training load, previous research has investigated training load validity against other measures of internal training load.
- The iTRIMP method displays dose-response validity with training outcomes in professional football. However, the relationships between iTRIMP, sRPE and external training load methods have yet to be examined in professional rugby league training.
- The widespread implementation of sRPE has been based on the assumption of validity due to strong relationships with other internal training load measures. However, these other measures of internal training load have been used despite themselves lacking evidence of their validity. In addition, despite the large relationships, there is still a considerable proportion of unexplained variance. Consequently, questions remain as to the sensitivity of single internal training load methods to capture the complete dose of training.

3. Experimental approach to the thesis

3.1. Review of Literature and Thesis Rationale

The review of the literature has highlighted that sports invest significant resources to understand the dose-response relationships between training load and outcomes (e.g., injury incidence, physical qualities), by quantifying the external and internal loads accrued during training- or competition-days. This facilitates the appropriate prescription of training to optimise adaptations for athletes. In particular, the review of the literature has highlighted that there are numerous methods adopted to represent the external and internal training load, each with their own evidence of validity.

There are a number of unconsidered areas within the literature. Firstly, understanding the differences in external and internal load per minute of training time between training modes is important for the practitioner to evaluate what stimulus is provided by each mode to appropriately periodise their field-based training programme. For example, if practitioners found that SSG's training did not provide players with an appropriate sprinting stimulus but speed training did, they could use this information to prescribe both training modes to ensure players were exposed to these demands during training. However, our understanding of how the external and internal training load per minute of training time differs between training modes in professional rugby league is limited and warrants further investigation (Chapter 4 aim).

Whilst this question would provide useful practical information on the periodisation of concurrent field-based training modes, investigating the validity of these measures is a key focus of the thesis given its wider reaching implications to manage negative training outcomes such as injury. There are two important aspects to establishing validity of training load measurements in load-outcome analyses which are to determine the most appropriate:

1.) mathematical method to calculate the training load over training periods

2.) variable (s) that provide the most valid representation of the training load.

Mathematical methods to have been developed to calculate the training load over training periods, with the most popular being the acute- and chronic-training-load-ratio (Gabbett, 2016). However, numerous training load metrics (e.g., total-distance, high-speed-distance, session rating of perceived exertion [sRPE]) have been used as individual predictor variables within the acute- and chronic-training-load-ratio to investigate load-injury relationships (Section 2.2.). Despite the advancements within training load monitoring, through techniques such as the acute- and chronic-training-load-ratio, without a valid quantification of training load for each mode of training, these dose-response relationships are likely to be suboptimal.

Establishing the agreement of a practical measurement to its true value is a fundamental consideration for sports scientists (Hopkins, 2000). For external load validity, the confidence that the criterion method (e.g. radar gun) represents the true value (e.g. speed) is high, given the history and relative ease of speed and distance measurement (Section 2.3.1.1.). However, given there are likely numerous psycho-physiological responses that result from the manipulation of the training process, the true value of the internal load is somewhat harder to specify. This difficulty increases further due to the limited physiological markers that can be easily collected in the field over longitudinal training periods. Therefore, research typically investigate validity by adopting heart-rate based measures as the criterion. However, in theory, given that the internal load encapsulates all psycho-physiological responses, it logical to question the notion that a single physiological measurement (i.e. heart-rate) can reflect the true value of the internal load construct, given this is likely to vary between the physiological systems and across the different modes of training and competition that players are exposed to. Therefore, given the difficulty in selecting an appropriate criterion method, a more robust approach to infer validity should be the capability of a training load measurement to possess dose-response relationships with training outcomes (e.g., changes in physical qualities). However, considering this approach, the coefficient of determination within studies suggest that a considerable (39-59%) proportion of the variance remains unexplained when using a single training load variable to explain the variance within changes in physical qualities (Section 2.4.1) or acute physiological responses to competition (Section 2.1.4 & 2.3.2.2). Collectively, these highlight the limitations of adopting a single variable to represent the training load construct. Given it is the theoretical internal load that governs training outcomes, methods that directly quantify this are preferred to understand load-outcome relationships. Yet, at present, given the limited methods available, it is plausible that external load measurements can provide additional information in relation to the outcomes of training. For example, high-speed running (>5 $m \cdot s^{-1}$) and the total number of collisions accounted for 58% (r=0.76 [95% CI: 0.51 to 0.91]) and 31% (r=0.67 [95% CI: 0.42 to 0.85]) of the variance in acute changes (12-hours post-match) in creatine kinase concentration respectively following professional rugby competition (Oxendale et al., 2015). It is possible therefore, that depending on the training mode, a combination of training load measures might be more sensitive and provide more information to the training stress elicited. This warrants further investigation.

Taking this into consideration, it appears a current limitation in validity and load-injury analyses is that although multiple methods are collected concurrently in practice, the consistent use of a single variable (e.g. total-distance) does not explore the possibility that a multivariate approach, including both internal and external load methods, might provide the most valid representation of the training load across modes of training. However, this has yet to be investigated. To investigate multivariate training load relationships, we propose the use of principal component analysis (PCA) which is a higher-dimensional analysis technique that can reduce multiple training load methods by decomposing the dataset matrix (if columns equal training load variables and rows equal different training-days) into principal components (Federolf et al., 2014). This allows the majority of the variance provided by the original variables to be captured within a reduced number of newly-formed, orthogonal principal components. As regression analyses are used to investigate load-injury relationships (Bowen et al., 2016; Murray et al., 2016; Malone et al., 2016), an important additional benefit of PCA, as the decomposed principal components are orthogonal, is that they share zero variance. This ensures that they contribute completely different training load information as predictor variables which avoids multicollinearity issues between predictor variables in regression analyses. Given the well stated shared variance that training load methods possess, this is an important consideration if evidence demonstrates a single training load variable is not sufficient to represent the training load. If the vast proportion of the variance between multivariate training load variables can be captured within a single principal component during certain training modes, this suggests that a single training load measure might indeed be a valid approach to represent the training load. However, if more than one principal component is needed to capture the vast proportion of the multivariate training load variance, this suggests adopting a single training load measure might underrepresent the true training load imposed. By conducting PCA for each training mode, we are able to understand how multivariate, rather than bi-variate training load relationships change between modes and provide more robust evidence of the validity of single training load measures (Chapter 6 aim). As highlighted in the literature review, there are numerous methods adopted by practitioners to quantify the training load and each method has their own evidence of validity. Therefore, to truly understand whether these multivariate relationships are influenced by the training mode, these relationships should be replicated using different training load methods collected from different players partaking in a training programme prescribed by different coaching staff (Chapter 7 aim) which will increase the generalisability of the findings. Finally, to provide a comprehensive assessment of the validity of these measures, a dose-response investigation is required. As players undertake numerous training modes concurrently, it is important to assess the dose-response validity of the measures with acute changes in performance (Chapter 8 aim).

3.2. Specific Aims of the Thesis

3.2.1. Chapter 4: Quantifying the external and internal training loads of professional rugby league training modes: consideration for concurrent field-based training prescription

The specific aims of the study in Chapter 4 were to:

1. determine the differences in the speed- and metabolic-power-threshold distances covered per minute of training time between professional rugby league conditioning [CON], small-sided games [SSG], speed and skills training modes.

2. determine the within-mode differences in the high-intensity distance covered above either 3.88 $m\cdot s^{-1}$ (high-speed) or 20 $W\cdot kg^{-1}$ (high-metabolic-power).

3. determine the between-mode differences in the individualised training impulse (iTRIMP) and session rating of perceived exertion (sRPE) methods during CON, SSG, speed and skills training.

3.2.2. Chapter 5: Within-individual variation in internal and external load measures at a given session rating of perceived exertion in professional rugby league players

The aims of the case study in Chapter 5 were to:

1. explore the within-subject variability (co-efficient of variation) in external- (Body Load™ and Total Impacts) and internal- training-load-methods (iTRIMP) during training sessions across a 4-week training period in which sessions demonstrated trivial differences in sRPE.

2. describe the differences in variation between two training modes (SSG vs skills).

3.2.3. Chapter 6: Combining internal- and external-training-load measures in professional rugby league

The aim of the research in Chapter 6 was to:

1. understand the multivariate relationships between two internal (iTRIMP and sRPE) and three external (Body Load™, Total Impacts, arbitrary-high-speed-distance) training load methods and how the training mode (CON, SSG, skills, speed, wrestle and strongman) influences the variance explained by individual methods via a principal component analysis.

3.2.4. Chapter 7: The effect of training mode on training load dimensionality in professional rugby league

The aim of the research in Chapter 7 was to:

1. re-investigate the multivariate relationships of two internal (HREI and sRPE) and two external (Player Load™, individualised-high-speed-distance) training load methods and how the training mode (CON and skills) influences the variance explained by individual methods via a principal component analysis.

3.2.5. Chapter 8: The effect of training mode on the 'dose-response' relationships between measures of training load and acute changes in performance

The aims of the research in Chapter 8 were to:

1. determine the dose-response relationship between individual external and internal training load measures and acute changes in physical performance following a single bout of conditioning and speed training
2. establish the effect of training mode on those relationships.

3.3. Participants

Rugby league players competing in three different levels of the performance pathway participated in the studies contributing to the thesis and their characteristics are described in Table 3.1:

Table 3.1. Participant characteristics for experimental studies in thesis

Chapters	Participants and standard	Age (y)	Height (cm)	Body Mass (kg)	Number of top-flight matches (either ESL or NRL)
4 to 6	17 professional ESL players	25 ± 3	186.0 ± 7.7	96.0 ± 9.3	106 ± 93
7	23 professional Kingstone Press Championship players	24 ± 3	184.8 ± 6.7	95.4 ± 8.6	60 ± 70
8	11 amateur players	22.0 ± 3	178.4 ± 5.4	88.5 ± 13.5	N.A.

3.4. Research Design

3.4.1. Chapters 4 to 7

A longitudinal observational research design was implemented for the research conducted in Chapters 4 to 7 in which training load variables, derived from GPS, tri-axial accelerometer, heart-rate and sRPE (Fig 3.1.), were collected concurrently for each training mode across three different 12-week pre-season preparatory periods from two professional rugby league clubs:

1. Chapters 3 and 5: Two ESL pre-seasons (2011 to 2012; 2012 to 2013)
2. Chapter 4: One ESL pre-season (2011 to 2012)
3. Chapter 6: One Championship pre-season (2014 to 2015)

Each training load variable collected were categorised within one of the following training modes:

1. *Small-Sided Games (SSG)*- Small-sided, high-intensity 'off-side' and 'on-side' conditioning games which aimed to concurrently improve rugby league specific fitness and execution of skills under fatigue;

2. *Conditioning (CON)*- Focus on high-intensity running and hill running which aimed to improve players maximal-aerobic-running-ability;

3. *Skills*- Focus on enhancing individual rugby league skills and team technical-tactical strategies;

4. *Speed*- Maximal intensity running drills which aimed to improve acceleration, speed, agility and sprinting technique.

5. *Strongman*- Resistance training which included compound movements of lifting and pulling unconventional objects that aimed to develop muscular hypertrophy and add an extra sense of competition and variety into the pre-season preparatory period. Strongman sessions included tyre pushes and flips and Prowler® pushes. The Prowler® is a training sled that can be dragged or pushed with the option of adding resistance.

6. *Wrestle*- Small area, high-intensity contact sessions aimed at improving both tackling and wrestling techniques.

Prior to the start of each research study, all players were familiarised with the training load methods. All studies were granted ethical approval by the Department of Sport, Health and Exercise Science Human Research Ethics Committee in accordance with the Declaration of Helsinki. Written informed consent was obtained from each player prior to the start of data collection for each study. The training programme and training modes were prescribed by each club's coaching staff during the entire observational periods during which players typically completed 4-5 training sessions per week. Weekly sessions usually included two skills sessions, two conditioning sessions and one skills-conditioning session. Figure 3.1. details the specific external and internal training load variables investigated for each research chapter, with methodological detail of each method described in section 3.5 and 3.6.

3.4.2. Chapter 8

To investigate the effect of training mode on the dose-response relationships between external and internal training load methods and acute changes in physical performance, participants were required to undertake 3 testing sessions. The first session involved the completion of baseline measures of physical performance (countermovement jump [CMJ], 20-m sprint and Yo-Yo Intermittent Recovery Test 1 [Yo-Yo IRT1]). On visits 2 and 3, participants then completed both a 45-minute conditioning or speed training session followed by (10-minutes post session) the same measures of physical performance in a randomised cross-over design. Training load measures (Fig 3.1.) were collected during both training sessions and for each session were correlated with the acute change (baseline *vs* either post-conditioning or post-speed) in physical performance to investigate these dose-response relationships. Given the differences in experimental approach compared to Chapters 4 to 7, further details to the experimental approach are highlighted in Section 8.2 of the thesis.

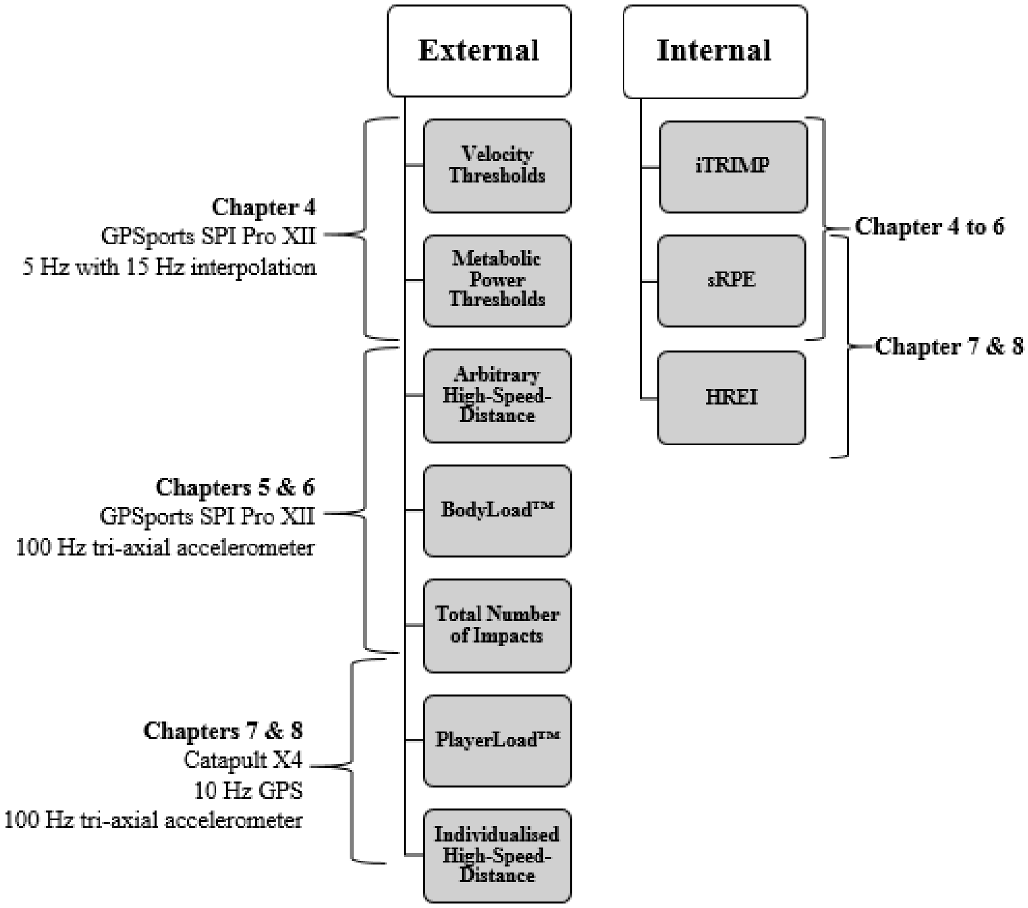


Fig 3.1. Overview of the external and internal load methods collected within thesis by experimental chapter. Abbreviations; iTRIMP: individualised training impulse; sRPE: session rating of perceived exertion; HREI: heart-rate-exertion-index.

3.5. External Training Load Methods

3.5.1. GPSports SPI Pro XII (Chapters 4 to 6)

The external load variables investigated in Chapters 4 to 6 were derived from SPI Pro XII (GPSports, Canberra, Australia) devices which contain a 5 Hz with 15 Hz interpolation GPS sampling rate and 100-Hz tri-axial accelerometer (BMA150, Bosch, Germany). The GPS sampling rate within this microtechnology unit has shown an acceptable level of accuracy and reliability for distance and speed measures during high-intensity, intermittent bouts (Section 2.3.1.1) . The reliability and validity of the tri-axial accelerometer has also shown acceptable reliability and validity (Section 2.3.1.2).

3.5.2. Arbitrary Velocity Thresholds (Chapter 4)

The distances covered per minute of training time across velocity-derived thresholds were implemented to provide a time-motion analysis of the running based external loads of different training modes (conditioning, SSG, speed and skills) as per previous studies (Gabbett et al., 2012): Total-distance; walk (0 to 1.94 $m \cdot s^{-1}$); jog (1.95 to 3.87 $m \cdot s^{-1}$), stride (3.88 to 5.4 $m \cdot s^{-1}$); sprint ($\geq$ 5.5 $m \cdot s^{-1}$); high-velocity distance ($\geq$ 3.88 $m.s^{-1}$). As discussed in section 2.3.2.2 of the literature review, the distances covered within velocity-derived thresholds have been extensively used to determine the external loads of team-sport competition but their use is limited so far in research to evaluate the running demands of professional rugby league training.

3.5.3. Arbitrary Metabolic-Power Thresholds (Chapter 4)

The distances covered in the following velocity-derived thresholds were implemented in Chapter 3 as per previous studies (Gaudino et al. 2013; Kempton et al. 2014): Equivalent distance (EQ-distance); low-power (0 to 10 $W \cdot kg^{-1}$); intermediate-power (10.1 to 20 $W \cdot kg^{-1}$); high-power (20.1 to 35 $W \cdot kg^{-1}$); elevated-power (35.1 to 55 $W \cdot kg^{-1}$); max-power (> 55.1 $W \cdot kg^{-1}$); high-metabolic distance ($\geq$ 20 $W \cdot kg^{-1}$). Whilst their use to describe the acceleration inclusive external load demands of competition is prevalent, this hasn't been described during professional rugby league training.

The distances covered within each metabolic-power threshold were calculated using the instantaneous energy cost equations provided by di Prampero et al. (2005) as used in previous studies (Osgnach et al., 2010; Gaudino et al., 2013; Kempton et al., 2014). The distance covered at high-metabolic-distance ($\geq$ 20 $W \cdot kg^{-1}$) was calculated to compare with high-speed running to determine differences in speed- and metabolic power-derived measures of external load. The equivalent distance (EQ-distance), which represents the steady state distance required to match the estimated energy expenditure inclusive of accelerative running was also calculated as per previous studies (Osgnach et al., 2010; Gaudino et al., 2013; Kempton et al., 2014). Metabolic power was calculated using the proprietary software (TeamAMS Version 2014.3, GPSports, Canberra, Australia) and exported to a custom made spreadsheet for data management

3.5.4. Total Number of Impacts (Chapters 5 and 6)

GPS housed tri-axis accelerometer data displayed in 'g' force and sampling at 100 Hz was used to collect the total number of impacts (Total Impacts). Total impacts identification was derived from the summation of impacts in the vertical (z), medio-lateral (y) and anterior-posterior (x) planes. The magnitude of impacts were demarcated according to the following acceleration zones provided by the system manufacturer: 5.0-6.0g: light impact (zone 1); 6.01-6.5 g: light to moderate impact (zone 2); 6.51-7.0 g: moderate to heavy impact (zone 3); 7.01-8.0 g: heavy impact (zone 4); 8.01-10.0 g: very heavy impact (zone 5); and >10.0 g: severe impact (zone 6). The impact counts within the six demarcated zones were summated to calculate the total number of impacts. Impacts can be detected, particularly in Zone 1, because of locomotor impacts due to hard acceleration/decelerations or changes in direction (McLellan et al., 2011). Therefore, physical contact/collision does not have to be present in order for an impact to be detected (McLellan et al., 2011).

3.5.5. Body Load™ (Chapters 5 and 6)

Player Body Load™ is an arbitrary measure of the total external mechanical stress because of accelerations, decelerations, changes of direction and impacts. Player Body Load™ was calculated using the algorithm included in the software provided by the manufacturers (TeamAMS Version 16.1, GPSports, Canberra, Australia). Player Body Load™ is calculated from the square root of the sum of the squared instantaneous rate of change in acceleration in the vertical (z), anterior-posterior (x) and medio-lateral vectors (y). The magnitude of the accelerations were classified into six zones (as described above) with a factor (1-6 factor for zones 1-6) applied to each zone. Each player's Body Load™ score was multiplied by the player's body mass, summed, and then expressed in arbitrary units (AU).

3.5.6. Catapult Optimeye X4 (Chapters 7 and 8)

The external load variables investigated in Chapters 7 & 8 were derived from Catapult Optimeye X4 devices (Catapult Innovations, Scoresby, Victoria) which contain 10Hz GPS sampling rate with in-built 100Hz tri-axial accelerometer. The GPS sampling rate within this microtechnology unit has shown an acceptable level of accuracy and reliability for distance and speed measures during high-intensity, intermittent bouts (Section 2.3.1.1) . The reliability and validity of the tri-axial accelerometer has also shown acceptable reliability and validity (Section 2.3.1.2).

3.5.7. PlayerLoad™ (Chapter 7 and 8)

An individual's PlayerLoad™ data were collected concurrently during each session using 10Hz GPS devices with in-built 100Hz tri-axial accelerometer (Optimeye X4, Catapult Innovations, Scoresby, Victoria). PlayerLoad™ is a modified vector magnitude and is expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three axes (X, Y, and Z) and divided by 100. PlayerLoad™ data were expressed in arbitrary units (AU). The validity and reliability of PlayerLoad™ has been discussed in Section 2.3.2.

3.5.8. Individualised High-Speed Distance (Chapter 7)

In order to individualise each player's demarcated high-speed threshold, players completed the 30-15 Intermittent Fitness Test (30-15IFT). The 30-15IFT consisted of 30s shuttle runs interspersed with 15s passive recovery periods as per previously described methods (Buchheit, 2008). Speed was set at 8 $km \cdot h^{-1}$ for the initial 30s run after which speed was increased by 0.5 $km \cdot h^{-1}$ every 30s (Buchheit, 2008). Players were required to run back and forth between two lines that were set 40m apart at a speed governed by a pre-recorded beep. The speed ($km \cdot h^{-1}$) achieved by each player during the last successfully completed stage of the test was recorded as their maximal running speed and subsequently used to demarcate their high-speed threshold in the Catapult software. The mean (SD) maximal running speed achieved in the current study was 19.6 ± 0.6 $km \cdot h^{-1}$.

3.6. Internal Training Load

3.3.1. Session Rating of Perceived Exertion (sRPE) (Chapters 4 to 8)

sRPE was calculated for each player during the study period using the method of Foster et al. (2001). Exercise intensity for sRPE was determined using Borg's CR-10 scale (Borg, Ljunggren

& Ceci, 1985) which was collected ~30 min following the completion of each training session. sRPE was then multiplied by the training session duration to calculate the sRPE training load in arbitrary units (AU). Prior to each research study, all players who participated in the study had been familiarised with the RPE scale including the interpretation of exertion in relation to the verbal anchors placed within the scale.

3.3.2. iTRIMP (Chapters 4 to 6)

In order to calculate the iTRIMP measure, players undertook an incremental stage test on a motorised treadmill (Woodway ELG55, Woodway, Weil an Rhein, Germany) with resting HR measured prior to the test. Players avoided any strenuous exercise in the 24 hours preceding the tests. Resting HR (HR_{rest}) was recorded (Polar F3, Polar Electro, OY, Finland) from the subjects in a resting state prior to the first test. The resting state included lying in a supine position in a quiet room. HR_{rest} was recorded as the lowest 5 s value during the 5 min monitoring period. Players then completed a modified lactate threshold test consisting of five, 4 min sub-maximal stages commencing at an initial running speed of 7 $km \cdot h^{-1}$ with 1 min recovery between stages. A finger capillary blood lactate sample was collected during the 1 min recovery period between each submaximal stage and immediately analysed in duplicate (YSI 2300, YSI Inc., Yellow Springs, OH). Treadmill speed was increased every stage by 2 $km \cdot h^{-1}$ until a maximal speed of 15 $km \cdot h^{-1}$ was reached. Following this, a ramp protocol was used to determine an individual's maximal heart rate (HR_{max}). The ramp protocol commenced at an initial velocity of 15 $km \cdot h^{-1}$ and increased 1 $km \cdot h^{-1} \cdot min^{-1}$ until volitional fatigue. Heart rate was collected throughout the treadmill test every 5 s using Polar HR straps (T14, Polar, Oy, Finland). The highest heart rate recorded at the completion of the ramp protocol was used in order to determine the individuals HR_{max}.

The HR_{max} measured during the maximal incremental test was used as the reference value for the iTRIMP calculation. The iTRIMP was calculated for each player for each training session for the duration of the study using previously described methods (Manzi et al., 2009). Briefly, the iTRIMP is described in formula one:

$$(1)\ \text{Duration x } \Delta\text{HR x aebx}$$

Where ΔHR equals $HR_{exercise} - HR_{rest}/HR_{max}\text{-}HR_{rest}$, a and b are constants for a given player, e equals the base of the Napierian logarithms and x equals ΔHR (Akubat et al., 2012). Each player's equation was generated from their own data collected from the incremental treadmill test. Heart rate was collected during each training session every 5 s using Polar HR straps (T14, Polar, Oy, Finland) which transmitted continuously to the GPS unit (SPI Pro XII, GPSports, Fyshwick, Canberra). Raw HR data for every training session were exported from the GPS manufacturer software (TeamAMS Version 16.1, GPSports, Canberra, Australia) into dedicated software to determine individual session iTRIMP values (iTRIMP Software, Training Impulse LTD, UK).

3.3.3. Heart-rate-exertion-index (HREI) (Chapters 7 and 8)

Manufacturer derived heart rate exertion index (HREI) was used to calculate the heart rate derived internal load in Chapters 6 & 7. This method follows the same principles as Edwards (1993) but utilises arbitrary exponential weighting factors:

(Duration in Zone 1 x 1) + (Duration in Zone 2 x 1.20) + (Duration in Zone 3 x 1.50) + (Duration in Zone 4 x 2.20) + (Duration in Zone 5 x 4.50)

Where zone 1 = 50-60% of HR_{max}, zone 2 = 60-70% HR_{max}, zone 3 = 70-80% HR_{max}, Zone 4 = 80-90% HR_{max} and zone 5 = 90-100% HR_{max} (Borresen & Lambert, 2009). HR was collected during each training session (every 5s) using Polar HR straps (T31 coded, Polar, Oy, Finland) that transmitted continuously to the GPS device (Optimeye X4, Catapult Innovations, Scoresby, Victoria). This method has been used as criterion method to validate sRPE (Section 2.4.2.)

3.7. Statistical Analysis

3.7.1. Chapter 4

To account for differences in training duration between training modes, all data were divided by session duration with all data expressed per minute. Data were log transformed to reduce the bias that results due to non-uniformity error. Magnitude based inferences were used to determine the practical meaningfulness of the differences in relative external and internal load across training modes (conditioning, SSG, skills and speed) (Hopkins, Marshall & Batterham, 2009). The magnitude of change in the dependent variables were assessed using Cohen's *d* effect size (ES) statistic ± 90% confidence intervals (CI) (Cohen, 2013). ES of <0.20, 0.20-0.60, 0.61-1.19, 1.20-2.00 and >2.00 were considered trivial, small, moderate, large, and very large respectively (Cohen, 2013). The threshold difference which was considered to be practically important (smallest worthwhile difference; SWD) was set at 0.2 x between-subject standard deviation (SD). Based on 90% CI, the thresholds used to assign qualitative terms to chances were as follows: <0.5%, *most unlikely*; 0.5-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, *possibly*; 75-95% *likely*; 95-99.5%, *very likely*; >99.5%, *almost certainly*. The magnitude of difference was considered practically meaningful when the likelihood was ≥75%. Where the 90% CI crossed both the upper and lower boundaries of the SWD (ES ± 0.2), the effect was described as *unclear* (Hopkins et al., 2009).

3.7.2. Chapter 5

A number of steps were taken to determine the eligibility of sessions for analysis. In order to 'anchor' sessions that displayed trivial differences in sRPE:

1) The between-subject standard deviation of the sRPE for each training mode was calculated;
2) The between-subject standard deviation for sRPE was then multiplied by a trivial effect size of 0.2 to determine the smallest worthwhile change and a maximal eligible range for sRPE (Hopkins, 2000). For each individual, sessions that had an sRPE within the smallest worthwhile change were included in the analysis.

For example, the between-subject sRPE standard deviation for small-sided games (SSGs) was 190 AU, which when multiplied by 0.2 = 38 AU. Therefore, training sessions that fell within 38 AU for SSGs were considered to possess trivial differences and were eligible for inclusion. As a result, 3 players were eligible for analysis (age 23 ± 2.1 y, height 181.3 ± 5.1 cm, body mass 90.9 ± 9.5 kg, VO_{2peak} 63 ± 11 $mL·kg^{-1}$·min-1, ∑7 skinfolds 57.3 ± 14.8 mm; 1st grade playing experience 149 ± 47 matches). Of these 3 players, 1 played as a halfback, 1 as a hooker, and 1 as a wide-running forward. Of the training modes completed by the players, SSGs and skills had 3 or more eligible individual sessions for 2 or more players and were eligible for analysis. For each individual, we calculated the co-efficient of variation (CV%) of Body Load™, Total Number of Impacts, arbitrary high-speed distance (> 5.5 $m·s^{-1}$) and iTRIMP to investigate the within-individual variation in these measures when sRPE demonstrated trivial differences.

3.7.3. Chapter 6 & 7

Before performing PCA during the two chapters, the Pearson correlation matrix was visually inspected to determine the factorability of the data for PCA (Tabachnick & Fidell, 2007). The suitability of the data was assessed using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity. A KMO value of 0.5 or above has been suggested to show the dataset is suitable for PCA (Kaiser, 1960; Hair, Anderson, Tatham & Black, 1995). KMO (approx. chi-square) values for Chapter 6 were 0.60 (261.9), 0.62 (305.8), 0.75 (186.8), 0.64 (109.3), 0.58 (113.3) and 0.50 (72.8) for small-sided games, skills, conditioning, speed, strongman and wrestle, respectively. KMO (~chi-square) values for Chapter 7 were 0.60 (284) and 0.59 (562) for conditioning and skills training. The Bartlett test of sphericity was significant for each training mode within chapters 6 & 7 ($p < 0.001$). For both chapters (6 & 7), PCA was used to reduce the data to a set of principal components. Each principal component contains a set of variables that are correlated with each other, whilst the principal components themselves do not correlate. Consequently, each principal component provides distinct information. Within Chapter 6, five training load measures (iTRIMP, sRPE, Body Load™, high-speed distance and total impacts) and within Chapter 7, four training load measures (HREI, PlayerLoad™, high-speed distance, sRPE) were subjected to a PCA for each training mode using a prior communality estimate of less than one. The stages involved in the calculation for a PCA are (a) deletion of the mean; (b) calculation of the covariance matrix of the data; (c) determination of the eigenvalues and eigenvectors of the covariance matrix and (d) rotation of the original data onto a coordinate system spanned by the eigenvectors of the covariance matrix (Federolf et al., 2014). Rotation was performed when two principal components were retained, and with the goal of making the component loadings more easily interpretable. A principal axis method was used to extract the components. Components with an eigenvalue of less than 1 were not retained for extraction (Kaiser, 1960). This is due to the notion that any component displaying an Eigenvalue greater than 1.00 is accounting for a greater proportion of variance than that contributed by any one variable. The Statistical Package for the Social Sciences (SPSS) (Version 20.0 for Windows; SPSS Inc, Chicago, IL) was used to conduct the analysis.

4. Quantifying the external and internal loads of professional rugby league training modes: consideration for concurrent field-based training prescription

4.1. Introduction

The intermittent movement, collision and skill components of professional rugby league match play require players to have a wide range of physical (e.g. repeated effort ability, speed) and technical qualities (e.g. passing, kicking, tackling ability) to attain successful competitive performance (Johnston, Gabbett & Jenkins, 2014). To induce varied training adaptations, practitioners manipulate the fundamental training principles (e.g. intensity, duration, type) to concurrently prescribe multiple modes of training such as small-sided games (SSG), technical-tactical and speed training (Gabbett et al., 2012; Lovell et al., 2013). Both the organisation of the prescribed *external* load (i.e. the intensity and duration of distance, speed, and acceleration activity) and the resulting *internal* load are key considerations within the overall training process (Impellizzeri et al., 2005). Currently, there are numerous methods used to quantify the two constructs, including heart rate (HR; internal) (Akubat et al., 2012; Manzi et al., 2013), perceptual (session rating of perceived exertion [sRPE]; internal) (Lovell et al., 2013), global positioning systems (GPS; external), and accelerometers (external) (Lovell et al., 2013). Primarily, these methods are used to determine the total session training load which is typically summated across both chronic (> 4 weeks total) and acute (1-weekly) training periods to manage global training load prescription (Gabbett, 2016). For large proportions of the calendar year, this training prescription must also be considered within an individual's time-course of recovery following the load imposed by competition (Gabbett, Jenkins & Abernethy, 2012). As a result, ensuring the appropriate concurrent prescription of multiple modes of training poses a complex challenge for practitioners, due to the need to balance an appropriate variance in training load that maximises training induced adaptations in a wide range of physical and technical qualities whilst also minimising negative outcomes (e.g. injury incidence) (Gabbett, 2016) Whilst the acute and chronic training load is an integral aspect of the monitoring process, the data provided by the aforementioned methods can also be used to determine the relative training load of each mode by dividing the total session load for a given method by the session duration. Understanding how the relative rather than absolute training load differs across training modes and to what magnitude, will allow practitioners to periodise future absolute training load for each training mode by changing the planned session duration within a field-based training programme.

For certain training modes such as SSG, the specificity of the external load to competition is an important focus (Gabbett et al., 2012) although the understanding of the external loads of rugby league training (Gabbett et al., 2012) is limited in comparison to competition (Johnston et al., 2014a; Kempton et al., 2014; Evans et al., 2015). The most commonly reported method to represent the external load is the absolute and relative (to time) total distance (Gabbett et al., 2012). Given the intermittent nature of rugby league, total distance is also frequently categorised into arbitrary velocity zones to highlight the locomotor activities performed (Gabbett et al., 2012). However, given spatial constraints are often prescribed within training drills (Halouani et al., 2014), representing the external load solely via velocity-derived methods could underestimate the contribution of acceleration and deceleration events, particularly maximal accelerations that can occur despite low-speeds (Osgnach et al., 2010; Varley et al., 2014). As a result, the metabolic power approach has been proposed as a method which incorporates the cost of accelerated running (Osgnach et al., 2010) and has subsequently been implemented to estimate the external load of soccer training (Gaudino et al., 2014) and rugby league match play (Kempton et al., 2014). Using comparable thresholds of high metabolic-power (> 20 $W \cdot kg^{-1}$) and high-speed (> 14 $km \cdot h^{-1}$) distances during professional rugby league competition, Kempton et al. (2014) reported high-metabolic-power to estimate greater distances across all playing positions, particularly in the hit-up forwards (76% increase). This was attributed to the hit-up forwards predominant activity within congested and spatially confined areas of the field during competition. This suggests that the distances determined from metabolic power could provide additional insight into the between-mode differences in external load of professional rugby league training, particularly those that involve spatial constraints. However, research detailing both the speed- and metabolic-power-derived-threshold-distances across training modes in professional rugby league has yet to be investigated.

Whilst details of the external training load is important to understand the overall training process, the internal load governs the training induced adaptations required to succeed in competition (Impellizzeri et al., 2005). Despite the importance of the internal load to the outcomes of training (Impellizzeri et al., 2005; Akubat et al., 2012; Manzi et al., 2013) there is limited information reporting how the internal load differs across common training modes utilised in rugby league. The heart rate based individualised training impulse (iTRIMP) has previously been used to quantify the internal loads of professional and youth soccer training and has shown dose-response validity with training outcomes (e.g. changes in fitness) (Akubat et al., 2012; Manzi et al., 2013). Alternatively, sRPE is a simple, inexpensive and widely adopted perceptual based method to quantify the internal load (Lovell et al., 2013). However, the limited information detailing the mode-specific training loads in professional rugby league training has reported only absolute external loads (Gabbett et al., 2012) or perceptual (sRPE) internal training loads (Lovell et al., 2013). Therefore, the aim of the current study was to establish the magnitude of difference of time-relative external and internal training load methods across the modes of training (conditioning, SSG, skills and speed) that are used to prepare professional rugby league players for the demands of competition. A secondary aim was to compare the within-mode distances derived from metabolic-power and velocity-derived methods of external load.

4.2. Results

Table 4.1 displays the mean ± SD of the relative external (both speed- and metabolic-power) and internal (iTRIMP and sRPE) training loads for each training mode (CON, SSG, skills and speed).

Table 4.1. Mean ± standard deviation for each relative external and internal training load measure during conditioning, SSG, skills and speed training.

Training Load Measure	**Conditioning**	**SSG**	**Skills**	**Speed**
Time (min)	52 ± 22	37 ± 14	40 ± 24	28 ± 8
Speed-distance				
Total (m·min^{-1})	82 ± 12	85 ± 8	57 ± 2	55 ± 8
Walk (m·min^{-1})	26 ± 4	26 ± 4	15 ± 3	9 ± 2
Jog (m·min^{-1})	11 ± 7	8 ± 1	3 ± 1	2 ± 1
Stride (m·min^{-1})	16 ± 7	12 ± 3	4 ± 1	6 ± 4
Sprint (m·min^{-1})	8 ± 9	6 ± 3	2 ± 1	9 ± 5
High-speed-distance (m·min^{-1})	24 ± 15	18 ± 6	6 ± 2	15 ± 8
Metabolic-Power-Distance				
Equivalent Distance (m.min^{-1})	93 ± 19	100 ± 11	71 ± 4	70 ± 8
Low Power (m·min^{-1})	32 ± 4	35 ± 4	34 ± 5	31 ± 6
Intermediate Power (m·min^{-1})	25 ± 5	22 ± 3	15 ± 16	8 ± 2
High Power (m·min^{-1})	18 ± 7	17 ± 3	6 ± 1	7 ± 5
Elevated Power (m·min^{-1})	7 ± 8	5 ± 1	3 ± 0.5	4 ± 1
Maximal Power (m·min^{-1})	2 ± 1	2 ± 1	2 ± 0	4 ± 1
High-metabolic-distance (m·min^{-1})	24 ± 7	24 ± 4	10 ± 1	15 ± 7
Internal Load				
iTRIMP (AU·min^{-1})	2 ± 1	2 ± 0.4	1 ± 0.5	1 ± 0.4
sRPE (AU·min^{-1})	8 ± 0.5	7 ± 0.4	5 ± 0.7	4 ± 0.6

Abbreviations: *SSG*: small-sided games; iTRIMP: individualised training impulse; sRPE: session rating of perceived exertion.

4.2.1. Relative speed-threshold-distances

Figure 4.1 shows the magnitude (Cohen's d effect size statistic (90% CI)) and likelihood of difference in relative (m·min^{-1}) speed-threshold-distances (total; walk; jog; stride and sprint) between training modes (CON vs SSG; CON vs skills; CON vs speed; SSG vs skills; SSG vs speed; skills vs speed).

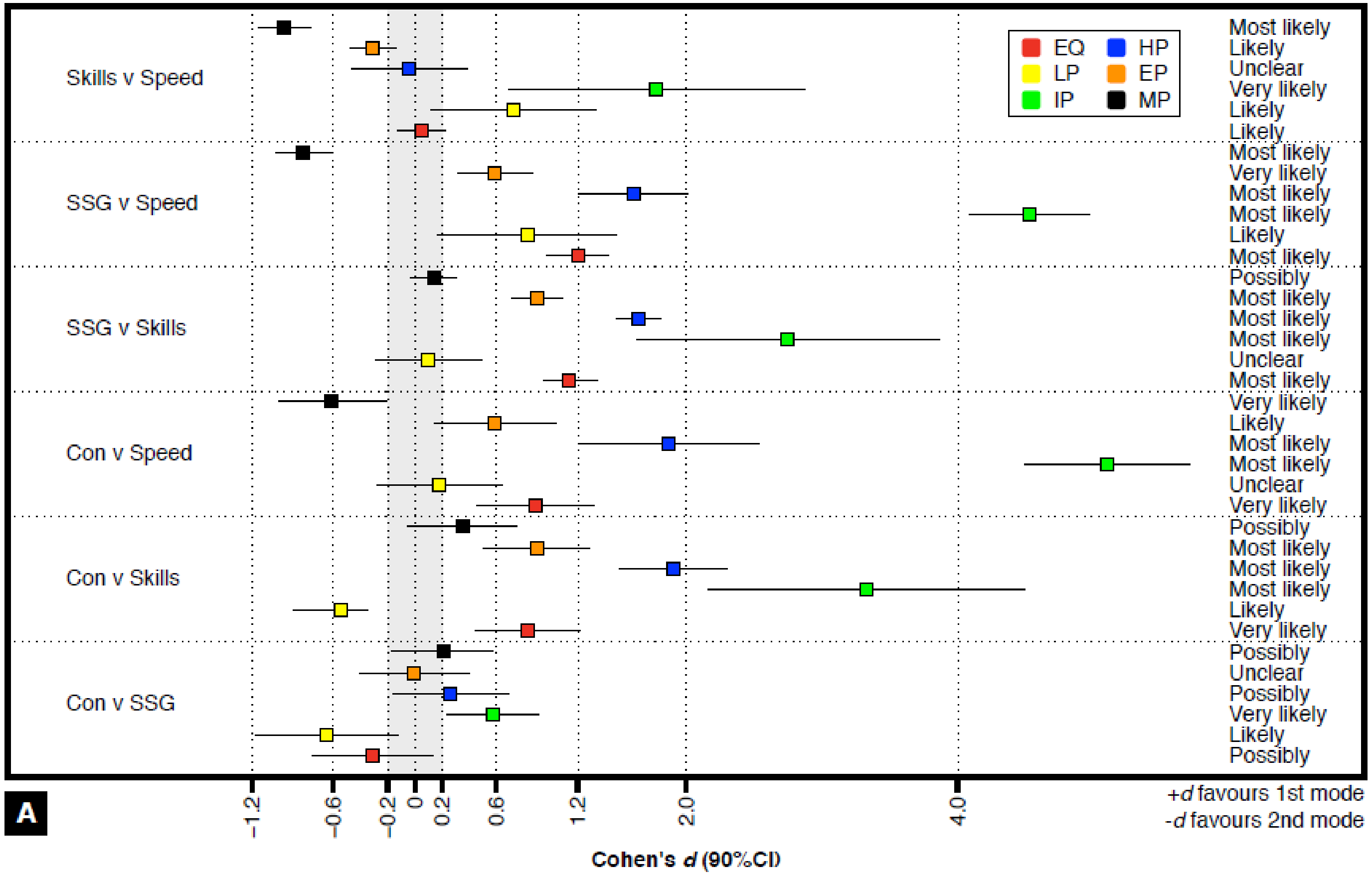


Fig 4.1. The difference in the speed-threshold-distances for each training mode comparison. Grey area represents trivial changes. Abbreviations: TD = total distance; CON = conditioning; SSG = small-sided games.

4.2.2. Relative metabolic-power-distances

Figure 4.2 shows the magnitude (Cohen's d effect size statistic [90% CI]) and likelihood of difference in relative ($m \cdot min^{-1}$) metabolic-power-derived-distances (equivalent; low-; intermediate-; high-, elevated-, and maximal-power) between training modes (CON vs SSG; CON vs skills; CON vs speed; SSG vs skills; SSG vs speed; skills vs speed).

4.2.3. Internal load

iTRIMP, was *almost certainly* greater during CON than skills (ES [90% CI]; descriptor: 2.37 [1.76 to 2.99]; very large) and speed (ES = 2.91 [2.19 to 3.64]; very large) training whilst this was *unclear* (ES [90% CI] = 0.02 [-0.45 to 0.49]; trivial) between CON and SSG. iTRIMP was *almost certainly* greater during SSG than skills (ES = 2.35 [1.75 to 2.95]; very large) and speed (ES = 2.89 [2.26 to 3.53]; very large). The difference in iTRIMP between skills and speed was *unclear* (ES = 0.54 [-0.24 to 1.32]; small).

sRPE was *likely* greater during CON vs SSG (ES = 0.61 [0.15 to 1.06]; moderate) and *almost certainly* greater during CON vs skills (ES = 6.49 [5.44 to 7.54]; very large) and speed training (ES = 8.21 [7.27 to 9.14]; very large). sRPE was *almost certainly* greater during SSG vs skills (ES = 5.89 [4.90 to 6.87]; very large) and speed training (ES = 7.60 [6.53 to 8.67]; very large). sRPE was *very likely* greater during skills vs speed (ES = 1.71 [0.24 to 3.19]; large).

4.2.4. High-Speed Distance vs High-Metabolic-Power Distance

The difference in high-speed-distance and high-metabolic-power-distance was *possibly* trivial for CON (ES [90% CI] = 0.19 [-0.19 to 0.56]; trivial) and *likely* trivial for speed training (ES = 0.04 [-0.15 to 0.23]). High-metabolic-power-distance was *almost certainly* greater than high-speed-distance during SSG (ES = 0.75 [0.48 to 1.02]; moderate) and skills (ES = 1.36 [0.99 to 1.72]; large).

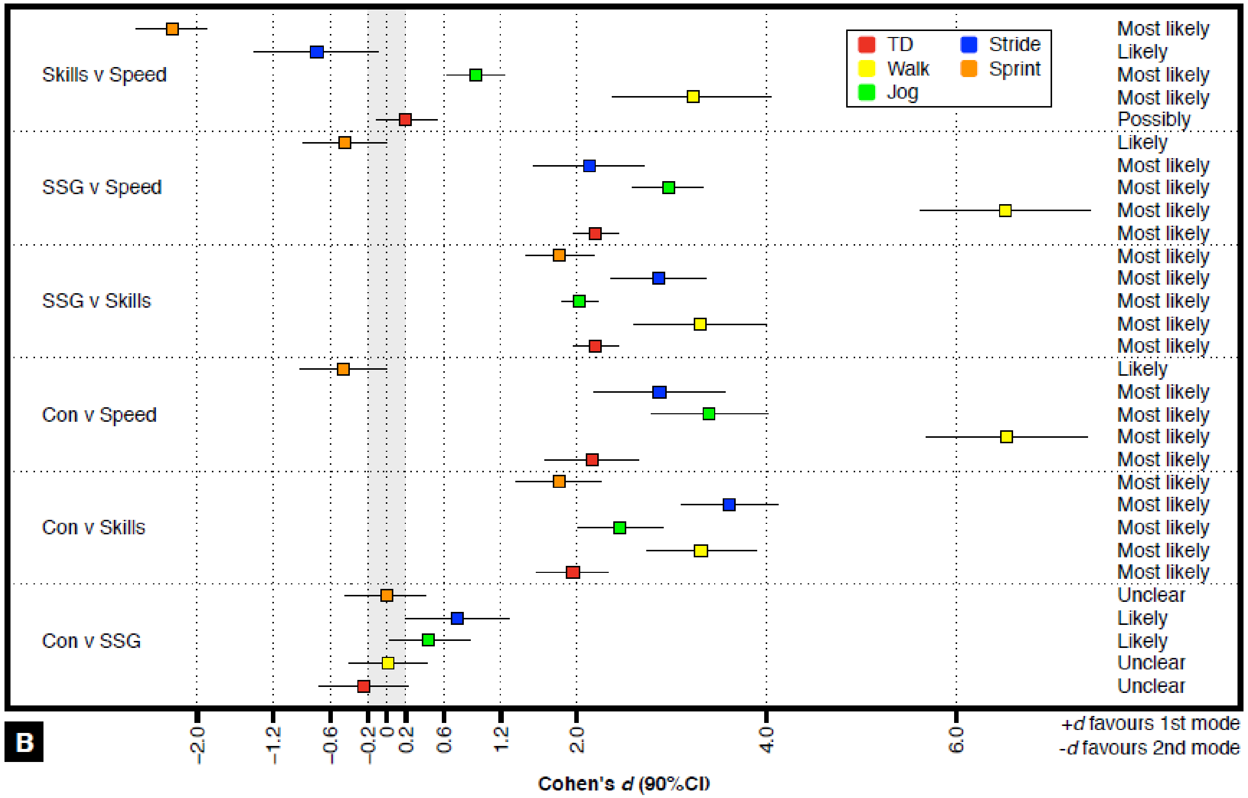


Fig 4.2. The difference in the metabolic-power derived threshold distances for each training mode comparison. Abbreviations: EQ = equivalent distance; LP = low power; IP = intermediate power; HP = high power; EP = elevated power; MP = maximal power; CON = conditioning; SSG = Small-sided games.

4.3. Discussion

The aim of the current study was to establish the magnitude of difference of time-relative external and internal training load methods across different modes of training (conditioning, SSG, skills and speed) that are used to prepare professional rugby league players for the demands of competition. A secondary aim was to investigate the within-mode differences in high-intensity distance covered as quantified above either 3.88 $m \cdot s^{-1}$ (high-speed) or 20 $W \cdot kg^{-1}$ (high-metabolic-power) for each training mode. The findings show substantial differences in the organisation of the external load per minute of training time across training modes (SSG, CON, skills and speed) which highlights the varied field-based running demands placed onto professional rugby league players as part of the overall training process. The difference in high-speed and high-metabolic-power distances within training modes suggest that the high-intensity running activity differs between modes. Players appear to cover greater proportions of high-intensity running activity accelerating during certain modes whilst maintain this activity at constant velocities in others. These differences in running demands appear to influence the magnitude of the relative internal load between modes.

4.3.1 External Training Load

The findings of the study show that professional rugby league players cover greater distances per minute of training time running at moderate speeds (1.95 to 5.49 $m \cdot s^{-1}$) and metabolic-power (10 to 34.9 $W \cdot kg^{-1}$) during CON than SSG (Figure 1 & 2). Within SSG, players were found to cover greater distances at high-metabolic-power ($\geq$ 20 $W \cdot kg^{-1}$) than high-speed ($\geq$ 5.5 $m \cdot s^{-1}$) whilst within CON trivial differences existed between the variables. As a result, players complete a greater proportion of high-intensity activity while accelerating and decelerating during SSG and maintain greater proportions of high-speed running during CON. Collectively, practitioners should consider these differences in the organisation of the external load when planning the two training modes to ensure the appropriate variety of external load prescription. The relative mean (SD) total-distance of ESL competition has been found to range from 83 (2) to 91 (2) m·min^{-1} whilst high-speed distance (> 3.88 m·s^{-1}) has ranged from 14 (2) to 16 (3) m·min^{-1}. The current study findings show that both CON and SSG expose players to similar relative-total- and greater high-speed distances than ESL competition (Evans et al., 2015).The mean high-metabolic-power distances found during SSG and CON also compare to those found in NRL match play (22 to 24 m·min^{-1}) (Kempton et al., 2014). Therefore, this supports previous research (Gabbett et al., 2012b) which suggests that SSG and CON can appropriately prepare players for the mean velocity- and metabolic-power derived running demands of competition. However, practitioners must also keep in mind that exposing players to the mean demands may increase the likelihood that players will be under-prepared for the most demanding passages of competition (Johnston et al., 2014b). Interestingly, players covered greater relative sprint distances during speed training than CON and SSG. In contrast, speed training subjected players to lower relative distances across all other speed- and metabolic-power-thresholds than SSG and CON (ES = large to very large). Therefore, despite the large increases in the vast proportion of the external load, practitioners must not assume that players are exposed to an appropriate maximal-intensity external load during SSG and CON. As a result, the findings show that speed training can provide players with the greatest near-maximal running demands per minute of training time without increasing the vast proportion of the overall relative external load and this strengthens the need to appropriately supplement speed training sessions within the overall training plan to prepare players for this intensity of locomotor activity.

When determining the difference in speed-derived methods, skills training subjected players to lower distances than CON and SSG across all thresholds (ES = large to very large). However, when incorporating accelerative activity, the magnitude of difference in the distance covered within a number of metabolic-power thresholds reduced (ES = small to large). This is supported by the large increases in the distance quantified at high-metabolic-power compared to high-speed during skills. This suggests that the magnitude of the external load increases when taking into account acceleration during skills training. Although the session aims of CON and SSG are focused predominately on the development of physical qualities, skills training focuses on enhancing passing, catching, tackling technique and defensive line shape within drills that consist of variable constraints (e.g. 10-m rule, changes in player numbers) (Gabbett, Jenkins & Abernethy, 2010). Therefore, during skills training, spatial confinements coupled with game-related congestion due to limited space between the attacking and defensive lines might lend itself to increased intermittent activity that may also increase acceleration events (Kempton et al., 2014; Delaney et al., 2016). In contrast, the session aims of CON focuses on greater periods of continuous activity and thus reduced accelerative activity. This appears to be reflected in the differences between the distances above either high-speed or high-power thresholds in the current study. Given skills training is the most frequently prescribed training mode across the season, the appropriate quantification of the external load during skills training is particularly important (Lovell et al., 2013). Therefore, to appropriately quantify the external load of skills training, practitioners should consider that adopting only speed-derived methods might underestimate the demands of this mode of training and therefore warrants supplementing accelerative activity into the distances covered to represent the external load during this mode.

4.3.2. Internal Training Load

Players likely perceived (sRPE) a greater internal load during CON than SSG with unclear differences observed in iTRIMP. A greater mean rating of perceived exertion during conditioning (8.8 ± 1.1) compared to SSG (7.2 ± 1.5) has also been reported in professional NRL players (Lovell et al., 2013). Whilst speculative, the greater perception of effort despite the absence of an increase in metabolic-power derived external load or HR based internal load could be a result of the involvement of the ball in SSG, which may lower the perception of effort despite similar external load demands to CON (Halouani et al., 2014). Further research is required to establish the mechanisms behind the increase in effort perception found during CON compared to SSG training in both current and previous studies (Lovell et al., 2013). Both CON and SSG exposed players to *almost certainly* very large increases in sRPE and iTRIMP compared to both skills and speed training. Therefore, it appears that speed training provides players with the greatest near-maximal running loads without a concomitant increase in internal load. This further strengthens the appropriateness of speed training as a supplementary training mode with an overall field-based training programme.

Although the inclusion of acceleration into the determination of the external load provides useful information to aid our understanding of rugby league training, it is important to evaluate the limitations of the metabolic-power method and the energetics approach by di Prampero et al. (2005). This centres on the assumption that the mass of the player is located at the centre of mass and therefore neglects the effect of limb motion on running (Osgnach et al., 2010). In addition, the model fails to account for the influence of air resistance or the energetic cost of eccentric work which could under represent deceleration events (Kempton et al., 2014; di Prampero et al., 2005). Finally, although the findings can be used by practitioners to ascertain the differences in external and internal load between the common training modes used to prepare players for competition, it must be acknowledged that the data were collected from only one ESL club. As a result, the magnitude of difference between the modes may be influenced by the group of players and particularly, coaching methodologies within each training mode which might not be representative of all rugby league clubs. However, the study also provides a comprehensive overview of how this data can be used in practice to evaluate the differences in the demands of a field-based training programme.

4.4. Conclusions & Practical Applications

The present study has provided a comprehensive comparison of the mean relative external and internal loads across modes of training (SSG, CON, skills, speed) in professional rugby league. The findings suggest wide differences in external and internal loads exist per minute of training time between training modes. Players cover greater distances at constant speeds during CON and greater distances accelerating during SSG and both modes subject players to greater relative external and internal loads compared to skills and speed training. However, both SSG and CON may not expose players to appropriate sprinting and maximal-power locomotor movements and therefore, speed training should be regularly supplemented to provide players with this exposure. The findings highlight the benefits of using metabolic-power variables to complement speed-derived methods for the practical implication of understanding the organisation of the external training load both within- and between-training-modes. Practitioners should therefore consider this within their evaluation of the relative field-based running demands to individualise the prescription of the running-based stimulus of the training programme. For example, based on the findings in the current study, if the training day was identified to include a requirement for an appropriate physiological stimulus after skills training, where players cover greater proportions of high-intensity activity accelerating, practitioners might consider the prescription of CON, rather than SSG, to provide players with greater proportion of exposure to high-speed rather than high-acceleration running.

- Practitioners should consider that whilst the overall external training load (e.g. total or equivalent distance per minute) can be similar between training modes, the intensity of this load can vary across types of training.
- Speed training exposes players to the greatest sprinting and maximal power running demands without an associated increase in internal load.
- Metabolic power measures of the external load appear to compliment speed-derived methods, particularly during skills and SSG training which involve randomised activity within spatial constraints.
- Practitioners can establish normative information by calculating the relative training load for each training mode and individual, which can be used to plan future training loads by multiplying the relative load by the planned session duration.

5. Within-individual variation in internal and external load measures at a given session rating of perceived exertion in professional rugby league players

5.1. Introduction

Monitoring the internal and external load is an important consideration in team sport players (Impellizzeri et al., 2005). Whilst the external load profiles the nature of the activity a player undertakes, the internal load reflects the physiological stress elicited on the athlete (Impellizzeri et al., 2005; Lovell et al., 2013). It has previously been suggested that the internal load response to a given training session is a result of stress placed on multiple physiological sub-systems (e.g. cardiorespiratory, neuromuscular and musculoskeletal) (Chiu & Barnes, 2003; Buchheit & Laursen, 2013). The degree of stress elicited on each system may vary between training sessions due to differences in the organisation of the external training load between training modes (Impellizzeri et al., 2005; Buchheit & Laursen, 2013). Therefore, a valid method of monitoring load must be sensitive to differences in stress placed on the physiological systems during all training modes in order to optimise favourable training outcomes (Impellizzeri et al., 2005). The session rating of perceived exertion (sRPE) has been proposed as a valid, simple and inexpensive perceptual method of monitoring the internal load (Lovell et al., 2013). However, the limited data describing the between-subject variability in sRPE during soccer match play has suggested low variability (Wrigley et al., 2012) despite other authors reporting high variability in measures of external load during competition in both rugby league (Kempton, Sirotic & Coutts, 2013) and soccer (Gregson, Drust, Atkinson & Salvo, 2007).

Despite this, there is a paucity of research exploring the within-individual variation in additional measures of load when a single measure demonstrates trivial differences between sessions. This is important to examine, as the implementation of a single load measure implies a capability of that method to appropriately reflect the total load imposed on athletes during training and competition. If other measures of load are demonstrating greater variability, this questions whether the actual load imposed is reflected by that individual measure. However, this is difficult to describe longitudinally, given the logical increases in external load expected at a given internal load as a result of changes in fitness following a training period. Therefore, we present a case study of three players where internal and external load measures provided additional information across multiple training sessions when sRPE demonstrate trivial differences during skills and small-sided games training in professional rugby league players.

4.3. Results

Table 5.1 displays the means (SD) of each training load measure during skills and SSGs training for the halfback, hooker and wide-running forward. Figure 5.1 and 5.2 displays the individual player training session values at a given individual sRPE for iTRIMP, Body Load™, high-speed distance and total impacts during skills and SSGs training respectively.

Table 5.1 Means (SD) of training load measures for each player for each training mode.

	Skills			SSG		
	Halfback	**Hooker**	**WRF**	**Halfback**	**Hooker**	**WRF**
Session Duration (min)	30 (0)	35 (1)	46 (1)	37 (2)	38 (2)	49 (1)
RPE (1-10)	6 (0)	6 (0)	6 (0)	7 (0)	8 (0)	7 (0)
sRPE (AU)	180 (0)	209 (8)	277 (8)	257 (11)	307 (12)	345 (4)
iTRIMP (AU)	39 (31)	24 (9)	25 (10)	97 (10)	96 (33)	119 (21)
HSD (m)	289 (171)	169 (105)	509 (226)	1024 (253)	387 (301)	719 (100)
Total Impacts (#)	1698 (964)	1888 (639)	926 (746)	2456 (211)	3915 (1563)	2299 (725)
Body Load™ (AU)	63 (58)	50 (16)	21 (12)	139 (4)	173 (29)	67 (25)

Abbreviations: WRF, wide-running forward; SSG, small-sided games; RPE, rating of perceived exertion; sRPE, session rating of perceived exertion; iTRIMP, individualised training impulse; HSD, high-speed distance.

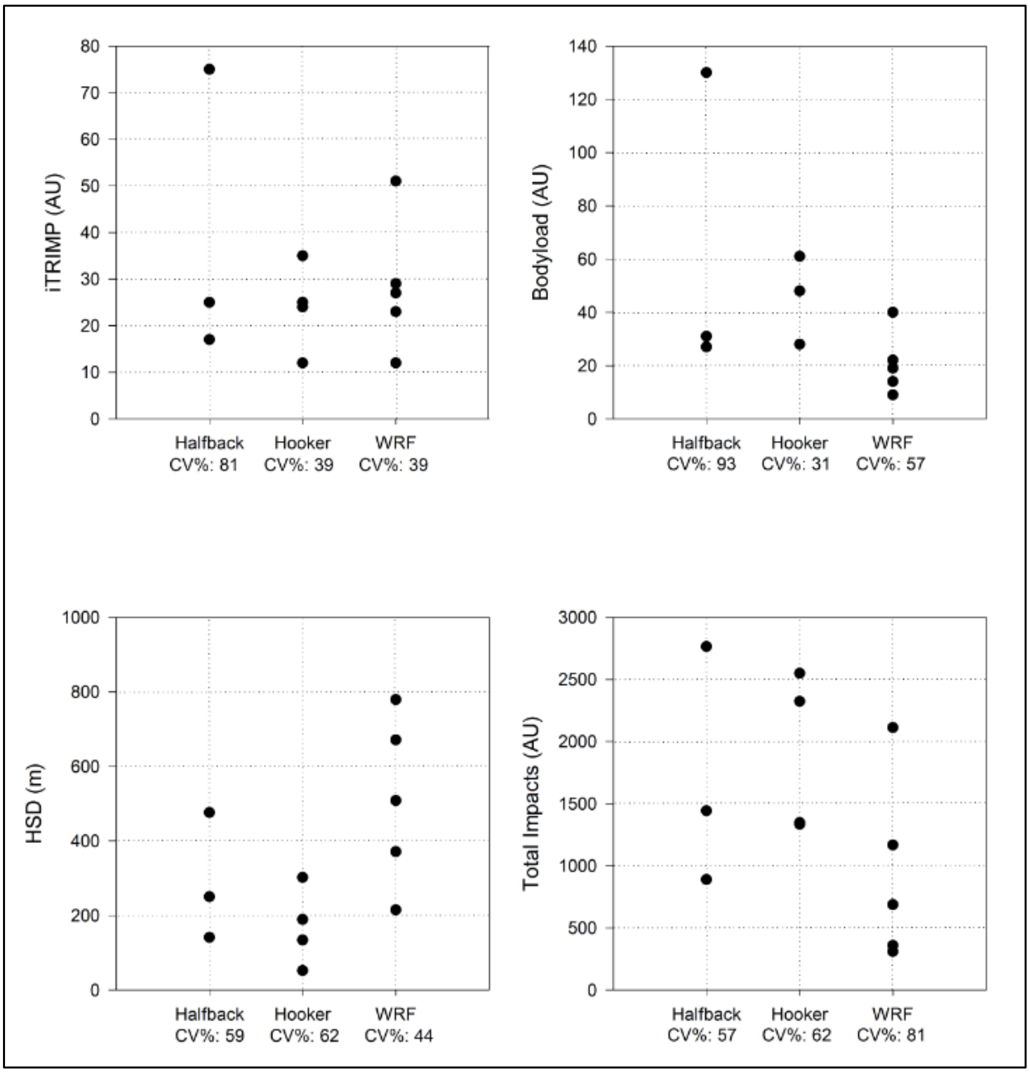


Figure 5.1. Individual eligible training load values for iTRIMP, Body Load™, high-speed distance (HSD) and total impacts for the halfback, hooker and wide-running forward (WRF) during skills training. Also showing the coefficient of variation (CV%) of the individual training load values for the halfback, hooker and WRF.

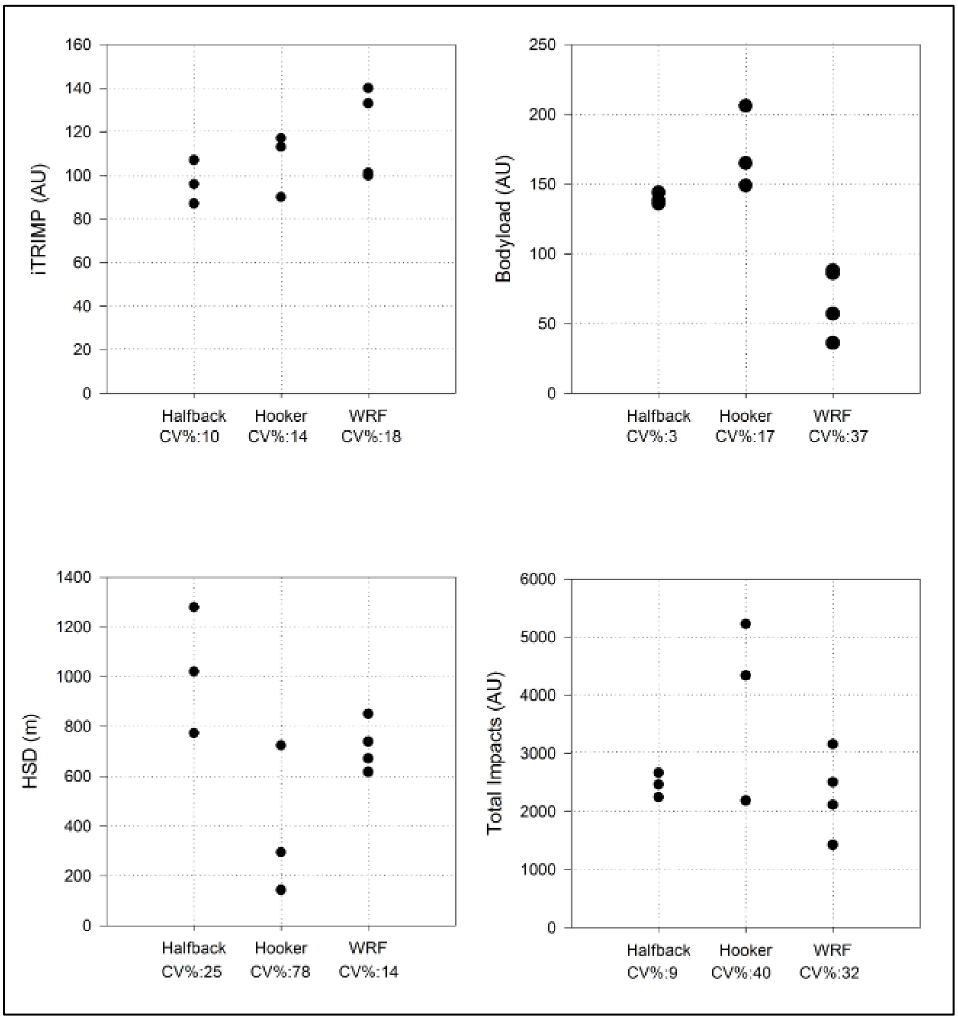


Figure 5.2. Individual eligible training load values for iTRIMP, Body Load™, high-speed distance (HSD) and total impacts for the halfback, hooker and wide-running forward (WRF) during small-sided games (SSG's) training. Also showing the coefficient of variation (CV%) of the training load measures for the halfback, hooker and WRF.

5.4. Discussion

Here we aimed to describe the within-individual variation present in measures of training load between training sessions at a given sRPE. To our knowledge, this is the first documentation of such an approach. Two interesting observations were found within the current study. The first was the within-individual variation present in additional measures of external and internal load despite the same perceptual internal load as determined by sRPE. For example, the CV% for iTRIMP ranged from 39% for the wide-running forward and hooker to 81% for the halfback during skills (Figure 5.1). Similar variation was also present in measures of external load. The second was a reduction in the magnitude of variation with additional measures of training load when comparing different training modes. For example, the range of variation in Body Load™ was reduced during SSGs (CV%: 3-37) when compared to skills training (CV%: 31-93). This reduction was also generally consistent with the other additional measures of training load. Consequently, this provides initial evidence that (1) other measures of internal and external load are providing additional information at a given internal load as determined by sRPE and (2) that the training mode influences the validity of measures of training load. It must be stated that the importance and mechanisms behind this additional information is currently speculative and requires ‘dose-response’ validity studies with a wide range of response tests (including cardiopulmonary, neuromuscular and musculoskeletal responses). However, it may be possible that sRPE provides information that better reflects the internal load on the cardiopulmonary system, given its previously reported strong relationship with heart rate and blood lactate (Alexiou & Coutts, 2008). This is reflected somewhat in the results of the current study, with lower within-individual variability observed within a heart rate-based internal load measure (iTRIMP) at a given sRPE when compared to measures of external load (high-speed distance, Body Load™ & total impacts), particularly during SSGs. However, different training session structures that have similar cardiorespiratory demands can elicit different demands on anaerobic sources (Buchheitt & Laursen, 2013) and/or neuromuscular load (Billat et al., 2001). Therefore, while the theoretical construct of internal load may hold true, questions remain as to the efficacy of using a single measure to reflect the total internal load, which may be influenced further depending on the training mode. Consequently, this could reduce the effectiveness of the decision making process in regards to individual training periodisation, influencing the management of injury risk and performance. However, the limited number of participants and session samples in this investigation limit the conclusions found and therefore further investigation is warranted.

6. Combining internal and external training load measures in professional rugby league

6.1. Introduction

Rugby league players engage in a diverse range of training modes in order to induce adaptations needed to succeed in competition (Impellizzeri et al., 2005). However, given the inter-individual variability in responses to any prescribed training session, it is imperative that sports scientists are able to utilise valid and reliable methods to monitor an individual's load during all training modes in order to optimise the training process (Impellizzeri et al., 2005). At present, there are numerous methods used to monitor both the internal and external load, including heart rate (HR) based TRIMP methods, session-RPE (sRPE) (internal training load) and microtechnologies such as GPS and accelerometers (external training load) (Lovell et al., 2013; Scott et al., 2013). However, due to the lack of a 'gold-standard' criterion, previous research has investigated load validity against other available measures of load (Lovell et al., 2013; Scott et al., 2013) or with changes in fitness measures (Manzi et al., 2013; Akubat et al., 2012). Very large associations have been reported between sRPE and Banisters TRIMP (r = 0.73) and Edward's TRIMP (r = 0.77) during in-season training of professional soccer players (Scott et al., 2013). Similar very large associations have also been found between sRPE and measures of external load including total distance (r = 0.80) and PlayerLoad™ (r = 0.84) (Scott et al., 2013). However, the validity of the criterion measures of internal load used to validate sRPE in previous studies has been questioned, as they may not reflect the individualised physiological response to high-intensity intermittent activity (Akubat et al., 2012; Manzi et al., 2013). As a result, the individualised TRIMP (iTRIMP) was developed to alleviate the limitations of previous TRIMP methods, with the iTRIMP displaying dose-response validity and sensitivity as a measure of the internal load in both youth and professional soccer players (Akubat et al., 2012; Manzi et al., 2013).

The difficulty in monitoring load is further compounded due to the wide range of training modes that rugby league players undertake, which on occasions includes collision and contact episodes

(Lovell et al., 2013). In chapter 4 of the thesis, we highlighted differences in the relative external loads between common training modes utilised in professional rugby league training, suggesting that the training modality influences the organisation of the external load that players are subjected. Despite this, there is very limited information available within the literature regarding how the training mode might influence the validity of the various load methods in rugby league. This is important to determine, as it may be possible that the load is underestimated during particular training modes. The relationship between sRPE and external load measures during various training modes in professional rugby league players has previously been described (Lovell et al., 2013). Whilst not the primary aim of that study, the training mode altered the strength of the relationships reported. For example, the association between sRPE and Body Load™ ranged from moderate ($r = 0.45$) during wrestling to large ($r = 0.64$) during skills conditioning (Lovell et al., 2013). Variation in the relationships between sRPE and other measures of load was also present amongst different training modes (Lovell et al., 2013). Further, in chapter 5 of the thesis, we highlighted large variation in additional measures of external and internal load when sRPE was held constant. This suggests that, depending on the training mode, different training load measures may provide different information attaining to the overall training process.

This is logical as training modes have differing external load structures in an attempt to produce different physiological adaptations. For example, speed sessions have extensive recovery periods due to the short-duration, maximal intensity bouts needed to stimulate adaptations that contribute to improved sprinting speed (e.g. muscle contraction velocity) (Lockie et al., 2012). This is in contrast to small-sided games, where the sessions are of a longer duration and of an intermittent nature in order to replicate the movement patterns of competition (Gabbett, Jenkins & Abernethy, 2010). The extensive rest periods found in modes such as skills and speed training have previously been suggested to reduce the perception of effort (Scott et al., 2013). Dependent on the training mode, it may be possible that training load measures could be used interchangeably. Conversely, in certain modalities a combination of load measures may be more sensitive to describing the training stress elicited. However, the influence of training mode on other measures of training load has yet to be described.

Therefore, the aim of the current study was to examine the influence of training mode on common measures of training load in professional rugby league players. In particular, we aimed to determine the structure of the interrelationships amongst measures of training load in order to define common underlying dimensions within the variables via a Principal Component Analysis (PCA). PCA is a mathematical technique used to reduce the dimensionality of any given data set which consists of a number of highly correlated variables, whilst still keeping as much of the variation in the data set as possible (Kaiser, 1960; Federolf et al., 2014). We hypothesised that the different external load structures of the various training modes will influence the strength of the variance explained by individual training load measures.

6.3. Results

A total of 716 individual training sessions were observed during the study with seventeen players providing 42 ± 13 sessions each. Table 5.1 displays the number of sessions and mean training loads for each training mode.

Table 6.1. Means ± SD of training load measures and session durations during each training modality

Mode	n	Duration (min)	iTRIMP (AU)	sRPE (AU)	BL (AU)	HSD (m)	Impacts (#)
SSG	88	37 ± 14	85 ± 72	247 ± 190	79 ± 85	479 ± 472	1835 ± 1819
Skills	263	40 ± 24	42 ± 32	182 ± 94	36 ± 33	252 ± 222	1069 ± 965
CON	170	52 ± 22	113 ± 62	441 ± 345	93 ± 73	797 ± 512	3202 ± 2490
Speed	99	28 ± 8	23 ± 18	97 ± 65	28 ± 18	232 ± 159	603 ± 400
Strongman	60	21 ± 8	53 ± 35	229 ± 81	9 ± 13	60 ± 93	391 ± 428
Wrestle	41	19 ± 8	18 ± 10	90 ± 43	11 ± 9	54 ± 77	269 ± 261

sRPE: Session rating of perceived exertion; SSG: small-sided games; CON: Conditioning; BL: Body Load™; HSD: High Speed Distance

Table 6.2, 6.3 and 6.4 displays the PCA, including eigenvalues for each principal component in each training mode, and the total variance explained by each principal component for each training mode. There was a single principal component identified for small-sided games and conditioning, whereas two principal components were identified for skills, speed, strongman, and wrestle training modes. Pearson correlations including 95% confidence intervals (CI) between the training load methods for the different training modes are also presented in Table 6.5, 6.6 and 6.7. Figure 6.1 shows the rotated component plots for the training modes in which more than one principal component was retained for extraction, including their position within the rotated space.

Table 6.2. Results of the principal-component analysis showing the eigenvalue, percentage of variance explained and cumulative percentage of variance explained by each principal component (PC) for conditioning and small sided games training modes as well as the unrotated (1 PC extracted) training load component loadings for the PC extracted (PC greater than eigenvalue-1 criterion).

	Component				
	1	2	3	4	5
Con					
Eigenvalue	2.59	0.81	0.69	0.52	0.39
% of Variance	51.76	16.12	13.80	10.44	7.88
Cumulative Variance %	51.76	67.88	81.68	92.12	100.00
Unrotated Component Loadings					
iTRIMP	0.74	-	-	-	-
sRPE	0.74	-	-	-	-
Body Load™	0.68	-	-	-	-
HSD	0.72	-	-	-	-
Impacts	0.71	-	-	-	-
SSG					
Eigenvalue	3.42	0.62	0.52	0.35	0.09
% of Variance	68.44	12.36	10.43	6.89	1.86
Cumulative Variance %	68.44	80.80	91.23	98.13	100.00
Unrotated Component Loadings					
iTRIMP	0.79	-	-	-	-
sRPE	0.86	-	-	-	-
Body Load™	0.79	-	-	-	-
HSD	0.84	-	-	-	-
Impacts	0.85	-	-	-	-

Abbreviations: Con, conditioning; iTRIMP, individualised training impulse; sRPE, session rating of perceived exertion; HSD, high-speed distance.

Table 6.3. Results of the principal-component analysis showing the eigenvalue, percentage of variance explained and cumulative percentage of variance explained by each principal component (PC) for strongman and skills training modes as well as the rotated (> 1 PC extracted) training load component loadings for each PC extracted (PC greater than eigenvalue-1 criterion).

	Component				
	1	2	3	4	5
Strongman					
Eigenvalue	2.37	1.21	0.85	0.30	0.17
% of Variance	47.49	24.20	19.09	5.91	3.32
Cumulative Variance %	47.49	71.68	90.77	96.68	100.00
Rotated Component Loadings					
iTRIMP	0.92	-	-	-	-
sRPE	0.92	-	-	-	-
Body Load™	-	0.82	-	-	-
HSD	-	-	-	-	-
Impacts	-	0.89	-	-	-
Skills					
Eigenvalue	2.38	1.03	0.70	0.58	0.31
% of Variance	47.60	20.71	13.99	11.55	6.16
Cumulative Variance %	47.60	68.31	82.29	93.84	100.00
Rotated Component Loadings					
iTRIMP	-	0.88	-	-	-
sRPE	-	0.77	-	-	-
Body Load™	0.86	-	-	-	-
HSD	0.49	0.46	-	-	-
Impacts	0.87	-	-	-	-

Abbreviations: Con, conditioning; iTRIMP, individualised training impulse; sRPE, session rating of perceived exertion; HSD, high-speed distance.

Table 6.4. Results of the principal-component analysis showing the eigenvalue, percentage of variance explained and cumulative percentage of variance explained by each principal component (PC) for speed and wrestle training modes as well as the rotated (> 1 PC extracted) training load component loadings for each PC extracted (PC greater than eigenvalue-1 criterion).

	Component				
	1	2	3	4	5
Speed					
Eigenvalue	2.32	1.02	0.86	0.48	0.33
% of Variance	46.38	20.34	17.16	9.51	6.62
Cumulative Variance %	46.38	66.72	83.88	93.39	100.00
Rotated Component Loadings					
iTRIMP	0.82	-	-	-	-
sRPE	0.86	-	-	-	-
Body Load™	0.50	0.65	-	-	-
HSD	-	0.85	-	-	-
Impacts	0.50	0.45	-	-	-
Wrestle					
Eigenvalue	2.21	1.31	0.93	0.42	0.13
% of Variance	44.28	26.26	18.51	8.42	2.53
Cumulative Variance %	44.28	70.54	89.05	97.47	100.00
Rotated Component Loadings					
iTRIMP	-	0.88	-	-	-
sRPE	0.42	0.76	-	-	-
Body Load™	0.94	-	-	-	-
HSD	0.44	-	-	-	-
Impacts	0.88	-	-	-	-

Abbreviations: Con, conditioning; iTRIMP, individualised training impulse; sRPE, session rating of perceived exertion; HSD, high-speed distance.

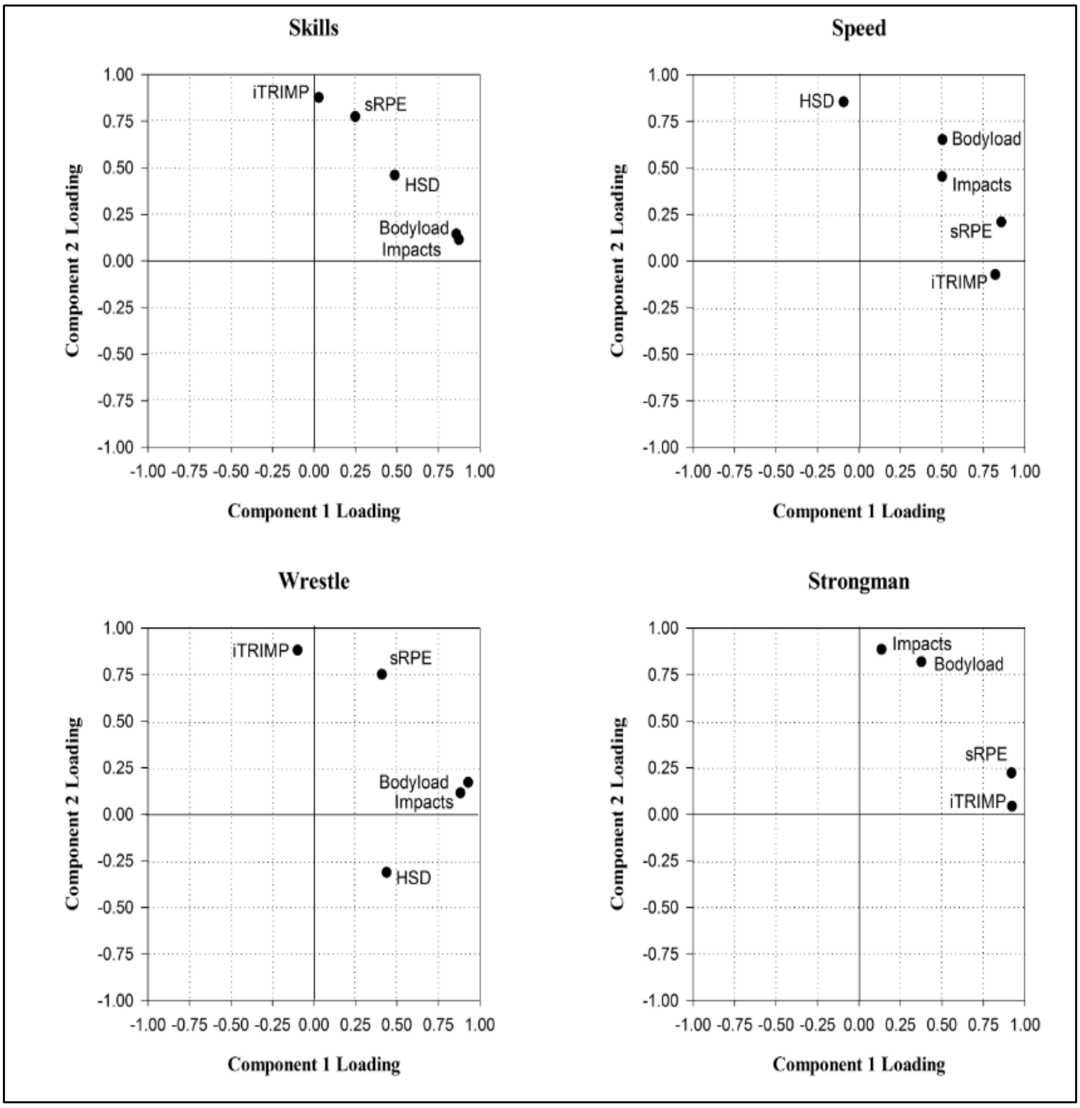


Figure 6.1. Rotated component plots of the training modes where more than 1 principal component was retained for extraction. Abbreviations: HSD, high-speed distance; sRPE, session rating of perceived exertion; iTRIMP, individualised training impulse.

Table 6.5. Pearson's product-moment coefficients for each training load measure during small-sided games and conditioning training. Includes 95% Confidence Intervals [CI] for each significant correlation.

	iTRIMP	**sRPE**	**Bodyload™**	**HSD**	**Impacts**
SSG					
iTRIMP	1.00	0.66^{***L}	0.62^{***L}	0.52^{***L}	0.50^{***L}
		[0.52-0.76]	[0.47-0.73]	[0.35-0.66]	[0.32-0.64]
sRPE	-	1.00	0.43^{***M}	0.75^{***VL}	0.70^{***VL}
			[0.24-0.59]	[0.64-0.83]	[0.57-0.79]
Body Load™	-	-	1.00	0.57^{***L}	0.69^{***L}
				[0.41-0.70]	[0.56-0.79]
HSD	-	-	-	1.00	0.61^{***L}
					[0.46-0.73]
Impacts	-	-	-	-	1.00
Conditioning					
iTRIMP	1.00	0.54^{***L}	0.62^{***L}	0.44^{***M}	0.33^{***M}
		[0.42-0.64]	[0.52-0.70]	[0.31-0.55]	[0.19-0.46]
sRPE	-	1.00	0.28^{***S}	0.34^{***M}	0.34^{***M}
			[0.14-0.41]	[0.20-0.47]	[0.20-0.47]
Body Load™	-	-	1.00	0.45^{***M}	0.41^{***M}
				[0.32-0.56]	[0.28-0.53]
HSD	-	-	-	1.00	0.37^{***M}
					[0.23-0.49]
Impacts	-	-	-	-	1.00

* Significant at 0.05 level ** Significant at 0.001 level *** Significant at 0.0001 level
Hopkins (2002) qualitative correlation coefficient descriptors: T: trivial (0-0.09), S: small (0.1-0.29), M: moderate (0.3-0.49), L: large (0.7-0.89), VL: very large (0.9-0.99).
Abbreviations: iTRIMP, individualised training impulse; HSD, high-speed distance; SSG, small-sided games.

Table 6.6. Pearson's product-moment coefficients for each training load measure during skills and speed training. Includes 95% Confidence Intervals [CI] for each significant correlation.

	iTRIMP	**sRPE**	**Bodyload™**	**HSD**	**Impacts**
Skills					
iTRIMP	1.00	0.47***M [0.37-0.56]	0.26**S [0.14-0.37]	0.30**M [0.19-0.41]	0.14*S [0.02-0.26]
sRPE	-	1.00	0.24***S [0.12-0.35]	0.32***M [0.21-0.42]	0.38***M [0.27-0.48]
Body Load™	-	-	1.00	0.38***M [0.27-0.48]	0.61***L [0.53-0.68]
HSD	-	-	-	1.00	0.32***M [0.21-0.42]
Impacts	-	-	-	-	1.00
Speed					
iTRIMP	1.00	0.58***L [0.43-0.70]	0.31**M [0.12-0.48]	0.08T -	0.15S [0.19-0.46]
sRPE	-	1.00	0.46***M [0.29-0.60]	0.16S -	0.46***M [0.29-0.60]
Body Load™	-	-	1.00	0.45***M [0.32-0.56]	0.41***M [0.28-0.53]
HSD	-	-	-	1.00	0.12S
Impacts	-	-	-	-	1.00

* Significant at 0.05 level ** Significant at 0.001 level *** Significant at 0.0001 level

Hopkins (2002) qualitative correlation coefficient descriptors: T: trivial (0-0.09), S: small (0.1-0.29), M: moderate (0.3-0.49), L: large (0.7-0.89), VL: very large (0.9-0.99). Abbreviations: iTRIMP, individualised training impulse; HSD, high-speed distance.

Table 6.7. Pearson's product-moment coefficients for each training load measure during each mode. Includes 95% Confidence Intervals [CI] for each significant correlation.

	iTRIMP	**sRPE**	**Bodyload™**	**HSD**	**Impacts**
Strongman					
iTRIMP	1.00	0.81***^{VL} [0.70-0.88]	0.32*^{M} [0.07-0.53]	0.02^{T} -	0.13^{S} -
sRPE	-	1.00	0.48***^{M} [0.26-0.65]	0.06^{T} -	0.29*^{S} [0.04-0.51]
Body Load™	-	-	1.00	-0.55^{L} -	0.68***^{L} [0.51-0.80]
HSD	-	-	-	1.00	-0.66^{L} -
Impacts	-	-	-	-	1.00
Wrestle					
iTRIMP	1.00	0.47**^{M} [0.19-0.68]	0.09^{T} -	-0.09^{T} -	-0.02^{T} -
sRPE	-	1.00	0.45*^{M} [0.17-0.67]	0.04^{T} -	0.35*^{M} [0.05-0.59]
Body Load™	-	-	1.00	0.28*^{S} [-0.03-0.54]	0.83***^{VL} [0.70-0.91]
HSD	-	-	-	1.00	0.06^{T}
Impacts	-	-	-	-	1.00

* Significant at 0.05 level ** Significant at 0.001 level *** Significant at 0.0001 level Hopkins (2002) qualitative correlation coefficient descriptors: T: trivial (0-0.09), S: small (0.1-0.29), M: moderate (0.3-0.49), L: large (0.7-0.89), VL: very large (0.9-0.99). Abbreviations: iTRIMP, individualised training impulse; HSD, high-speed distance.

6.4. Discussion

The primary finding of the current study is the identification of more than one principal component for skills, speed, wrestle, and strongman training. For those training modes where two principal components were identified, the component loadings appear to align themselves with either internal load measures or external load measures. For example, during skills training, the highest loadings for the first principal component are for Body Load™ (0.86) and total impacts (0.87), both external load measures, whereas the highest loadings for the second principal component are for iTRIMP (0.88) and sRPE (0.77), both internal load measures. However, when looking between training modes it can be seen that the first principal component, which explains the greatest amount of variance, alternates between internal and external load measures depending on the type of training. For example, during skills training, the greatest variation is explained by the external load measures Body Load™ and total impacts. However, during speed training, the greatest amount of variance is explained by the internal measures of sRPE and iTRIMP. These results provide initial evidence that (1) a combination of internal and external training load measures explains a greater proportion of the variance observed than either internal or external measures on their own, and (2) that neither the internal or external measures of load consistently explain the greatest amount of variance across modes of training. As a result, the use of one internal or external training load measure during certain modes of training may underestimate the actual training dose. Moreover, the training load measure that explains the greatest amount of variance in one training mode may not do so in another training mode.

The presence of two principal components during skills training is potentially an important finding, as skills training can comprise almost half of the training sessions during the competitive season (Lovell et al., 2013). Previous research (Lovell et al., 2013) has reported smaller correlations between sRPE and other measures of training load during skills training when compared to small-sided games and conditioning. Therefore, the use of one load measure within this training mode could potentially lead to a substantial underestimation of the training dose, which could impact on team performance and injury risk. Whilst the mechanisms behind the present findings are currently speculative, during skills training players spend a large proportion of the time standing or moving at low speeds due to an increase in coaching instruction, tactical focus and waiting to perform the drills interspersed with very short-duration but maximal-intensity locomotor movements. This could potentially lead to a reduction in the perception of effort or delay in HR response (Scott et al., 2013). Therefore, the use of at least one external load measure and one internal load measure may be a better approach when monitoring the training load during skills sessions.

The presence of a single principal component and large component loadings for all five training load measures during small-sided games and conditioning suggests that these training load measures are providing similar information. This is supported by the large within-individual correlations between sRPE and all measures of load during small-sided games and conditioning reported in previous research (Lovell et al., 2013). The external load structures of training modes such as small-sided games involve much higher intensity periods (15.5 PlayerLoad™·min^{-1}) compared to open skills training (10.5 PlayerLoad™·min^{-1}) (Boyd et al., 2013). The findings by Boyd et al., (2013) have been confirmed in chapter 3 of the thesis. Therefore, during small-sided games and conditioning there is a prolonged external load component due to the intermittent nature of the activity, which involves a high number of accelerations and decelerations with an increased frequency and a greater magnitude of distance covered at high-speed (Boyd et al., 2013) (Chapter 3). This ultimately leads to a similarly high internal load response (Impellizzeri, et al., 2005). Logically therefore, whether the dose is high or low, the load measures respond in a similar way and account for a similar amount of the variance explained by the single principal component. Although the current study has found that in some training modes there is a single principal component and therefore training load measures might be used interchangeably, it has previously been suggested that only measures that relate to changes in fitness or performance should be utilised (Manzi et al., 2009; Akubat et al., 2012). Consequently, further research is required to establish the dose-response relationship of a combination of external and internal load measures for the individual training modes. Such an approach may elucidate how training load measures could be combined in both research and applied work, which would allow a greater proportion of the variance to be accounted for when compared to the use of a single training load measure. Finally, although previous research suggests that tri-axial accelerometers in general show acceptable reliability (Boyd, Ball & Aughey, 2011), further research is required to examine the reliability of the accelerometer and derived measures of Body Load™ and total impacts as used within the current study.

6.5. Conclusions & Practical Applications

The current study has shown that for skills, speed, wrestle, and strongman training there was more than one principal component identified, suggesting that a combination of both internal and external training load measures are required to maximise the variance explained. During small-sided games and conditioning there was only a single principal component identified which suggests training load measures could be used interchangeably. However, the dose-response relationship with changes in fitness or performance for the combined internal and external training load measures needs to be determined in future studies.

- Training mode should be considered when deciding on the training load measure used.
- For small-sided games and conditioning training it appears that training load measures could be used interchangeably.
- For skills, speed, wrestle, and strongman training a combination of internal and external training load measures should be considered.

7. The effect of training mode on training load dimensionality in professional rugby league

6.1. Introduction

The demands of professional rugby league require players to possess a wide range of physical qualities (Gabbett, Stein, Kemp, & Lorenzen, 2013). As a result, rugby league players are subjected to a variety of training modalities, ranging from traditional conditioning to skills based training (Lovell et al., 2013). Training modes are designed to elicit varying magnitudes of load onto the physiological sub-systems (e.g. cardiorespiratory, neuromuscular and musculoskeletal) in order to develop the physical qualities needed to succeed in competition (Buchheit & Laursen, 2013). However, given the inter-individual variability in internal load response to a prescribed external load (Impellizzeri et al., 2005), and its influence on the outcomes of training (Akubat et al., 2012; Colby et al., 2014), it is crucial that practitioners' are able to utilise valid and reliable methods to monitor the loads placed on rugby league players across all training modes to optimise periodisation (Impellizzeri et al., 2005).

There are numerous technologies and methods used to quantify the internal and external training load including heart rate (HR) based (Lovell et al., 2013; Akubat et al., 2012), perceptual based (session rating of perceived exertion [sRPE]) (Lovell et al., 2013), global positioning systems (GPS) and accelerometer based technologies (Lovell et al., 2013; Colby et al., 2014). Within those areas of load quantification, there is a variety of methods used. For example, the use of HR to quantify the internal load has ranged from Banisters' TRIMP (Lovell et al., 2013) to the individualised TRIMP (iTRIMP) (Akubat et al., 2012; Weaving et al., 2014) whilst the determination of high-speed- distance has ranged from arbitrary (Lovell et al., 2013; Weaving et al., 2014) to individualised methods (Abt & Lovell, 2009) derived from 5Hz (Gabbett et al., 2012), 5Hz with 15Hz interpolation (Lovell et al., 2013) and 10Hz (Rampinini et al., 2015) GPS sampling frequencies. However, due to the absence of a "gold standard" criterion measure, previous research has investigated the validity of measures to quantify training load by correlating them against other available measures of training load (Impellizzeri et al., 2004; Alexiou & Coutts, 2008; Lovell et al., 2013). These investigations have has also included pooled data from various modes of training (Impellizzeri et al., 2004). For example, within individual correlations between sRPE and Edward's TRIMP have ranged from r = 0.54 [95% CL: 0.14 to 0.86] to 0.78 [0.45 to 0.92] (Impellizzeri et al., 2004). Despite statistically significant relationships being identified, the wide confidence intervals demonstrate the imprecision and therefore uncertainty in these relationships. Criticisms have also been levied against the methods used as criterion measures of training load as they may not reflect the individualised physiological response to high-intensity intermittent activity (Abt & Lovell, 2009) or have so far shown a lack of dose-response validity with training outcomes (i.e. changes in performance or fitness) (Akubat et al., 2012). As a result, the validity of individual measures of training load remains unclear. Further, although the relationships derived from pooled training mode data may provide evidence of global training load validity, those same relationships may be altered when taking into account individual training modes that are designed by strength and conditioning coaches and sports scientists to elicit varying demands/adaptations on the various physiological systems (Buchheit & Laursen, 2013). This is an important area to consider, as the actual training load may be underestimated during particular training modes, which could influence the optimal planning of an individual's training process and associated training outcomes such as injury risk and performance (Impellizzeri et al., 2005; Colby et al., 2014).

In our previous study (Chapter 6), we examined the influence of training mode on measures of external and internal training load in professional rugby league players over a chronic period of training (two 12-week pre-season periods). We reported that a combination of internal load (iTRIMP, sRPE) and external load (Body Load™, total impacts and high-speed distance) explained a greater proportion of the variance during certain training modes (skills, speed, strongman and wrestle) when compared to either internal or external load measures alone. Moreover, the training load measures contributing to each principal component changed depending on the training mode. For example, during skills training the external load measures explained 48% of the variance with internal load measures explaining a further 20%. However, during speed training it was the opposite, with internal load measures explaining 46% of the variance and external load measures explaining a further 21%. This strongly suggests that a single external or internal load measure is unable to capture all training-related stress across all training types. Alterations in the strength of the relationships between training load measures have also been shown in previous studies (Lovell et al., 2013).

Using a single method of quantifying the training load may therefore be suboptimal in reflecting the full demands placed on the various physiological systems during certain training modes. Depending on the training mode, it may be possible that training load measures could be utilised interchangeably. Equally, in other training modes a combination of load measures may be more sensitive in highlighting the training stress elicited. However, it is possible that factors such as differences in GPS sampling frequency, and its influence on the validity and reliability of high-speed movements (Johnston et al., 2014; Rampinini et al., 2015), differences in accelerometer reliability and validity (Boyd et al., 2011; Kelly et al., 2015), players, coaching philosophies and team periodisation could all influence the conclusions drawn. As a result, due to the paucity of current information available detailing the influence of training mode on the validity of measures of both the external and internal training load, plus the wide range of variables and technologies used to quantify both theoretical constructs, a replication study is warranted (Ioannidis, 2005; Bishop, 2008).

The aim of the current study was to replicate the aims of our previous study in chapter 6 of the thesis, whilst using different but commonly utilised methods to represent either the external or internal training load, together with a shorter training period, and with players competing at a different standard of competition. For the current study, we focused on two of the most frequently utilised training modes in rugby league (skills and traditional conditioning) and aimed to determine the structure of the interrelationships among measures of training load to define common underlying dimensions in the variables via a principal component analysis (PCA). PCA is a mathematical technique used to reduce the dimensionality of any given data set that consists of a number of highly correlated variables, while still keeping as much of the variation in the data set as possible (Kaiser, 1960; Federolf, Reid, Gilgien, Haugen, & Smith, 2014).We hypothesised that the different external load structures of the skills and conditioning training would influence the strength of the variance explained by individual training load measures.

7.3. Results

A total of 640 individual training sessions were observed during the study with 23 players providing 28 ± 5 sessions each. Table 7.1 highlights the number of sessions and mean training loads for conditioning and skills training.

Table 7.1. Training-load measures and session durations during each training mode, mean ± SD

Training Mode	n	Duration	HREI	sRPE	PlayerLoad™	HSD
Skills	448	40 ± 24	100 ± 69	309 ± 183	351 ± 150	202 ± 265
Conditioning	192	25 ± 12	59 ± 32	183 ± 345	232 ± 81	599 ± 455

Abbreviations: sRPE, session rating of perceived exertion; HREI, heart rate exertion index; HSD, high-speed distance.

Table 7.2 displays the PCA, including eigenvalues for each principal component during skills and conditioning training and the total variance explained by each principal component for each training mode. There was a single principal component identified for skills training and two principal components identified for conditioning training, explaining 56.62% and 85.44% of the variance respectively. Pearson correlations including 95% confidence intervals between the training load methods for the two training modes are presented in Table 7.3.

Table 7.2. Results of the PCA, showing the Eigenvalue, percentage (%) of variance explained and the cumulative % of variance explained by each Principal Component (PC) for skills and conditioning. Also showing the unrotated (1 PC extracted) or rotated (> 1 PC extracted) training load component loadings for each PC that were extracted (PC greater than the eigenvalue-one criterion).

	1	2	3	4
Skills				
Eigenvalue	2.27	0.80	0.72	0.22
% of Variance	56.62	20.03	17.92	5.42
Cumulative Variance %	56.62	76.66	94.58	100.00
Unrotated Component Loadings				
HREI	0.78	-	-	-
sRPE	0.66	-	-	-
Playerload	0.92	-	-	-
HSD	0.62	-	-	-
Conditioning				
Eigenvalue	2.24	1.18	0.32	0.27
% of Variance	56.01	29.42	7.90	6.66
Cumulative Variance %	56.01	85.44	93.34	100.00
Rotated Component Loadings				
HREI	0.89	-	-	-
sRPE	0.90	-	-	-
PlayerLoad™	0.80	0.44	-	-
HSD		0.96	-	-

Abbreviations: HREI, heart rate exertion index; sRPE, session rating of perceived exertion; HSD, high-speed distance

Table 7.3. Pearson's product-moment coefficients for each training load measure during skills and conditioning training. Includes 95% Confidence Intervals (CI) for each significant correlation.

	HREI	**95% CI**	**sRPE**	**95% CI**	**PlayerLoad™**	**95% CI**	**HSD**	**95% CI**
Skills								
HREI	1.00	-	0.30***^{M}	[0.23-0.4]	0.72***^{L}	[0.67-0.76]	0.22***^{S}	[0.13-0.31]
sRPE	-	-	1.00	-	0.47***^{M}	[0.39-0.54]	0.27***^{S}	[0.18-0.35]
PlayerLoad™	-	-	-	-	1.00	-	0.47***^{M}	[0.39-0.54]
HSD	-	-	-	-	-	-	1.00	-
Conditioning								
HREI	1.00	-	0.73***^{L}	[0.66-0.79]	0.55***^{L}	[0.44-0.64]	-0.19**^{S}	[-0.32 to -0.05]
sRPE	-	-	1.00	-	0.56***^{L}	[0.45-0.65]	-0.21**^{S}	[-0.34 to -0.07]
PlayerLoad™	-	-	-	-	1.00	-	0.24***^{S}	[0.1-0.37]
HSD	-	-	-	-	-	-	1.00	-
Impacts	-	-	-	-	-	-	-	-

Hopkins (2002) qualitative correlation coefficient descriptors: T: trivial (0-0.09), S: small (0.1-0.29), M: moderate (0.3-0.49), L: large (0.7-0.89), VL: very large (0.9-0.99). * Significant at 0.05 level ** Significant at 0.001 level *** Significant at 0.0001 level

7.4. Discussion

The main finding of the study is the identification of multiple dimensions (two principal components) in one of the modes of training, thereby confirming the results of our previous study (Chapter 6: Weaving et al., 2014). In the current study, we identified one and two principal components during skills and conditioning training, respectively. This finding provides further evidence that the training mode influences the variance explained by individual measures used to represent the training load in professional rugby league players. More specifically, within both the current and previous findings (Chapter 5: Weaving et al., 2014), it is important to note that in almost every instance where training modes displayed multiple principal components, the component loadings for each principal component included training load measures derived from the same external or internal load category. For example, in our previous study (Weaving et al., 2014) we identified two principal components in skills training. The first principal component explaining 48% of the variance included Body Load™, high-speed distance, and impacts – all measures of external load. The second principal component explaining an additional 20% of the variance included iTRIMP and sRPE – both measures of internal load. Likewise, in the current study we identified two principal components for conditioning training. The first principal component loaded most heavily on HREI and sRPE – both measures of internal load, with the second principal component including PlayerLoad™ and HSD – both measures of external load. Therefore, it appears the implementation of one internal or external training load measure during certain modes of training could potentially underestimate the actual training dose elicited and as a result, the implementation of multiple measures of training load is important to capture as much information as possible regarding the training load imposed on players. It appears that measures of both external and internal training load are needed but individual measures representing the same external or internal load category could be used interchangeably. Although both external and internal measures appear to be required, the importance placed on one or the other appears to be influenced by the training mode, such that in some modes measures of internal load account for greater variance yet in other training modes it is the measures of external load that account for greater variance.

Consequently, we cannot state that either internal measures or external measures are a more valid quantification of training load, only that measures from both categories appear to capture different aspects of training and are therefore required.

Within the current study, the presence of a single principal component during skills training suggests that the training load measures are providing similar information and could be used interchangeably. Conversely, the presence of two principal components during conditioning training suggests that the training load measures are providing different information and the implementation of a single measure of training load may be suboptimal in reflecting the actual training dose. However, in terms of the number of principal components extracted within specific training modes, the identification of one principal component during conditioning training and two principal components during skills training conflicts with our previous findings (Weaving et al., 2014). In our previous study (Weaving et al., 2014) we identified a single principal component during conditioning training, suggesting that the training load measures utilised were providing similar information and could be used interchangeably. However, in the current study we identified two principal components during conditioning training. The first principal component loaded mostly on measures of internal load (HREI, sRPE) with the second principal component loading on measures of external load (HSD, PlayerLoad™). In the current study, high-speed distance, individualised based upon the maximal speed achieved during the $30\text{-}15_{IFT}$, explained additional variance during conditioning as shown by its high factor loading on the second principal component. In our previous study (Weaving et al., 2014), an arbitrary (>15km·h^{-1}) based determination of high-speed distance was unable to account for additional variance, as only a single principal component was identified during conditioning. As the major aim of conditioning training is to provide a high-intensity running stimulus to develop a player's aerobic fitness, the use of an individualised high-speed threshold during conditioning training appears to provide additional information of the high-speed external demands during this training mode. Differences in GPS sampling rate could have also influenced the findings, as greater validity of high-speed running quantification has been reported for the 10Hz MinimaxX GPS devices when compared to the GPSports SPI ProX 15Hz devices (Johnston et al., 2014). Previously (Chapter 5: Weaving et al., 2014), we identified two principal components during skills training. In particular, we reported that external training load measures (Body Load™, total impacts, high-speed distance) accounted for the greatest proportion of the total variance (48%) with internal load measures (iTRIMP, sRPE) contributing an additional 21%. However, in the current study, internal load measures of HREI and sRPE did not explain any additional variance during skills training. Differences in the methods used to quantify the internal load via heart rate data could explain some of the discrepancies between the results. The use of arbitrary heart rate zones and arbitrary weightings utilised within the HREI method within the current study has previously been criticised (Akubat et al., 2012) as they do not reflect the individualised response to exercise (Abt & Lovell, 2009). The iTRIMP method is based on each individual's relationship between the fractional elevation in heart rate and blood lactate concentration, with each individual heart rate data point recorded during each training bout weighted according to this relationship. This method has previously shown dose-response validity with changes in fitness over a given training period in both endurance (Manzi, Iellamo, Impellizzeri, & D'Ottavio, 2009) and team sports players (Akubat et al., 2012; Manzi, Bovenzi, Impellizzeri, Carminati, & Castagna, 2013). Therefore, differences between arbitrary and individualised methods pertaining to the quantification of the internal load via HR-based TRIMP may explain the additional variance accounted for by the iTRIMP method in our previous study. However, given the applied nature of training load monitoring, at present, the logistical difficulties surrounding the determination of the heart rate-blood lactate relationship used within the calculation of the iTRIMP and the frequency in which this relationship is likely to change has to be considered. Furthermore, due to the variety of skill and tactical qualities needed to succeed in rugby league competition, it is possible that during skills training, a wide range of activities/drills covering a wide range of intensities may be present within this mode. As a result, by conducting this study over an acute period, there is potential for much less variation in training session structure and aims within skills training which may be a cause of the discrepancies between the two studies. Further, the differences in playing standard and coaching philosophy between the teams participating in these two studies may help to provide additional explanations for the conflicting results. As a result, given the predominance of skills training as a training mode within the periodisation of weekly training in professional rugby league (Lovell et al., 2013), further research is warranted to examine the influence of different forms of skills training on the validity of training load measures.

Despite the current and previous findings (Lovell et al., 2013; Chapter 5: Weaving et al., 2014) it has previously been suggested that in order to strengthen the validity of training load measures, only those that show a dose-response relationship with training outcomes such as changes in fitness or performance should be used (Akubat et al., 2012; Manzi et al., 2013). As a result, further research is required to establish the dose-response validity of a combination of external- and internal-load measures for each individual training mode. Ideally, this should involve a wide range of currently utilised methods to further examine the influence of training mode on the validity of measures of training load.

7.5. Conclusions & Practical Applications

The current study has shown that the training mode (conditioning and skills) influences the variation explained by measures of both the external and internal training load in professional rugby league players. The findings provide further evidence that a combination of internal and external training load measures should be considered during certain training modes in order to capture the most information relating to the training stress placed on players. Furthermore, the dose-response relationship between the individual measures and changes in fitness or performance should be established in future studies.

- Consider the influence of training mode when deciding on methods used to quantify training load.

- Consider measuring the training load using combinations of external and internal load measures.
- Consider the effect of individualisation of training load in future studies.

8. The effect of training mode on the 'dose-response' relationship between measures of load and acute changes in performance and measures of fatigue

8.1. Introduction

Rugby league players participate in numerous training modes in order to develop the wide range of physical qualities needed to succeed in competition (Meir et al., 2001; Till et al., 2013; Gabbett et al., 2012). Within each training mode, practitioners manipulate the organisation (e.g. volume and intensity) of the external training load (e.g. distances) to elicit different magnitudes of stress (internal load) on predominately the cardiorespiratory, neuromuscular and musculoskeletal subsystems (Buchheit & Laursen, 2013a; Buchheit & Laursen, 2013b). However, the inter-individual variability in response to a given training session means that practitioners must be able to call on valid methods to monitor an individual's load during all training modes to reduce the likelihood of negative training outcomes such as injury risk (Gabbett & Domrow, 2007; Rogalski et al., 2014) and to optimise the overall training process (Impellizerri et al., 2005).

Currently, numerous methods exist to represent the internal and external training load, including heart rate (HR)-based, perceptual-based (session rating of perceived exertion), global positioning systems (GPS) and accelerometer-based technology. Due to the absence of a 'gold-standard' criterion measure of training load, the examination of load validity has focused on investigating relationships with other available measures of load (Impellizzeri et al., 2004; Alexiou & Coutts, 2008; Scott et al., 2013; Lovell et al., 2013). For example, such investigations have suggested the validity of session rating of perceived exertion (sRPE) due to strong relationships with other measures of internal load such as Banister's TRIMP (Scott et al., 2013) and external load measures such as total distance and Body Load™ (Lovell et al., 2013).

However, while these associations provide useful information, criticisms around the validity of the criterion internal load measures previously used (Akubat et al., 2012) coupled with a lack of 'dose-response' investigations with training outcomes, suggests that the validity of training load methods has yet to be fully established. Given the importance of training load to the outcomes of training, establishing the dose-response relationship between measures of training load and training outcomes appears to be of greater importance to further properly validate these methods (Akubat et al., 2012; Manzi et al., 2013; Gil-Rey et al., 2015).

Previous studies have investigated the dose-response relationship between iTRIMP and chronic changes in aerobic fitness in professional youth and senior soccer players (Akubat et al., 2012; Manzi et al., 2013). Large associations between iTRIMP and changes in running speed at 2 $mM \cdot L^{-1}$ of blood lactate (r = 0.67) have been reported in professional youth soccer players (Akubat et al., 2012). Large associations have also been reported between iTRIMP and changes in VO_{2max} (r = 0.77), VO_2 at the ventilatory threshold (r = 0.78) and Yo-Yo Intermittent Recovery Test 1 performance (r = 0.69) in professional soccer players (Manzi et al., 2013). Further, despite the proposed validity of sRPE as a measure of the internal load (Impellizzeri et al., 2004; Alexiou & Coutts, 2008; Scott et al., 2013; Lovell et al., 2013), conflicting dose-response associations have been reported for training outcomes (Akubat et al., 2012; Gil-Rey, Lezaun & Los Arcos, 2015). Akubat et al. (2012) reported no significant associations between sRPE and changes in a wide range of physiological measures (e.g. Δ in speed and heart rate at the lactate threshold and at the onset of blood lactate accumulation) following 6 weeks of training in professional youth soccer players. However, Gil-Rey et al. (2015) observed most likely very large associations between differentiated sRPE (muscular [r = 0.71; 95% CI: 0.42 to 0.87]; respiratory [r = 0.69; 95% CI: 0.40 to 0.85]) and a continuous time to exhaustion test following 9 weeks of training in professional youth soccer players (Gil-Rey et al., 2015). As it is likely that the difference in the method of RPE use (i.e. global v differentiated sRPE) could account for the discrepancies between the results, it is still currently unclear how sensitive global sRPE is for monitoring both acute and chronic changes in physical performance.

Moreover, the coefficient of determination for these relationships suggest that only 50% and 48% of the change in aerobic fitness can be explained by muscular and respiratory sRPE, respectively. This clearly demonstrates that sRPE alone cannot account for all of the training-induced stress in soccer, a sport involving substantially less physical contact compared to rugby league and a narrower range of training modes.

Whilst the studies discussed provide valuable information on the dose-response validity of current internal training load methods, they have focused predominately on the dose-response relationship with chronic adaptations, which can be suggested to be aligned with adaptations within the cardiopulmonary system (e.g. Δ velocity at lactate threshold) (Akubat et al., 2012; Manzi et al., 2013). As discussed in section 2.2. within Selye (1956) general adaptation syndrome and Banisters (1991) fitness-fatigue model, following a given bout of training, there is an acute reduction in physical function and performance. Establishing the acute dose-response relationships of training load measures is important to determine, as chronic dose-response relationships may not occur if acute relationships do not. This information is also useful for practitioners to gauge the likely changes in physical status following acute bouts of training. Further, given the longitudinal design, these studies have also grouped training load data from all training modes together. While theoretically it is the internal load that is required to initiate training-induced adaptations, questions remain as to the validity and adequacy of current individual internal load methods to represent this theoretical construct across the variety of physiological stresses imposed and across all modes of training (Weaving et al., 2014). This is an important area to consider, as previously in chapters five, six and seven, we have shown that the training mode influences the variance explained by individual measures used to represent either the external or the internal training load.

However, the influence of training mode on the dose-response relationship between measures of the external and internal training load and changes in physical performance has yet to be established. It is difficult to investigate the effect of training mode upon those relationships within a professional team sport setting over a chronic training period, as the training loads accumulated across all training modes are likely to contribute to any change in chronic measures of training outcome. Therefore, the aim of the current study was to (1) determine the dose-response relationship between individual external and internal training load measures and acute changes in physical performance following a single bout of conditioning and speed training (2) to establish the effect of training mode on those relationships.

8.2. Methods

Participants completed three indoor testing sessions, each separated by 7 days. Each testing session on the same day and at the same time of day to limit circadian influences on the performance tests (Drust et al., 2005). During the second and third testing sessions, participants either completed a 45-minute speed or conditioning training session which each participants order was determined in a randomised cross-over design. Participants were asked to refrain from any strenuous activity during the 48 hours preceding each testing session. Prior to testing, participants completed a standardised warm-up consisting of 5 minutes of self-paced low-intensity running and mobility exercises. During all testing procedures, participants wore a commercially available GPS unit (Optimeye X4, Catapult Innovations, Scoresby, Victoria) with the associated heart rate telemetry (T31 coded, Polar, Oy, Finland). During the first visit, participants completed baseline measures of performance - countermovement jump (CMJ), 20-m sprint and Yo-Yo Intermittent Recovery Test 1 (Yo-Yo IRT1)), with this order maintained throughout the study period.

During the CMJ, participants were required to execute a maximal vertical countermovement jump on a jumping mat (SmartSpeed Jump Mat, Fusion Sport, HaB International Ltd, Warwickshire, UK). Participants were instructed to place their hands on their hips. They then self-selected the depth of the countermovement from an extended leg position down and immediately into a maximal concentric movement for maximal height. Participants completed three jumps, with the highest jump used for further analysis (Gil-Rey et al., 2015). Following the completion of the CMJ, players undertook sprint testing. The sprint testing consisted of three maximal sprints of 20 m, with 60 s rest between each sprint. Running time was recorded using a photocell timing system (SmartSpeed Timing Gate, Fusion Sport, HaB International Ltd, Warwickshire, UK). Participants performed the sprint from a standing start, with their front foot placed 0.5 m behind the start line. Split times were recorded at 10 m and 20 m. The fastest run time from the three attempts was used for further analysis. Following the sprint testing, players performed the Yo-Yo Intermittent Recovery Test 1 (Yo-Yo IRT1). Participants completed 2 x 20 m shuttle runs interspersed with 10 s of active recovery until volitional exhaustion or until they failed to meet the distance twice at the commencement of the beep as per previous methods (Bangsbo, Iaia & Krustrup, 2008). The total distance run was used for further analysis. The Yo-Yo IRT1 has shown good reliability (ICC: r = 0.98 and CV = 4.6% (Krustrup et al., 2003)). The highest heart rate recorded during the Yo-Yo IRT1 was used as the participants HR_{max}. Participants also provided a rating of perceived muscle soreness prior to the first testing session to assess baseline measures of perceived muscle soreness as used previously (McLean et al., 2010). The rating was given using a 5-point Likert scale ranging from 1 (very sore) to 5 (feeling great) (McLean et al., 2010). Participants then completed the questionnaire 24 hours post completion of testing sessions 2 and 3.

During the second testing session, participants either completed a 45-minute speed or conditioning training session and again completed CMJ, 20 m sprint and Yo-Yo IRT1 at 10 minutes post-training. During the third testing session, the same procedures were completed with the exception of the training mode, where participants completed the final mode. The changes in the performance measures following either speed or conditioning training were compared to the baseline values collected during the first testing session. Due to the indoor nature of testing and the subsequent unavailability of orbiting satellites, PlayerLoad™ was used to represent the external training load with HREI and sRPE collected to represent the internal load.

During the speed training session, participants first completed 16 x 10 m maximal effort sprints with 90 s recovery between sprints. Following a 4 min recovery period, participants then completed 12 x 20 m maximal effort sprints with 90 s recovery between sprints.

During the conditioning session, participants first completed 8 min of continuous self-paced 20-metre shuttle runs followed by 4 min of 20-m shuttle active recovery. Following the completion of a 4-minute passive recovery interval, participants then completed 2 x 2 min of shuttle runs for maximal distance (1st set: 20 m shuttles, 2nd set: 10 and 20 m shuttles) with 2 min of active recovery between bouts. Following four minutes of passive recovery, participants then completed 2 x 5 x 30 s, 10 and 20 m maximal shuttle runs with 30 s recovery between efforts and 1-min active recovery between sets. Finally, following 4 min of passive recovery, participants completed 4 x 20 s 20 m maximal shuttle runs with 10 s passive recovery between bouts. The aim of the conditioning session was to expose participants to sets of continuous based running that, as the session progressed, exposed the participants to increasing running intensity with a simultaneous reduction in duration. The session durations for both conditioning and speed sessions were both set to 45 minutes.

8.2.1.Statistical Analysis

Descriptive results are shown as means ± standard deviation. Following assumption verification, differences in sRPE, PlayerLoad™ and HREI between conditioning and speed training were determined using paired t-tests. Pre to post differences in CMJ height, 10 and 20 m sprint time and the metres completed during the Yo-Yo IRT1 following conditioning and speed training were also determined using paired t-tests. Statistical significance was set at $P < 0.05$. Based on 90% confidence intervals, the thresholds used to assign qualitative terms to chances were as follows: <1% almost certainly not, <5% very unlikely; <25% unlikely; <50% possibly not; >50% possibly; >75% likely; >95% very likely; >99% almost certain (Batterham & Hopkins, 2006). The magnitude of difference (expressed as Cohen's *d*) was considered practically meaningful when the likelihood was ≥ 75%. Cohen's *d* effect sizes (ES) of 0.00-0.19, 0.20-0.60, 0.61-1.19, and >1.20 were considered trivial, small, moderate and large, respectively (Hopkins, Marshall, Batterham & Hanin, 2009).The relationships between the different training load methods and acute changes in performance measures were determined using Pearson's product-moment correlation coefficients. Qualitative interpretations of the correlation coefficients, defined by Hopkins (2002) (0– 0.09 trivial; 0.1–0.29 small; 0.3–0.49 moderate; 0.5– 0.69 large; 0.7–0.89 very large; 0.9–0.99 nearly perfect; 1 perfect) were provided for all correlations. Correlations with a confidence interval ranging from substantially positive (> 0.1) to substantially negative (< -0.1) were deemed 'unclear'. The Statistical Package for the Social Sciences (SPSS) (Version 22.0 for Windows; SPSS Inc, Chicago, IL) was utilised to conduct the analyses.

8.2. Results

The mean training loads during conditioning for sRPE, PlayerLoad™ and HREI were 225 ± 51 AU, 329 ± 62 AU and 88 ± 14 AU respectively. The mean training loads during speed for sRPE, PlayerLoad™ and HREI were 90 ± 59 AU, 118 ± 39 AU and 37 ± 16 AU respectively. There was an *almost certainly* large difference in sRPE (mean difference: -163 ± 68 AU; *P* = <0.0001; 90% CI: -220 to 107; ES = -3.57), *almost certainly* large difference in PlayerLoad™ (mean difference: -293 ± 72 AU; *P* = <0.0001; 90% CI: -353 to -233; ES = -7.23) and an *almost certainly* large difference in HREI (mean difference: -56 ± 17 AU; *P* = <0.0001; 90% CI: -70 to -42; ES = -4.04) between conditioning and speed training.

During conditioning training there were *unclear* relationships between sRPE and PlayerLoad™ (r = 0.01; 95% CI: -0.59 to 0.61; *P* = 0.98), sRPE and HREI (r = -0.10; 95% CI: -0.66 to 0.53; *P* = 0.77) (Figure 7.2) and PlayerLoad™ and HREI (r = -0.06; 95% CI: -0.56 to 0.64; *P* = 0.87). During speed training there was a *very likely* very large association between sRPE and PlayerLoad™ (r = 0.72; 95% CI: 0.03 to 0.95; *P* = 0.04), an *unclear* association between sRPE and HREI (r = 0.53; 95% CI: -0.28 to 0.90; *P* = 0.18) (Figure 7.2) and *very likely* very large associations between PlayerLoad™ and HREI (r = 0.81; 90% CI: 0.25 to 0.96) during speed training.

Following speed training there was a *very likely* small decrease in CMJ height (mean change: -1.93 cm; 95% CI: -0.61 to -3.26; *P* = 0.01; ES = 0.28) and a *very likely* small decrease in metres completed during the Yo-Yo IRT1 (mean change: -125 m; 95% CI: 16 to 234; *P* = 0.03; ES = 0.33).

Following speed training an *almost certainly* large increase in perceived muscle soreness (mean change: -2.50 points; 95% CI: -1.86 to 3.13; *P* < 0.0001; ES = 3.84) was observed compared to baseline. *Most likely* trivial and small pre to post differences in 10 (mean change: -0.03 s; 95% CI: -0.07 to 0.02; *P* = 0.24; ES = -0.16) and 20-metre (mean change: -0.05 s; 95% CI: -0.12 to 0.01) sprint time were observed following speed training compared to baseline.

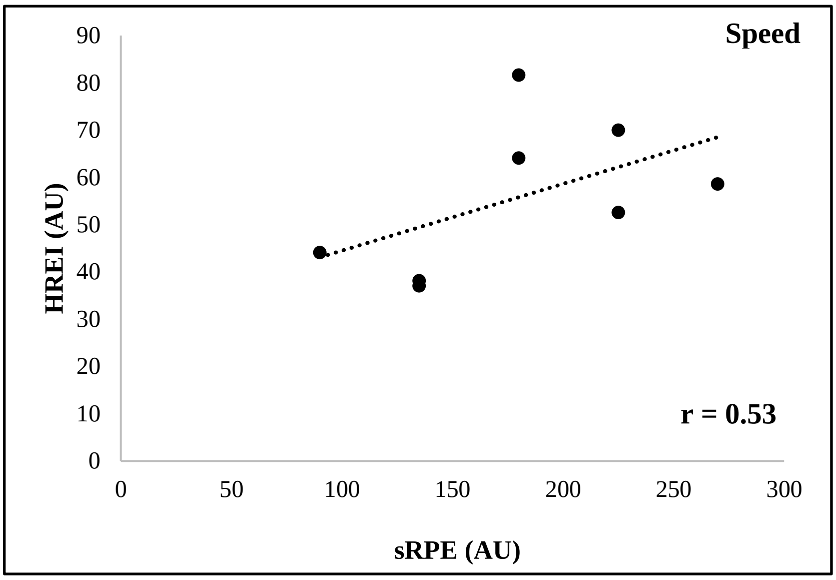
Following conditioning training there was an *almost certainly* moderate decrease in CMJ height (mean change: -4.23 cm; 95% CI: -1.82 to -6.65; *P* = 0.003; ES = 0.73) and an *almost certainly* moderate decrease in the metres completed during the Yo-Yo IRT1 (mean change: -225.45 m; 95% CI: 109 to 342; *P* = 0.002; ES = 0.66) compared to baseline. Following conditioning training there was an *almost certainly* large increase in perceived muscle soreness (mean change: -2.27 points; 95% CI: -1.53 to 3.01; *P* = < 0.0001; ES = 3.54) compared to baseline. *Most likely* trivial small pre to post differences in 10 (mean change: -0.06 s; 95% CI: -0.13 to 0.00; *P* = 0.06; ES = -0.40) and 20 m (mean change: -0.09 s; 95% CI: -0.16 to 0.01; *P* = 0.03; ES = -0.49) sprint time were also observed following conditioning training compared to baseline.

Table 8.1 highlights the correlation coefficients during conditioning and speed training for the training load measures and changes in performance measures.

Table 8.1. Pearson's product-moment coefficients and 95% confidence limits during conditioning and speed training for all training load measures correlated to acute changes in a variety of performance measures.

	Δ CMJ	**Δ 10 m**	**Δ 20 m**	**Δ Yo-Yo IRT1**	**Δ Muscle Soreness**
	R [95% CL]	R [95% CL]	R [95% CL]	R [95% CL]	R [95% CL]
Conditioning (n = 11)					
sRPE	-0.16[S]	0.03[T]	0.12[S]	**-0.57[L]**	-0.40[M]
	[-0.69 to 0.49]	[-0.58 to 0.62]	[-0.43 to 0.61]	**[-0.87 to -0.05]**	[-0.81 to 0.26]
Likelihood	*Unclear*	*Unclear*	*Unclear*	***Likely***	*Unclear*
PlayerLoad™	-0.12[S]	-0.29[S]	-0.16[S]	-0.20[S]	-0.33[M]
	[-0.67 to 0.52]	[-0.76 to 0.38]	[-0.69 to 0.49]	[-0.71 to 0.45]	[-0.78 to 0.34]
Likelihood	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*
HREI	0.04[T]	-0.48[M]	-0.32[M]	0.00[T]	0.17[S]
	[-0.57 to 0.62]	[-0.84 to 0.17]	[-0.77 to 0.35]	[-0.60 to 0.60]	[-0.48 to 0.70]
Likelihood	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*
Speed (n = 8)					
sRPE	-0.03[T]	-0.41[M]	-0.51[L]	**0.63[L]**	-0.12[S]
	[-0.72 to 0.69]	[-0.86 to 0.41]	[-0.89 to 0.30]	**[0.01 to 0.90]**	[-0.76 to 0.64]
Likelihood	*Unclear*	*Unclear*	*Unclear*	***Likely***	*Unclear*
PlayerLoad™	0.09[T]	-0.16[S]	-0.27[S]	0.36[M]	-0.01[T]
	[-0.66 to 0.75]	[-0.78 to 0.61]	[-0.82 to 0.54]	[-0.46 to 0.85]	[-0.71 to 0.70]
Likelihood	*Possibly Not*	*Unclear*	*Unclear*	*Unclear*	*Unclear*
HREI	0.49[M]	-0.43[M]	-0.46[M]	0.36[M]	0.44[M]
	[-0.33 to 0.89]	[-0.87 to 0.39]	[-0.88 to 0.36]	[-0.46 to 0.85]	[-0.38 to 0.87]
Likelihood	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*

Hopkins (2002) qualitative correlation descriptors: T, trivial (0–.09); S, small (.1–.29); M, moderate (.3–.49); L, large (.5-.69); VL, very large (.7–.89); nearly perfect (.9–.99). Abbreviations: CMJ, countermovement jump; Yo-Yo IRT1, yo-yo intermittent recovery test level 1; sRPE, session rating of perceived exertion; HREI, heart rate exertion index. *Significant at .05 level. **Significant at .001 level. ***Significant at .0001 level.



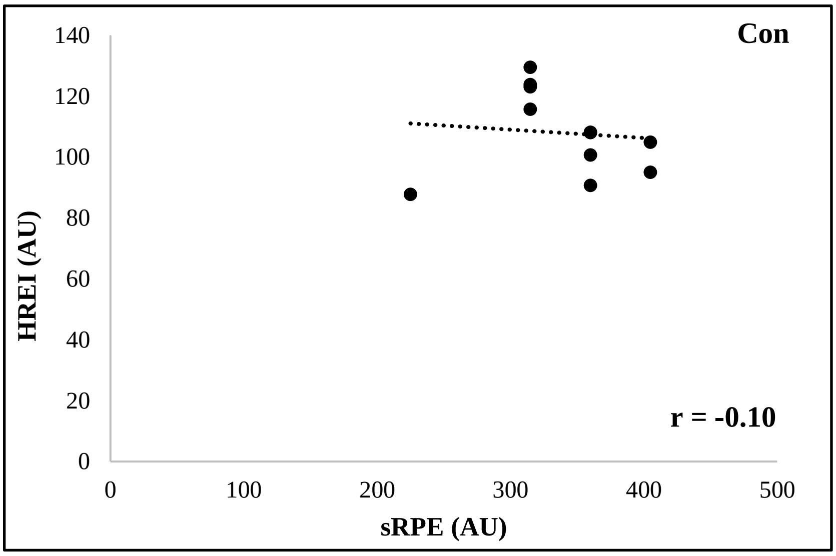


Figure 8.1. Scatterplot showing the relationship between sRPE and HREI during speed (top scatterplot) and conditioning (bottom scatterplot) training.

8.3. Discussion

In the current study, differences in the organisation of the training mode (e.g. exercise to rest ratio) resulted in large increases in the perceptual, heart-rate- and accelerometer-derived methods used to represent the internal and external load during conditioning training compared to speed training. Those differences existed despite their identical session duration (45 min). This finding provides further evidence that the training mode influences the relative external and internal demands imposed on rugby league players and supports previous findings reported in Chapter 4 of the thesis. The differences in demands between training modes appear to influence the strength of the relationships between methods used to represent the external and internal load, with much stronger relationships observed between measures during speed training as opposed to conditioning training. For example, whilst *unclear* trivial relationships were observed between sRPE and PlayerLoad™ (r = 0.01; 95% CI: -0.59 to 0.61; P = 0.98) during conditioning training, *very likely* very large association between sRPE and PlayerLoad™ (r = 0.72; 95% CI: 0.03 to 0.95; P = 0.04) were observed between the same measures during speed training. Whilst the *unclear* relationships found during conditioning limit the inferences made, the findings support our findings throughout the thesis and of others (Alexiou & Coutts, 2008; Lovell et al., 2013), which suggests the training mode influences the strength of the relationships, and therefore the amount of variance explained by individual methods of training load quantification.

However, looking at mode-specific relationships, the trivial associations (r = -0.10 to 0.01) observed between the training load measures during conditioning training conflicts with our findings in Chapter 7, as much stronger relationships were observed between the same measures (r = 0.55 to 0.73). Stronger relationships during conditioning have also been reported in previous studies (Alexiou & Coutts, 2008; Lovell et al., 2013). In particular, in the present study only a single conditioning session was used in the correlation analysis, compared with a mean of 28 ± 5 conditioning sessions provided by 23 players within the study in Chapter six. The possible greater variety in the organisation of the conditioning sessions included within the analyses (12 players providing 28 sessions) during the study in Chapter 7, coupled with differences in sample size between the studies, could account for some of the discrepancies in the strength of the relationships. The influence of sample size and between-subject correlation analysis is highlighted in Figure 8.1, where during conditioning, homogeneity in sRPE is present between subjects with four players providing the same RPE (RPE = 8; 36% of total sample) despite considerable variation in the acute changes in performance response following both conditioning and speed training. For example, the coefficient of variation (CV%) in changes to Yo-Yo IRT1 performance following conditioning and speed training were -61% and -56% respectively. This also provides further evidence of the inter-individual variability in response to the same prescribed external load (Bouchard & Rankinen, 2001). Establishing how methods used to quantify the training load relate to this inter-individual variability in changes in physical performance should be considered to examine the assumption of training load validity rather than solely correlating with other available 'criterion' measures of load (Manzi et al., 2009; Akubat et al., 2012; Manzi et al., 2013). While the relationships between internal training load methods with changes in fitness across a chronic training period in professional football players have previously been reported (Akubat et al., 2012; Manzi et al., 2013), this is the first examination into how both external and internal training load measures relate to acute changes in physical performance following different modes of training.

The current study is the first to observe meaningful relationships between sRPE and acute changes in Yo-Yo IRT1 performance following both conditioning and speed training. This suggests that the between-subject variability of sRPE is capable of reflecting the variability in acute changes in maximal, intermittent, team-sport specific running performance that greatly taxes both aerobic and glycolytic energy pathways (Krustrup et al., 2003) across different modes of training. This is supported somewhat by previous findings, where meaningful relationships have been reported between differentiated sRPE (muscular and respiratory) and likely small changes in a continuous time to exhaustion test following 9 weeks of training in professional junior football players (Gil-Rey et al., 2015). However, Akubat et al. (2012) observed no significant relationship between sRPE and the changes in a multitude of measures of adaptation (e.g. change in velocity at lactate threshold) following 6 weeks of training in professional junior football players. While the differences in sRPE method (global v differentiated RPE), test (Yo-Yo IRT1 v continuous time to exhaustion), study period (acute v chronic) and sample size limit the comparisons between investigations, the results of the present study provide initial evidence of the potential acute dose-response validity of sRPE. This coupled with the low cost and simplicity in data collection ensures sRPE is an attractive method to promote the widespread quantification of an individual's internal training load. Whilst investigations into dose-response sRPE validity are limited, there is a plethora of research that supports the validity of sRPE due to the meaningful relationships observed with 'criterion' measures of training load (Impellizzeri et al., 2004; Alexiou & Coutts, 2008; Lovell et al., 2013). However, methods that have previously been utilised as criterion methods have themselves failed to relate to changes in the outcomes of training (Akubat et al., 2012). This is supported somewhat in the current study. For example, despite likely large associations between sRPE and HREI (r = 0.53; 90% CI: -0.14 to 0.87; $P = 0.18$) during speed training, only sRPE demonstrated meaningful (likely large) associations with the very likely small changes in Yo-Yo IRT1 performance following this training mode. This, coupled with previous findings (Akubat et al., 2012), highlights the potential limitations of assessing training load validity by correlating with 'criterion' measures of training load as previously done (Impellizzeri et al., 2004; Alexiou & Coutts, 2008).

Additional investigation on how methods used to represent the external load relate to acute training outcomes is useful to determine the validity of this theoretical construct to reflect the outcomes of training and its implementation as a possible proxy of the internal training load (Impellizzeri et al., 2005). In the current study, PlayerLoad™, used to represent the external training load, showed only a meaningful moderate relationship with the change in perceived muscle soreness following conditioning training. Given the higher frequency of meaningful relationships found by sRPE, this somewhat supports the previous notion that it is the theoretical internal training load that governs training-induced adaptations and subsequent training outcomes (Impellizzeri et al., 2005; Alexiou & Coutts, 2008; Manzi et al., 2009; Akubat et al., 2012; Lovell et al., 2013; Manzi et al., 2013). However, multi-factorial responses following professional rugby league competition have previously been proposed (Twist & Highton, 2013) and it is likely, although to varying magnitudes, that multi-factorial responses will be present following different prescribed training modes. In order to satisfy the assumption of validity for individual training load methods, those individual methods should show meaningful relationships across the varied responses. In order to make fully informed decisions regarding the overall training process, practitioners require individual measures to reflect changes across the different responses, given their potential to contribute differently to a variety of acute and chronic outcomes of training (Banister, 1991; Chiu & Barnes, 2003; Impellizzeri et al., 2005; Colby et al., 2014). In the current study, only a single training load method (sRPE) displayed a meaningful relationship with changes in the same measure of performance across both modes of training. However, this did not occur across each of the performance tests. Further, within the relationships reported there is possibly a meaningful proportion of variance unexplained by individual training load methods. For example, the amount of variance explained by sRPE in the changes in Yo-Yo IRT1 following speed training was 40%. Determining whether a combination of training load methods explains an additional meaningful proportion of the variance in changes in the outcomes of training compared to an individual method is an important consideration. However, a major limitation of the present study and with other research in this area (Stagno et al., 2007; Manzi et al., 2009; Akubat et al., 2012) is the small sample size. This ultimately limited the capability of statistical analyses, which could answer this question. It is also important to note that the confidence intervals have been reported, and confidence in the inferences regarding the strength of the relationships should be interpreted within those bounds. The frequent wide confidence intervals in the present study appear to limit the inferences drawn from this investigation considerably. To provide further clarity on the findings within this study, additional research with a larger sample size is required. This should include a sample size that permits valid statistical techniques (e.g. multiple linear regression) to assess whether a combination of training load measures better explain the variance in acute changes in physical performance following different training modes compared to individual measures alone. In a practical sense to enable this depth of data collection to be conducted within applied settings, further research should attempt to establish the acute within-individual associations between sRPE and changes in a physical performance test. This could be useful to practitioners to determine a player’s likely short-term maximal physical performance status following the completion of a given locomotor-based training modality. However, the additional load imposed on players due to maximal performance tests such as the Yo-Yo IRT1 is an important consideration for practitioners (Twist & Highton, 2013) and therefore, future research should ascertain the validity and reliability of alternative performance tests that subject players to a minimal load. This would allow the test to be integrated within the routine monitoring practices following the completion of individual training modes over a longitudinal period, which would allow the within-individual relationships to be established further. Investigations such as these would provide useful information for practitioners within the training process-outcome monitoring procedures to optimise further the likelihood of positive training outcomes and simultaneously, for researchers to ascertain the validity of measures of training load quantification.

8.4. Conclusions & Practical Applications

- Conditioning training results in large increases in external and internal demands when compared to speed training.
- Those differences appear to alter the strength of the relationships between external and internal training load methods.
- sRPE appears to be sensitive to changes in perceptions of muscle soreness and maximal, intermittent running performance following different modes of training.
- A method used to represent the external training load was only sensitive to changes in perceptions of muscle soreness following speed training.
- A single training load measure was unable to relate to the acute changes across all performance tests within a training mode.
- The small sample size and wide confidence intervals limit the inferences made within the current study. A larger sample is needed to determine whether a combination of internal and external load measures can better reflect the changes in acute training outcomes.

9. Overall summary and practical applications

9.1. Research Chapters Review

Given the demanding multi-modal training and competition schedules of professional rugby league players, optimising the methods we use to quantify each of those demands is integral to ensure the appropriate individualised periodisation of training. This will assist in maximising performance and minimising negative outcomes such as underperformance and injury risk. In recent years, a number of methods have been adopted by applied practitioners working within professional teams with each demonstrating their own evidence of validity (Section 2.3 and 2.4). Throughout the thesis, the difficulties in adopting suitable criterion method to represent the internal load have been presented. Therefore, the use of a single criterion method is inappropriate to investigate validity of this construct. In addition, given we measure the training load to understand the dose-response relationships with training outcomes such as changes in physical qualities or injury incidence, this approach should be a focus to infer validity. However, the review of the literature highlighted that adopting a single method to represent the training load leaves a considerable amount of unexplained variance in training outcomes. Therefore, multiple training load variables, including external load metrics, might be a better approach to represent the training load or to investigate these dose-response relationships. The review of the literature also emphasised that whilst previous research has highlighted possible 'global' training load validity of individual measures, there was a dearth of information attaining to whether these same training load measurements were valid at the training mode level. Calculating the load typically involves numerous levels of analysis including within each training mode, during each training- or competition-day, and across acute (e.g. 7-days) and chronic (e.g. 28-days) periods of training. However, the load imposed during each training mode contributes to all other levels of training load analysis and consequently ensuring valid quantification is critical to ensure the validity of subsequent load analyses. Therefore, the major aim of the thesis was to determine the effect of training mode on the validity of common measures of both the external and internal training load with particular reference to whether adopting a single training load variable is a valid approach to represent the training load.

The results in section 3 showed that wide differences in the external and internal load are present per minute of training time between different training modes. This suggests that these modes will expose players to different compositions in the magnitude of load. Following this, an important question arises to how these different training structures influence the validity of single training load measures to represent the training load. Across multiple sessions completed over a short-term (4-weeks) training period (Chapter 5), large variations in Body Load™, the total number of impacts and high-speed-distance were found when a singular TL method (sRPE) showed no variation. This provided preliminary evidence that when a single method (sRPE) demonstrates trivial differences in the training load imposed, other training load methods provide additional information. From an applied perspective, adopting a single method to make inferences of the load subjected to players could have potentially negative consequences when making inferences regarding short-term training periodisation. For example, hypothetically, a player may have rated three sessions (via sRPE) the same. Practitioners utilising this data are likely to make inferences that those three sessions are providing the same stimulus and therefore similar responses in the days post-training. However, when considering additional measures of training load, during those three sessions the player was exposed to for example, vastly different high-speed running demands. Given the previously reported association between high-speed running demands and markers of exercise induced muscle damage (e.g. creatine kinase) (Oxendale et al., 2015), it is possible that those three training sessions actually elicited different demands and therefore different magnitudes and variety of response in the days post-training. As a result, practitioners could prescribe inappropriate training loads in subsequent training days and therefore, the implementation of a singular measure of training load quantification might limit the optimisation of the training process. However, the case study approach used within this chapter limits the generalisability of the findings and hence further investigation was required.

To investigate this notion further, an examination into how those differences in the demands of different training modes highlighted in chapter 4 of the thesis, influence the variation explained between individual external and internal training load measures over a chronic period of training was clearly warranted. Previously, researchers investigating load validity had highlighted singular correlations between an individual training load measure, predominately sRPE, with other available measures of both external and internal load in isolation. However, there was limited investigation into whether the variance explained between those different reported relationships (e.g. sRPE & total distance, sRPE & high-speed running) are explaining the same or additional variance. Therefore, multivariate analysis is required to answer this question to which we implemented PCA.

The results presented in chapter 6 of the thesis suggest that the differences in load structure between modes found in Chapter 4 influence the variance explained by individual measures of either internal or external training load quantification. This finding was consistent with the limited research that has reported training load correlations demarcated by training mode (Alexiou & Coutts, 2008; Lovell et al., 2013), where alterations in the strength of the relationships have been reported between different training modes. Within a different professional club and coaching staff, using different measures to represent the internal and external training across an acute, rather than chronic period of training, the results reported within chapter 7 of the thesis provide further evidence that the training mode influences the variance explained by individual measures of external and internal training load. The findings in both chapter 6 and 7 of the thesis, in modes where multiple principal components were identified, individual methods used to represent the internal load appear to provide the same information to a given principal component as determined by their similarly consistent loadings. Conversely, this observation occurred within individual measures used to represent the external training load. For example, in chapter 5, we identified two principal components in skills training. The first principal component explaining 48% of the variance included Body Load™, high-speed distance, and impacts – all measures of external load. The second principal component explaining an additional 20% of the variance included iTRIMP and sRPE – both measures of internal load. Likewise, in chapter 6, we identified two principal components for conditioning training. The first principal component loaded most heavily on HREI and sRPE – both measures of internal load, with the second principal component including PlayerLoad™ and HSD – both measures of external load. Therefore, a possible important practical finding arising is that if practitioners used solely any individual external or internal training load measure, they are unlikely to be accounting for the most variance across all types of training. In some instances, an external training load measure captures the most variance of that particular training mode. Likewise, in other training modes an internal training load measure captures the most variance between the measures. As a result, this strongly suggests that practitioners need to monitor both an external and an internal training load measure in certain training modes, to capture as much information as possible regarding the stress of training. However, to predict training outcomes such as injury, which use regression analyses, multicollinearity between predictor variables (i.e. training load measures) is an issue. This strengthens the use of multivariate techniques such as PCA which can produce new predictor variables which are uncorrelated with each other. For research purposes, techniques such as this warrant further investigation. If the use of multivariate techniques are found to be more predictive of training outcomes, there is a need for athlete management software companies to incorporate this level of analyses as part of what they offer to the fast-paced practitioner to maximise the confidence in the data collected in the field.

9.2. Applications of the thesis to the rugby league practitioner

- SSG and conditioning expose players to the greatest relative external and internal loads.
- Conditioning and SSG games training subject players to similar speed- and accelerative-based running demands per minute of training time although players perceive that conditioning is harder.

- There is a greater proportion of high-intensity running completed whilst accelerating during SSG compared to conditioning whilst players are exposed to a greater proportion of running at constant speeds. These differences should be considered during the planning of training.
- Speed training should be supplemented alongside conditioning/SSG/skills training to expose players to the greatest maximal running stimulus of the four modes.
- Be aware that by using only speed-derived external load methods, the actual external load could be underrepresented during skills training by failing to account for the greater proportion of accelerative-based activity.
- Practitioners should determine the ‘usual’ training load imposed per minute of training time for each training mode. This information can then be multiplied by session duration to understand the likely total load imposed for each training mode to plan future field-based training programmes. For example, if you establish that the typical high-speed distance load for a player is 10 $m \cdot min^{-1}$ and you prescribed SSG for 50 minutes you could plan that this mode would produce 500m of total high-speed running load. This knowledge allows you to manipulate the duration of the session to schedule concurrent modes within a training period.
- To investigate long-term dose-response relationships (e.g. load-injury), practitioners need to include both an external and internal training load measure in their decision making to capture the load imposed across training modes. To ensure valid decisions are made regarding the training programme, these analyses should be refined (i.e. multivariate analysis) and athlete monitoring companies should look to implement these approaches within their software.

9.3. Future Research Directions

The review of the literature and the findings of the thesis suggest that research into the quantification of the training load in professional rugby league is still within its infancy. Anecdotally, skills and resistance training are two of the most frequently utilised training modes throughout the annual training programmes of professional rugby league players. The varied aims of skills training, which encapsulate activities such as tackling and free-running during attacking set-plays, mean there is likely to be considerable variation in the external and internal demands within this training mode both across different individual sessions, positional groups and phases of the season. Therefore, if we are to optimise the monitoring process in professional rugby league, it is important that we strive towards a better understanding of both the dose and response to this specific mode of training and how this varies between positions and individuals. This is difficult to conduct during the season due to congested and concurrent training and competition schedules at the elite level. To assist this, the development of a valid physical performance test that can be routinely conducted during the season, whilst imposing an 'acceptable' magnitude of additional load onto players is important. This notion has been considered in other sports (i.e. AFL) and warrants further investigation (Veugelers et al., 2016). This, in combination with other markers of training response (Twist & Highton, 2013), would allow us to establish the most valid combination of training load methods that can quantify the load imposed onto players during skills training. Further, the influence of training mode on the validity of training load measures investigated within the thesis did not extend to resistance training. The importance of muscular strength/power to successful match performance in rugby league coupled with the resulting high frequency of these sessions means these sessions are likely to contribute a large proportion of the total weekly load. Therefore, given the findings of the thesis, an investigation into whether a combination of external and internal training load methods can reflect the load imposed during this mode also warrants further investigation.

Finally, given the points raised throughout the thesis surrounding the multi-factorial nature of training load, the actual training load measures investigated within this thesis, either external or internal load, will represent a small proportion of the information that is needed to represent the total load in team sports such as rugby league. In the age of wearable technology, it is important to continue to ask questions of the technology to confirm that it measures what it claims to measure but more importantly, as the miniaturisation and validity of wearable technology continues to develops and so too does our capabilities to handle large datasets, we need to take multivariate approaches to combine this rich information to truly integrate this data into decision making in the field (Cornforth et al., 2015).

10. References

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11. Appendices

Participant Letter of Invitation

Department of Sport, Health & Exercise Science

UNIVERSITY OF Hull
Faculty of Science

Project title	The influence of training mode on the acute 'dose-response' relationship between measures of load and changes in fatigue
Principal investigator	Name: Dr Grant Abt Email address: g.abt@hull.ac.uk Contact telephone number: 01482 463397
Student investigator (if applicable)	Name: Dan Weaving Email address: d.weaving@2008.hull.ac.uk Contact telephone number: 07595538734

Dear Sir or Madam

This is a letter of invitation to enquire if you would like to take part in a research project at The Sport, Health and Exercise Science Laboratory, The University of Hull

Before you decide if you would like to take part it is important for you to understand why the project is being done and what it will involve. Please take time to carefully read the Participant Information Sheet on the following pages and discuss it with others if you wish. Ask me if there is anything that is not clear, or if you would like more information.

If you would like to take part please complete and return the Informed Consent Declaration form.

Please do not hesitate to contact me if you have any questions.

Yours faithfully,

Dan Weaving

Participant Information Sheet

Project title	The influence of training mode on the acute 'dose-response' relationship between measures of load and changes in fatigue
Principal investigator	Name: Dr Grant Abt Email address: Contact telephone number:
Student investigator (if applicable)	Name: Dan Weaving Email address: Contact telephone number:

What is the purpose of this project?
The purpose of the project is to determine the sensitivity of common measures of training stress that are utilised in professional Rugby League to common measures of fatigue. This information is used to attempt to maximise each individual's performance and reduce injury risk and will allow us to determine initially which measures of training stress are most suitable for Rugby League.

Why have I been chosen?
We are looking for 18-30 year old men who regularly in Rugby League training and competition, have no existing medical conditions, are not currently taking prescription drugs, and are not suffering from any injuries. You have been sent this information because we believe you might fit these requirements.

What happens if I volunteer to take part in this project?
First, it is up to you to decide whether or not to take part. If you decide to take part you will be given this Participant Information Sheet to keep and asked to complete the Informed Consent Declaration at the back. You should give the Informed Consent Declaration to the investigator at the earliest opportunity. You will also have the opportunity to ask any questions you may have about the project. If you decide to take part you are still free to withdraw at any time and without needing to give a reason.

What will I have to do?
You will be asked to attend three testing sessions held at the Sport, Health and Exercise Science Laboratory at the University of Hull. On arrival, you will be met by the investigator who will brief you on the testing procedures and answer any questions or concerns that you might have. After signing a consent form, the investigator will ask you to complete a pre-exercise medical questionnaire requesting some information on your present state of health. For the first session, you will be required to attend the Sport, Health and Exercise Science laboratory for a baseline battery of tests. You will firstly be required to fill in a questionnaire which will include quantifying your feelings of fatigue, sleep quality, general muscle soreness, stress levels and mood on a scale of 1-5. Following these measures, you will be required to complete a further three tests. This will include a 20-m sprint assessment, countermovement jump and the Yo-Yo intermittent recovery test 1. The sprint assessment will involve sprinting maximally from a standing start position for 20 metres. Immediately following the completion of the 20 metre sprint, you will be required to slow down as quickly as possible back to a standing position. For the countermovement jump test, you will be required to complete a maximal jump on a jump timing mat. You will be required to begin in an upright position with your hands firmly on your hips to which you will then bend your knees rapidly to approximately 90^{o} before jumping as high as possible. Following this you will be required to complete the Yo-Yo intermittent recovery test 1. This test will consist of repeated 2 x 20m runs at an increasing speed which is controlled by audio bleeps from a pre-recorded device. Between each running bout, you will have a 10 second rest period. This is a maximal test and you will be required to run for as long as you feel is possible. You will be given verbal encouragement during the test to ensure maximal exertion. During the test, your heart rate will be recorded using the GPS system (further details below). The following week you required to complete a training session. The training sessions will involve either a conditioning session or speed session to which you will be familiarised to prior to this stage. You will first complete a standardised warm up and following which you will be required to supply the investigator with your perceived level of exertion for the warm up. Following this you will complete the prescribed training session. During the training session, you will be required to wear a GPS device that will be housed within a custom made vest and a heart rate strap that will be situated across your chest. The two pieces of equipment are designed not to impede and are regularly used within elite Rugby League clubs. The devices are designed to assess the demands of the training. You will be fully familiarised with wearing the equipment prior to the commencement of the study. Following the completion of the training session, you will be required to complete the battery of tests again which have been previously described above and will also be required to rate the intensity of the session using a rating of perceived exertion scale. You will be fully familiarised with the scale prior to this point. This testing session is expected to last 75 minutes.

The following week you will be required to complete the training session which you didn't complete in the first training week and will again complete the post-training session battery of tests. This session again is expected to last 75 minutes.

The testing sessions (with the exception of the treadmill test) have been organised with the club captain of HURL to coincide with the training times of the club. Therefore, there is limited extra commitment required outside of your regular training times for this study.

Finally, you will be asked to refrain from engaging in any strenuous or unaccustomed exercise 48 hours before any testing visit and to avoid ingesting food 4 hours before your visit. Please bring and wear comfortable sports clothing and sports shoes for each testing session. After you have completed the tests the investigator will give you a debrief sheet explaining the nature of the research, how you can find out about the results, and how you can withdraw your data if you wish. Water will be available for you to drink throughout your visit, although you will not be able to drink during the time you are performing testing procedures. It is estimated that the total time to complete this study will be five hours. There will be private changing and shower facilities available, situated next to the laboratory, if you wish to use them.

Will I receive any financial reward or travel expenses for taking part?
No.

Are there any other benefits of taking part?
You will gain insight to your current fitness levels and also your current acute response to training sessions which can be used to guide your current training.

Will participation involve any physical discomfort or harm?
Due to the maximal nature of some of the tests, it is possible you may feel some physical discomfort such as nausea. However, as you regularly participate in team sports, you are likely to be accustomed to high intensity exercise. Discomfort may also be present when wearing the mask which collects expired air during the trials. You will be appropriately familiarised with the use of the mask and all other procedures during the familiarisation testing. All efforts will be made during the testing process to make you feel as comfortable as possible.

Will I have to provide any bodily samples (e.g. blood or saliva)?

No.

Will participation involve any embarrassment or other psychological stress?
There will be a small element of psychological stress during the Yo-Yo and treadmill tests as we require you to exercise up to your maximal physical limit. However, as you have been identified as having team sports playing experience, it is likely this feeling will already be familiar with you.

What will happen once I have completed all that is asked of me?
As a participant in the current study, you will receive feedback by email on the results obtained during the study, including any data which you deem useful, by the latest of 6 weeks post testing completion. The student investigator is available to answer any queries you may have regarding personal feedback or any queries on any part of the study. You will be fully debriefed on the current study via a debriefing sheet which will be available following the completion of the testing.

How will my taking part in this project be kept confidential?
From the commencement of the study, as a participant you will be allocated an anonymous participant number that will always be used to identify any data that you provide to us. Name and other details such as your medical details will not be associated with any data collected. The consent and pre-exercise medical questionnaire forms will be stored separately from your data. Any paper records will be stored in a locked filing cabinet with the research team having the only available access. All electronic data will be stored on a password protected PC. Any information you provide will be stored in line with the 1988 Data Protection Act, with data destroyed 5 years following the completion of the study.

How will my data be used?
Any data will only be available to the research team. The data collected will help to produce a study as part of a PhD thesis project and possibly will be published in a peer-reviewed journal. However, it would not be possible to identify you. If you would like a copy of the study we can arrange for you to receive it as soon as it is possible.

Who has reviewed this study?

This project has undergone full ethical scrutiny and all procedures have been risk assessed and approved by the Department of Sport, Health and Exercise Science Ethics Committee at the University of Hull.

What if I am unhappy during my participation in the project?

You are free to withdraw from the project at any time. During the study itself, if you decide that you do not wish to take any further part then please inform the person named in Section 18 and they will facilitate your withdrawal. You do not have to give a reason for your withdrawal. Any personal information or data that you have provided (both paper and electronic) will be destroyed or deleted as soon as possible after your withdrawal. After you have completed the research you can still withdraw your personal information and data by contacting the person named in Section 18. If you are concerned that regulations are being infringed, or that your interests are otherwise being ignored, neglected or denied, you should inform Dr Andrew Garrett, Chair of the Department of Sport, Health and Exercise Research Ethics Committee, who will investigate your complaint (Tel: 01482 463866; Email: a.garrett@hull.ac.uk

How do I take part?

Contact the investigator using the contact details given below. He or she will answer any queries and explain how you can get involved.

Name: Dan Weaving Email: d.weaving@2008.hull.ac.uk Phone: 07595538734 ormed Consent Declaration

Project title	The influence of training mode on the acute 'dose-response' relationship between measures of load and changes in fatigue
Principal investigator	Name: Dr Grant Abt Email address: g.abt@hull.ac.uk Contact telephone number: 01482 463397
Student investigator (if applicable)	Name: Dan Weaving Email address: danielweaving@gmail.com Contact telephone number: 07595538734

Please

Initial

I confirm that I have read and understood all the information provided in the Informed Consent Form (EC2) relating to the above project and I have had the opportunity to ask questions.

I understand this project is designed to further scientific knowledge and that all procedures have been risk assessed and approved by the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull. Any questions I have about my participation in this project have been answered to my satisfaction.

I fully understand my participation is voluntary and that I am free to withdraw from this project at any time and at any stage, without giving any reason. I have read and fully understand this consent form.

I agree to take part in this project.